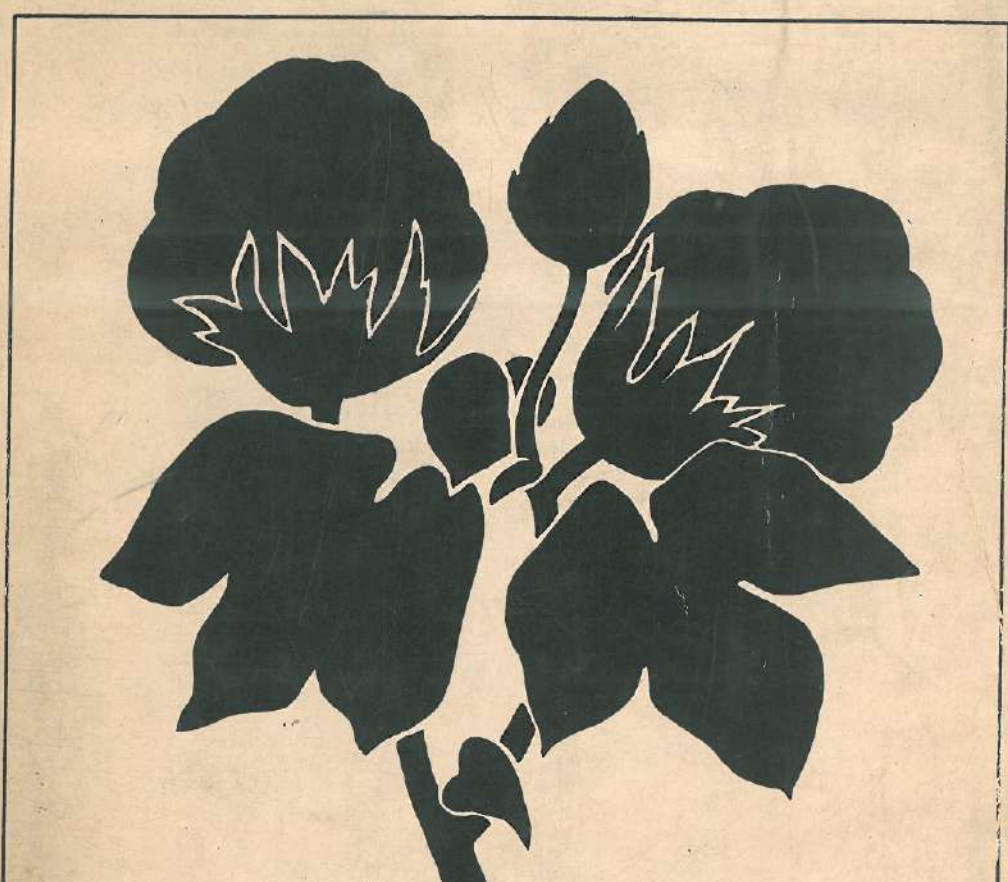
COTTON in a Competitive World



The Textile Institute

Cotton in a Competitive World

Papers of the 63rd Annual Conference
of The Textile Institute
Organized in collaboration with
The Textile Association of India

January 18th–23rd 1979
Indian Institute of Technology, Delhi

Edited by P W Harrison BSc CText FTI MIInfSc

The Textile Institute, Manchester 1979

The Textile Institute
10 Blackfriars Street
Manchester M3 5DR

ISBN 0 900739 30 4

Produced by Professor D. S. Varma of the Indian Institute of Technology, Delhi.
Photosetting and printed at Thomson Press (India) Limited, Faridabad, India

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1—COTTON: ITS POSITION AND PROGRESS IN WORLD TEXTILE MARKETS

By H. E. Koedam

Cotton's position in the textile market is surveyed, and it is shown how in recent years it has met the challenge set by the increasing production of synthetic fibres. The part played by the International Institute for Cotton is outlined, and a confident forecast is made of cotton's likely future. Preferences of users of cotton and polyester-fibre fabrics are discussed, and it is shown that cotton is regarded very favourably by the majority of those included in this survey.

1. INTRODUCTION

As the leading raw material for textile manufacture, cotton's current situation and outlook are closely intertwined with the supply-and-demand trend for textiles in Western Europe and, indeed, world-wide. The many complex issues that must be understood, interpreted, and harnessed to survive in the dynamic and highly competitive textile business are decisive not only for the future of the textile manufacturer, but also for cotton as well.

2. COTTON'S POSITION IN THE TEXTILE MARKET

Cotton, which has been used as a textile fibre for 5000 years, accounted fifty years ago for no less than 85% of the world consumption of major fibres. But, in the first two decades following the end of World War II, cotton's monopolistic position in the textile market was ruptured by the development and subsequent market introduction of a series of man-made fibres, particularly the synthetic fibres. In the mid-1960s, cotton's share in the world's mill consumption of fibres had dropped rapidly to not much more than 60%. The share of wool, the other major natural fibre, had shrunk to 8%. Meanwhile, the man-made fibres had captured 30% of the total world fibre consumption in a few decades.

Several leading cotton-producing countries could not accept this rapid decline of cotton in the textile market. They were convinced that cotton could remain a truly viable and competitive raw material for textile manufacturing provided that consumers could be persuaded to prefer, and buy, cotton textiles at a price that would provide a rewarding income to the farmer and an adequate profit to the textile manufacturer. This revival of cotton would, they realized, not happen by itself. Cotton's market position had to be defended and strengthened by modern, aggressive techniques, particularly in its major export markets of Western Europe and Japan. Accordingly, the International Institute for Cotton was established in 1966 and started its marketing activities in 1967.

To understand cotton's market performance to-day and its potential in the years ahead, it is necessary to trace briefly the developments that have taken place since 1967. When the Institute set out to develop its marketing strategy twelve years ago, market-research studies were carried out to determine cotton's image profile at the consumer level. These surveys revealed that consumers were aware of and appreciated several positive fibre properties of cotton, such as its high degree of absorbency and non-irritability to the skin, its thorough launderability, its vivid prints, and its versatility. Unfortunately, as the market data also clearly showed, these positive considerations were not enough to make the consumers prefer and purchase cotton textiles. They compared cotton negatively with synthetic fibres in several essential respects: cotton needed ironing and a relatively long time to dry, it wrinkled in wear, cotton products had poor lustre, and—most important of all—they were not fashionable. Consumers regarded cotton textile items as cheap, not only in money terms but above all in terms of something outdated, not fitting to their life style.

For cotton to succeed as a viable fibre in the textile market, this image had to be changed. In its marketing and sales-promotion activities, IIC capitalized on the advantages of cotton while concentrating its technical research and development projects on overcoming the major disadvantages of cotton. The marketing campaigns, carried out in co-operation with leading textile manufacturers and retailers, featured modern, attractive cotton products.

By the end of the 1960s and the beginning of the 1970s, market-research surveys were already pointing to a positive change in consumer opinions about, and attitudes towards, cotton and its products. Consumers in Western Europe and Japan increasingly described cotton as a comfortable, up-to-date material, suitable for modern life and good enough to follow—in fact, good enough to lead—fashion trends. Such changed attitudes have, of course, helped tremendously in the acceptance and sales of 100% cotton products.

At the same time, promising research progress has been made, and several processes, such as the liquid-ammonia technique and the M.A. (minimum-application) process, have reached the stage of commercial utilization.

Meanwhile, cotton's progress in regaining a strong position in the textile markets of Western Europe and Japan has continued. The stage has now been reached where not only is cotton's image positive in the mind of the modern consumer but the consumer's appreciation of cotton and its products in many respects also exceeds their appreciation of the competing fibres, including polyester fibre. The latter is, of course, cotton's most direct competitor. An IIC study, assigned to a market-research agency in Sweden, one of the most sophisticated textile markets in Western Europe, measured among other things consumer opinions about cotton compared with other fibres. Women of 18–26 years and 27–35 years were asked to give a rating to their appreciation of cotton and polyester fibre with respect to a series of fibre properties and other relevant factors. Apart from ironing considerations, cotton received a very favourable score, as shown in Table I. Similar studies confirm the results obtained in Sweden.

This favourable attitude of consumers towards cotton products is confirmed by a number of surveys measuring, among other things, the actual volume of

Table I

Attitudes towards Clothing Made of Cotton and Polyester Fibre

	Women of 18–26 Years		Women of 27–35 Years	
	Cotton	Polyester Fibre	Cotton	Polyester Fibre
Breathes	6.8	4.0	7.0	2.3
My favourite material	6.6	4.0	6.8	2.5
Comfortable (in general)	7.0	3.0	6.9	2.6
Comfortable (when sweating)	5.8	3.8	6.3	2.6
Cool	6.9	4.1	6.8	2.8
Soft to the skin	6.8	4.0	6.7	2.9
Modern	6.8	3.3	6.4	3.6
Suits to-day's life style	6.6	4.0	6.6	3.9
Washes clean	5.8	5.5	6.8	4.3
Easy to wash	6.5	5.5	5.7	4.4
Easy to sew	6.8	4.1	6.6	4.5
For going to a party	5.4	4.8	6.0	4.5
Easy to iron	1.4	5.3	4.7	4.9

7 = very positive
1 = very negative

consumer purchases of major textile products by fibre content. As an illustration, the purchase data are given in Table II for three EEC countries—West Germany, the Netherlands, and the United Kingdom—for the full calendar year 1977 compared with 1976.

Table II

Consumer Purchases for Major End-uses

	Share of 100% Cotton Items (1977 Compared with 1976)	
	Stable/up	Down
W. Germany	22	4
The Netherlands	15	11
The U.K.	15	8

After the considerable rise in the share of 100% cotton items in the Dutch purchases of these major textile products in previous years, cotton's progress in 1977 slowed down in the Netherlands. Purchase of 100% cotton items for fifteen end-uses remained stable or went up, against a fall of the 100% cotton items in eleven end-uses. In Germany and the U.K., however, the 100% cotton items either maintained or expanded their share in the large majority of the end-uses covered in the survey.

3. COTTON'S FUTURE

Major factors influencing over-all textile consumption are the projected trend of general economic activity, the specific movement of the textile cycle in the years to come, and the increasing choice of goods and services offered to the consumers, while their incomes may be restrained for a number of years. These factors, together with several other considerations, will obviously have an impact on textile offtake in general. Cotton's outlook in terms of actual sales of cotton products is, of course, subject to these over-all trends and influences. But again, within the context of the market of to-morrow, whether in 1980 or 1985, cotton must defend and strengthen its place in the textile market.

Demand creation by marketing efforts and product development is the task before IIC, to be carried out in co-operation with various cotton organizations in European countries. In this respect, reference should be made to the proposal of the World Bank, UNDP, and the Rockefeller Foundation to create a substantially expanded programme for cotton marketing and research. This proposal is the result of a direct request from IIC; the acceptance and the implementation of this extensive plan would be a multiplication of the current efforts of the Institute.

As well as the demand side, it is necessary to consider the supply side for cotton in the years ahead. A major question is whether there will be sufficient cotton available in the future at prices that are competitive in comparison with other fibres, mainly polyester fibre.

Some representatives of the man-made-fibre sector of the textile industry have expressed the view that the supply of cotton in future will not be sufficient to meet demand because, as they say, 'the arable land in the world is needed for food crops' or 'the hungry world can no longer afford to allocate land for the production of industrial raw materials, like cotton'. This false claim should be refuted once and for all because it is often echoed in the trade and consumer press. Cotton is indeed grown for the lint providing the raw material for the textile industry. But, in terms of weight, two-thirds of the cotton crop consists of seed that is processed into high-quality edible oil and protein-rich cottonseed cake for animal nutrition. Cottonseed-oil production has amounted to about 3 million tons annually in recent years. Production of cottonseed cake has varied between 3.2 and 3.7 million tons annually. This huge volume of cotton by-products, ranking very high in the world supply of edible oil and vegetable-oil cake, is produced—together with 13 million tons of cotton fibre—on no more than 2.2% of the world's arable land cultivated for crops. If pasture land is added to the area under crop, the total world acreage allocated to cotton is only 0.7% of the world surface that is actually used for agricultural purposes.

If consideration is also given to the fact that cotton is a non-perishable, high-value cash crop providing employment and income to at least 125 million people in the developing world, the social and economic need to expand, not reduce, cotton production is obvious. Fortunately, there is sufficient potential to increase world cotton production in response to a larger demand, as follows.

> Firstly, cotton acreage in Latin and North America, Africa, and Australia can be expanded if the demand justifies it. The U.S.S.R. has been very successful in increasing its production in the last few decades, and that country has further plans to expand its cotton acreage. Several countries in Asia, such as Afghanistan, Thailand, the Philippines, and Indonesia, have made promising progress in growing more cotton.
>
> Another way of meeting a rising demand is to maximize the cotton yield per acre. There are still great possibilities in this respect. It is interesting that 30.4 million bales of cotton were produced annually on some 82 million acres in the period 1934–38. By the 1974–75 season, the same acreage yielded a crop of 64.6 million bales.

In summary, cotton interests all over the world and their governments vigorously reject the suggestion made by man-made-fibre interests that the production of cotton should be abandoned or even be curtailed. Indeed, the goal of the world cotton community is to maintain and strengthen the market potential for cotton and its products.

Price is another important consideration in anticipating cotton's potential in the years ahead. It is a fact that cotton is no longer the cheap fibre of the 1950s and 1960s. Since the beginning of this decade, the price of cotton has moved steadily upward, albeit with some sharp fluctuations for short periods. This long-term rise partly reflects the inflationary trend apparent everywhere in the world, not only for cotton but also for most other commodities and manufactured goods. However, in addition, the renewed consumer interest in cotton has once again made cotton a desirable textile raw material, for which a fair price must be paid. Except for short-term price fluctuations, owing to various factors such as the impact of weather conditions and currency unrest combined with speculative movements, there is no reason to expect a steep rise in cotton's price level in the years to come. Although cotton, selling currently at approximately US $ 0.70–0.74 per lb in Western Europe, is now slightly more expensive than cotton-type polyester-fibre and rayon staple, it is very likely that the difference in the price of cotton and these man-made fibres will narrow in the near future. It is no secret that the man-made fibre producers have experienced huge losses in recent years: in Western Europe alone, these amounted to approximately $ 1 billion in 1975, $ 600 million in 1976, and again almost $ 1 billion in 1977. The only way to cut these losses and to operate again on a profitable level is to increase the price of the man-made fibres as fast as the market can absorb such an increase.

Thus, the cotton-supply situation in terms of volume and price should be judged healthy in the years to come. Cotton's demand situation, as is true for all products offered in a free-economy, competitive-market concept, needs support to stimulate consumer offtake. In co-operation with industry and trade, IIC is fully prepared to give this support to cotton. This assignment is now, and will become in future, easier to achieve than it was ten years ago because consumers now want cotton products, and satisfying their demand will mean benefits to all sectors with an interest in cotton products: the farmer, the textile manufacturer, and the retail trade.

APPENDIX

IIC is an inter-governmental organization of cotton-producing countries around the world aimed at strengthening demand for cotton and cotton textiles. To achieve its objective, IIC undertakes utilization research and market-development programmes. Eleven countries are members of IIC:

Brazil	Ivory Coast	Tanzania
Greece	Mexico	Uganda
India	Nigeria	U.S.A.
Iran	Spain	

Argentina has announced its intention of becoming the twelfth member of the Institute.

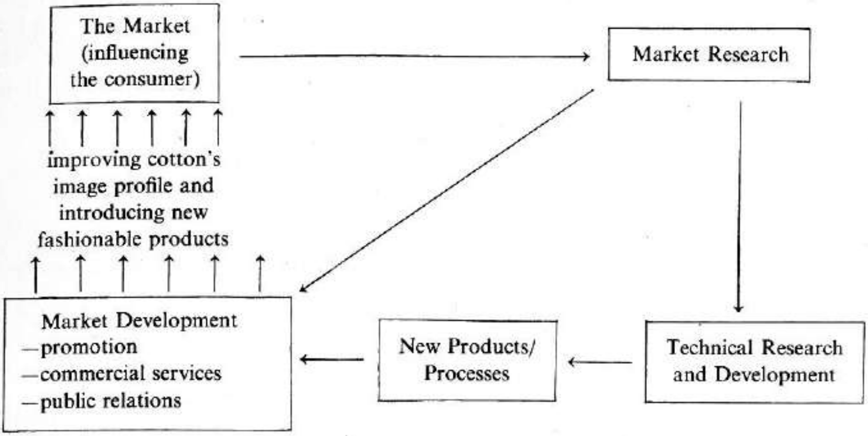
The present structure of IIC is as follows:

IIC GENERAL ASSEMBLY
↓
IIC EXECUTIVE COMMITTEE
↓
EXECUTIVE HEAD OFFICE (Washington)
↓
OPERATIONAL HEADQUARTERS (Brussels)
↓
Management
Administration
Market Research
Marketing

Marketing Support Activities by:
Country (Co-operation) Offices in:
- Amsterdam
- Barcelona
- Frankfurt
- London
- Milan
- Osaka
- Oslo
- Paris
- St Gallen
- Stockholm
- Tampere
- Vienna

Technical Research and Development (TRD)
Manchester
↓
Regional Offices
- West Europe (Hengelo, the Netherlands)
- Japan (Osaka)

A simplified summary of IIC strategy is shown below.



2—ECONOMIC AND AESTHETIC FACTORS IN THE FUTURE OF COTTON

By K. Slater and F. Hoffmeyer

During the past few years, cotton has declined in importance as a textile fibre, mainly as a result of the appearance of synthetic materials. In the years to come, however, there is likely to be a shortage of natural resources, a fact that could result in decreased production of these competitors. In the process, cotton may well recover its position to some extent.

Factors that may affect this possibility include aesthetic ones, such as comfort, durability, and ease of maintenance, together with economic ones. These factors, particularly the economic ones, which are only just becoming important in this respect, are examined in some detail and the effects they have had on cotton trends within the recent past are analysed. Subjective estimates of future changes in them are then made and used in an attempt to predict the future of cotton, on the assumption that their effects will remain equally significant. It is realized that the predictions, extending to the year 2025, are highly speculative, but it is suggested that cotton production will continue to increase, though commanding a steadily decreasing share of the world fibre market. The diminishing supplies of natural resources, the effect of political manipulation of oil supplies, and the potential value of research into finishes designed to enhance cotton's aesthetic value are suggested as factors that could reverse the trend by which cotton seems to be declining in importance at present.

1. INTRODUCTION

In the past few decades, we have seen a dramatic decline in the once-supreme popularity of cotton as a fibre, due almost entirely to the advent of synthetic fibres. From a share of some 75% of the world fibre market 40 years ago, production has fallen steadily until cotton now accounts for less than half of total textile-fibre use. It has been confidently predicted during this period that cotton could be almost completely replaced by synthetic fibres before the end of the century, to become a 'luxury' fibre in the same category as silk and linen. On the other hand, recent startling price increases in oil, the source of raw materials for the synthetic-fibre industry, have occurred as a result of political action, and the very real possibility of exhaustion of world oil supplies suggests that synthetic-fibre production may well become limited itself within the next few decades.

It is thus appropriate to examine the factors that have contributed, or may shortly contribute, to the past and potential trends in world production of cotton. Of particular interest are the aesthetic properties of the fibre, in contrast to those of the synthetic fibres, and these may be subdivided into categories of appearance, comfort, and durability. In addition, of course, the economic factors governing the production of natural and synthetic fibres will also have a major effect on consumption patterns, and these, too, must be considered.

2. FACTORS IN WORLD FIBRE PRODUCTION

2.1 Appearance Factors

In choosing a garment, for purchase or for use on a specific occasion, the consumer must feel that he or she will obtain psychological satisfaction from wearing it. This normally involves a conscious wish to 'look good' in the garment, so that appearance is often a prime reason for the choice. Factors of interest in a new garment obviously include style and colour, but perhaps the only ones directly related to a fibre property (apart from such considerations as dyeability and sewability) are drape, handle, and lustre. Once the garment has been used, however, a wide range of fibre properties becomes important. Visual neatness is affected by crease-retention, wrinkle-resistance, and pilling. Colour change can occur as a result of light exposure, laundering, or the effects of such factors as perspiration, crocking, dye shade changes, and bleach sensitivity. Finally, garment cleanliness can be influenced by water- or oil-repellency, soil-retention, staining, greying during laundering, and other such phenomena, controlled at least partly by fibre properties.

2.2 Durability Factors

In order that a garment may be considered satisfactory in use, it must remain presentable for an appreciable length of time. A natural corollary of this stipulation is the fact that the fabric must be durable, and durability factors must therefore be considered in deciding whether a fabric or garment is aesthetically satisfactory. Once again, fibre properties play a part in meeting this requirement. These may be inherent in the fibre itself, as exemplified by tensile strength, tearing strength, and abrasion-resistance, or may result from changes occurring over an extended period of time. Degradation of the fibres, manifested by a reduction in strength, may occur as a result of exposure to light, laundry procedures, chlorine, perspiration, and other environmental factors, depending on the fabric end-use. Careless use or storage can lead to a loss of desirable properties by biological attack, whether caused by insects or by mildew and other such agents. In addition, reaction to heat, whether of a hot iron or of an open flame, can also affect durability. Again, fibre characteristics have at least a partial effect in influencing these properties.

2.3 Comfort Factors

As before, comfort factors may be subdivided into those considered in initial purchase and those which make themselves known after wear and thus influence long-term satisfaction of the consumer. In the former category may be included weight, thickness, cover, and elasticity, which are readily apparent on inspection. Other comfort-related properties, however, may not become obvious until the garment is worn in adverse climatic conditions and may only then display characteristics that make it undesirable. Thermal transmission is an obvious example, particularly in cold weather with wind-chill present, whereas moisture absorption, moisture-vapour transmission, and air-permeability are of importance in hot humid weather. Secondary effects, such as condensation with freezing in winter and the development of liquid saturation or odour in summer, can result as a consequence of unsatisfactory performance in these comfort-related aspects. Electrostatic propensity and skin-irritation tendencies also help in determining long-term comfort. Once again, fibre properties can play a significant part in most of these considerations.

2.4 Economic Factors

Until fairly recent times, the 'battle' between cotton and synthetic fibres was fought only on the grounds of the appearance, durability, and comfort-related properties of the various fibres, but in the past few years a new consideration has arisen, that of economic necessity. Raw materials, production processes, marketing factors, and other influences will determine, in the foreseeable future, the percentage share of the market that any given fibre will command.

In terms of raw materials, of course, the cotton plant will presumably remain the basis for that fibre, and new sources will consist of improved varieties of the plant to give better yields in terms of quality or quantity. Agricultural research may also increase the yield per hectare of existing varieties or, by irrigating new areas of the earth's surface, may modify a region's soil so that it becomes capable of supporting new cotton plantations. Conversely, climatic changes may cause crop failure in existing cotton-growing areas, while higher land prices or the increasing demand for food brought about by population growth may force a change from cotton to other crops and so reduce the availability of the fibre. Synthetic-fibre production may be enhanced by the discovery of new oil sources, or methods of producing the fibres from other raw materials may be developed. Synthetic-fibre production, however, may equally well decline as natural resources are depleted or as oil prices climb to the point at which fibres depending on such sources are unable to compete economically with natural or regenerated ones.

Production factors influencing the availability of fibres include new technology in harvesting, or creating, a fibre, the advent of more automation, and the tendency on the part of underdeveloped nations to set up industries for manufacturing synthetic fibres rather than importing them. Labour costs, too, can influence the situation, particularly since cotton production tends to be more labour-intensive than that of the new fibres. Marketing factors of importance include consumer demand, the influence of advertising, the cost of transportation, and the practice of stockpiling to create an artificial shortage (and hence higher prices) in a competitive market. Finally, of course, miscellaneous factors that cannot usually be foreseen should nevertheless not be ignored. Political manipulation and its extreme form, war, are the obvious examples, but the very fact that this type of influence is unpredictable implies that other examples, which may not even be recognizable as potentially important, must exist.

For the sake of clarity, all these many properties have been summarized in Table I, and an attempt has been made to identify each one as being favourable, unfavourable, or irrelevant to increased production of cotton and synthetic fibres, respectively. It must be remembered, of course, that the factors not considered can have an influence; characteristics may be modified, for example, by the use of finishes, and the behaviour of one fibre type may be better than that of the other even when they have the same rating. In the context of this paper, however, it is the basic properties of the fibre alone that are considered in attempting to forecast the future of cotton.

3. FACTORS INFLUENCING THE FUTURE OF COTTON

It is readily apparent that cotton must, if it is to survive as a major fibre, compete with other natural fibres, with regenerated-cellulose fibres, and with synthetic fibres. Wool and silk, the major competitors among the natural fibres,

Table I

Fibre Factors Governing Fibre Production

Appearance	Cotton			Synthetic Fibres		
	F	U	I	F	U	I
Colour change	X			X		
Crease-retention		X		X		
Drape	X			X		
Handle	X			X		
Lustre	X			X		
Pilling		X		X		
Versatility	X			X		
Wrinkle-resistance		X		X		
Durability						
Abrasion-resistance	X			X		
Biological attack		X		X		
Chlorine-degradation	X			X		
Flame		X		X	or X	
Ironing	X				X	
Laundry-degradation	X			X		
Light-degradation	X			X		
Perspiration-degradation	X			X		
Tearing strength	X			X		
Tensile strength	X			X		

F = Favourable
U = Unfavourable
I = Irrelevant

Table I *(contd)*

Comfort	Cotton			Synthetic Fibres		
	F	U	I	F	U	I
Air-permeability			X			X
Cover			X			X
Elasticity	X			X		
Electrostatic propensity	X				X	
Moisture absorption	X				X	
Skin irritation	X				X	
Thermal transmission			X			X
Thickness			X			X
Water-vapour transmission			X			X
Weight			X			X
Economic						
Advertising improvement	X			X		
Agricultural research	X			X		
Automation	X			X		
Climate changes	X	or X				X
Consumer demand	X			X		
Higher labour costs		X				X
Higher land prices		X				X
Natural-resource depletion			X		X	
New fibre-production methods			X	X		
New national synthetic industries			X	X		
New oil sources			X	X		
New technology	X			X		
Oil-price increase			X		X	
Political manipulation			X		X	
Population growth		X				X
Rising transportation costs		X			X	
Stockpiling		X			X	
War			X		X	

are more expensive than cotton and are likely to remain so for reasons inherent in their cultivation, apart from the fact that, in general, they are suited to almost completely different end-uses. It is therefore with the man-made fibres that cotton has to contend if it must continue to exist.

A detailed examination of Table I indicates that many of the factors favour neither fibre type particularly more than the other. In the first three categories of appearance, durability, and comfort, the easy-care advantages of synthetic fibres are balanced by the comfort-enhancing advantages of cotton, so that these factors alone would give no net superiority to either type, as is approximately indicated by the current situation. It is thus in the economic aspect that the major factors influencing the future of cotton must be sought.

Many of these factors are so unpredictable that it is impossible to use them in logical arguments attempting to forecast the usage of cotton. Agricultural research, major changes in climate, the discovery of new oil sources or methods of fibre production, changes in consumer demand or advertising skills, and political moves and wars impeding oil supplies may all take place at any time, but we can foresee neither their occurrence nor their effect on the textile situation. Of the remaining factors, new technology, increasing automation, transportation costs, and stockpiling favour neither type of fibre preferentially. It would therefore seem that any prediction of the future fate of cotton as a fibre must rely principally on the remaining factors of land- and oil-price changes, population growth, natural-resource depletion, the economic progress in developing nations, and labour costs. It is possible to make some kind of prediction of all these and hence of the future of cotton. Obviously, any such prediction is fraught with uncertainty and can be doomed by any one of a large number of unforeseen factors, but it is the only available guide to the likely survival of cotton that exists, and a forecast undertaken from this basis, with all its doubts, is of some interest at least.

4. CURRENT TRENDS IN RELEVANT FACTORS

In order to produce a realistic estimate of future trends in cotton production, a detailed literature search intended to establish the situation obtaining over the past few years was first carried out. Since the literature consulted was extensive, the sources of raw data used have been summarized in Table II, which gives the information obtained, the years for which it is quoted, and a number indicating the source as listed in the references at the end of the paper.

Table II

Details of Data Used in Developing Predictions

Data Tabulated	Years	Reference
World cotton production	1966–75	1
World cotton acreage	1958–70	2
World average cotton prices	1968–77	3
World synthetic-fibre production	1966–75	1
Crude petroleum prices, world	1961–77	4
World population figures	1959–76	5
U.S. consumption of fibres	1960–76	6
EEC consumption of fibres	1971–75	7
U.S. Index of farm-wage rates	1960–74	8
Canadian Index of farm-labour rates	1954–77	9
Values of farm capital in Canada	1961–75	10
World regenerated-fibre production	1960–76	11
World energy supplies	1950–76	12
Industrial production (developing nations)	1957–76	13

From these data were calculated price indices for cotton, crude oil, farm land, and farm-labour wages, a value of 100 being taken for the year 1961. Some of the information refers to localized regions, but it is hoped that this normalization to an index will lead to figures reasonably representative of world-wide trends. The year 1961 was selected arbitrarily for the reference level, since information for all calculations is readily available for that year. The changes in each of these indexed prices are given in Figures 1–4. Population growth in the world, again assessed by using the same indexing method, was recorded and is

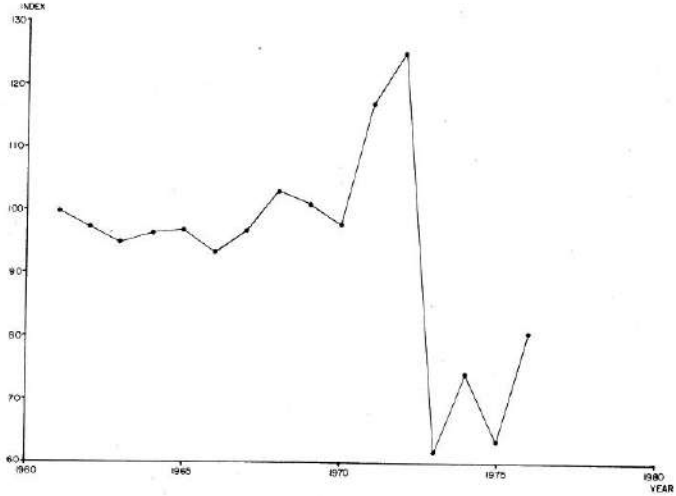


Fig. 1
Cotton price index, 1961–76

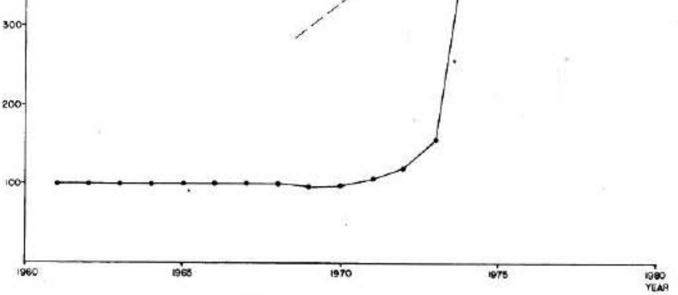


Fig. 2
Crude-oil price index, 1961–76

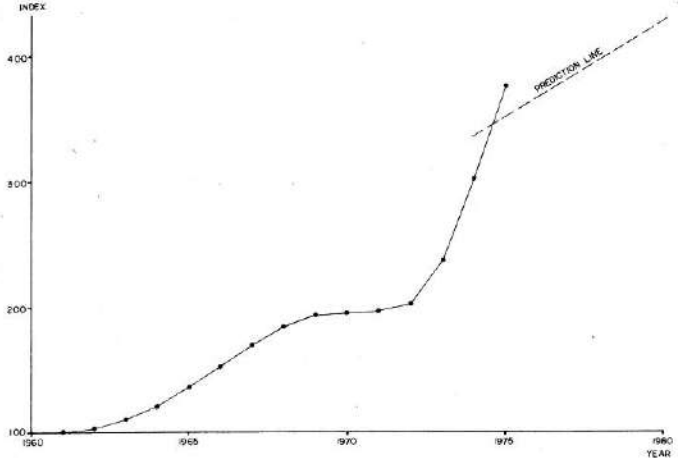


Fig. 3
Farm-land value index, 1961–75

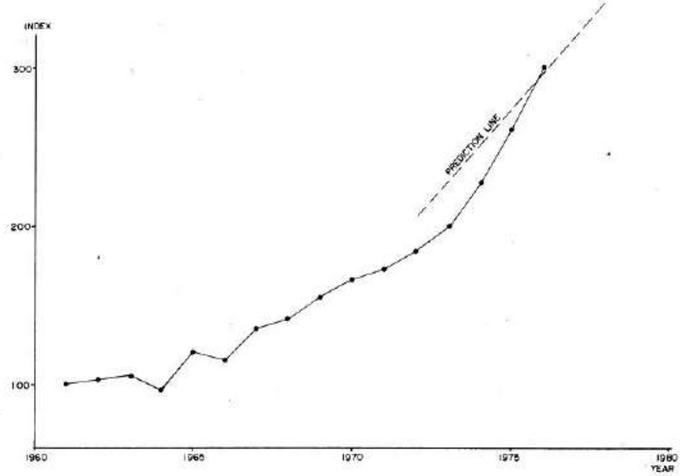


Fig. 4
Farm-labour wage index, 1961–76

shown in Fig. 5. In addition, the percentage shares of the world fibre market for cotton and for synthetic fibres were calculated and are shown in Fig. 6, which illustrates dramatically the recent rise in popularity of the latter type of textile.

Attention was then turned to the question of determining the degree of industrialization in underdeveloped countries and the rate of depletion of natural resources, both of which are extremely difficult to quantify. For the former factor, a chart recording the index numbers of industrial production of all nations in the world was consulted, and from it a list of those countries commonly regarded as underdeveloped was made by arbitrary subjective means. From this list were selected all those countries for which a value of the industrial-

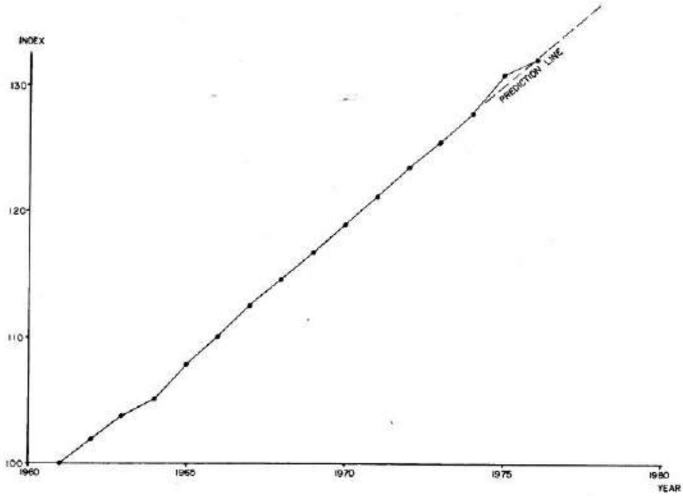


Fig. 5
World population index, 1961–76

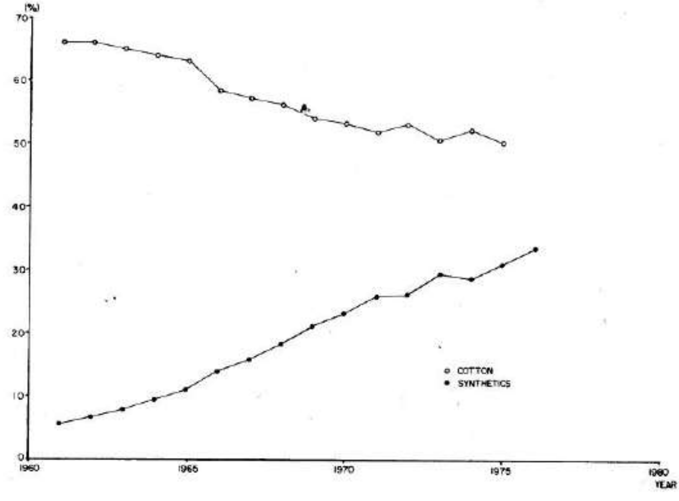


Fig. 6
Cotton and synthetic-fibre production as a percentage of world total

production index for general manufacturing for all the years 1961–75 was given, and the mean value of this index (corrected so that a base of 100 for 1961 was used) was calculated. This index was used as an indication of the degree of industrialization in developing nations, and its change with time is shown as Fig. 7.

With regard to natural-resource reserves, it proved impossible to find any numerical estimate of values for this factor. Various experts have predicted, however, that the world's oil supplies will be depleted to negligibly small amounts

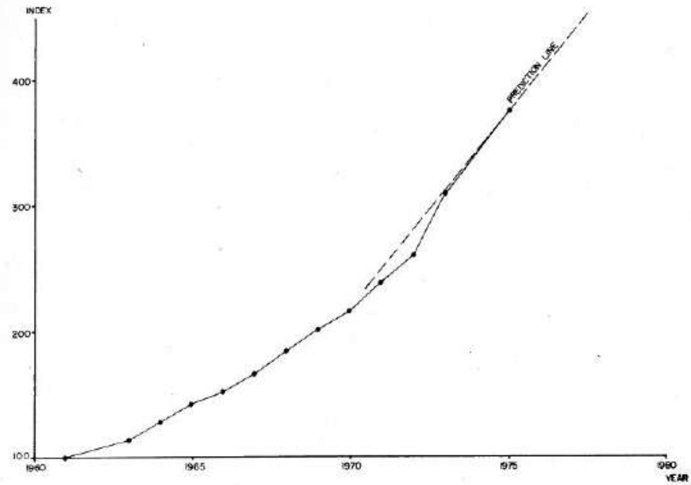


Fig. 7
Index of industrialization in developing nations, 1961–75

(in comparison with annual demand) within 50 years. An attempt was made to predict the year when demand will exceed supply, but recent dramatic changes in each of these factors have reversed sharply the previous upward trend of both the curves, and this discontinuity, which occurred in 1976, is too new to allow any deductions about future events to be made from earlier figures. Obviously, however, natural-resource disappearance can only favour an increase in cotton production. The rising price of oil, as it becomes scarcer, will make synthetic fibres less competitive, and the increased scarcity of wood, with even the chips and the sawdust being used for particle board and paper, will tend to diminish the production of viscose and acetate, potential competitors for cotton. It was thus decided that this particular factor, even though it could not be quantified, could not diminish any optimism for cotton's future and may even reverse an apparently adverse trend.

The next step taken was therefore to attempt correlations between cotton's percentage share of world fibre production and the other relevant factors. Direct correlations with each factor individually, as might be expected, were generally poor, but it appeared that farm-labour costs ($R^2 = 77.7$) and farm-land prices ($R^2 = 55.3$) are likely to have significant effects on cotton's future. Crude-oil prices ($R^2 = 31.9$) do not yet seem to have a large effect, but, when factors were taken in pairs, the combined effect of crude-oil prices and farm-labour costs ($R^2 = 95.1$) appears to be closely correlated with cotton's share of the market. When all factors were combined into a single regression equation, the results were obtained that are given in Table III, which shows the coefficient for each factor in the analysis. As expected, increases in industrialization, population, and land prices tend to decrease cotton production, while increasing oil prices tend to increase it. An apparent anomaly is seen in that increasing farm-labour wages tend to increase cotton production, but the coefficient is a small one and there is presumably some effect of other variables. In order to test the accuracy of the derived equation, actual values of cotton's share of the fibre market over the fifteen years covered by all the data (as in Fig. 6) were plotted and compared with those percentages predicted by the equation. The resulting curve is shown in Fig. 8, and the high regression coefficient ($R^2 = 98.4$) is indicative of a high precision. A similar procedure was then carried out for cotton-production

Table III

Multiple-regression Coefficients for Percentage Cotton Share of World Fibre Production

Factor	Coefficient
World population index	−0.52751
Index of industrialization in developing nations	0.00977
Crude-oil price index	0.02553
Farm-land value index	−0.06054
Farm-labour wage index	0.01613
Constant	120.77

Table IV

Multiple-regression Coefficients for World Production of Cotton

Factor	Coefficient
World population index	648.53
Farm-land value index	−114.71
Crude-oil price index	23.57
Index of industrialization in developing nations	52.23
Farm-labour wage index	−49.91
Constant	−33775.76

figures, results being quoted in Table IV and, for testing and validity of the equation, in Fig. 9.

Each indexed graph was subjected to computer analysis, where applicable, or to visual assessment where necessary, in conjunction with personal discussion with economists, in order to obtain extrapolated data to give a prediction of future trends over the next few years. These prediction lines are shown on the graphs for which they have been calculated. They are, of course, highly speculative and are heavily dependent on factors for which no guarantee of stability can be expected, as already mentioned. Nevertheless, barring these unforeseeable eventualities, the extrapolated index figures obtained do provide a basis that may reasonably be used for other estimates.

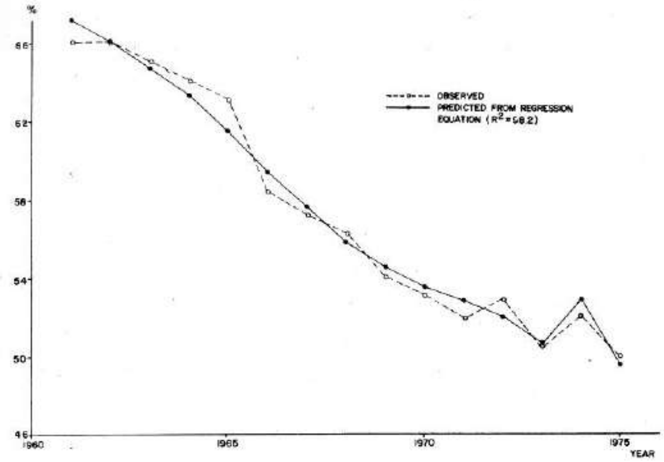


Fig. 8
Prediction of cotton percentage of fibre market, 1961–75

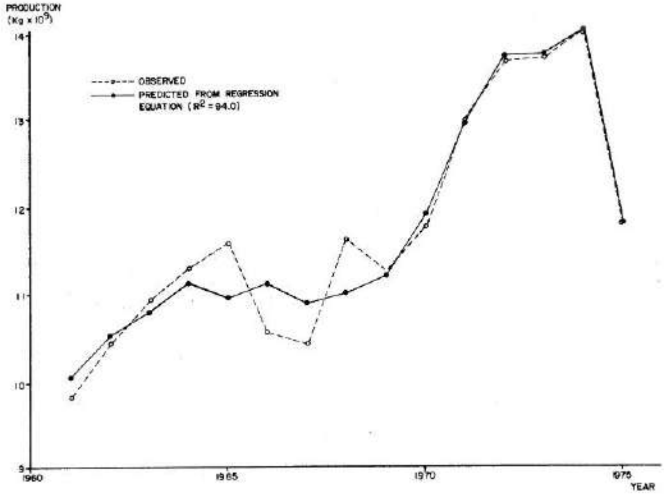


Fig. 9
Prediction of cotton production, 1961–75

5. PREDICTION OF COTTON'S FUTURE

The method of prediction used in attempting to foresee future events in the cotton sector of the textile industry is now fairly obvious. From the extrapolated data obtained for each of the relevant quantifiable factors, a value for each index at intervals over the fifty years from 1976 to 2025 was obtained, at yearly intervals for the period 1976 to 1980 and at five-yearly intervals thereafter. Each of these values in turn was then substituted into the equations represented by Tables III and IV, respectively, so that forecasts of cotton's share of the fibre market and of the absolute production figures for the fibre were obtained. The graphs illustrating these predictions are given as Figures 10 and 11, in which the production figures for cotton are seen to increase steadily but the fibre's share of the market to continue to decline. The rate of decline has, however, diminished,

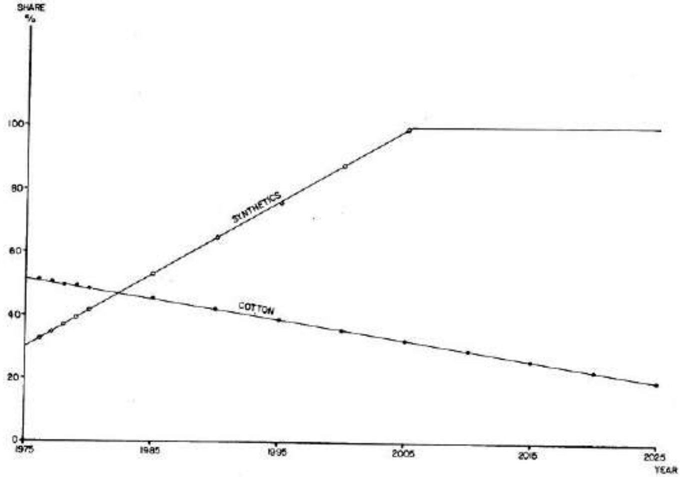


Fig. 10
Prediction of market percentage shares for different fibres to 2025

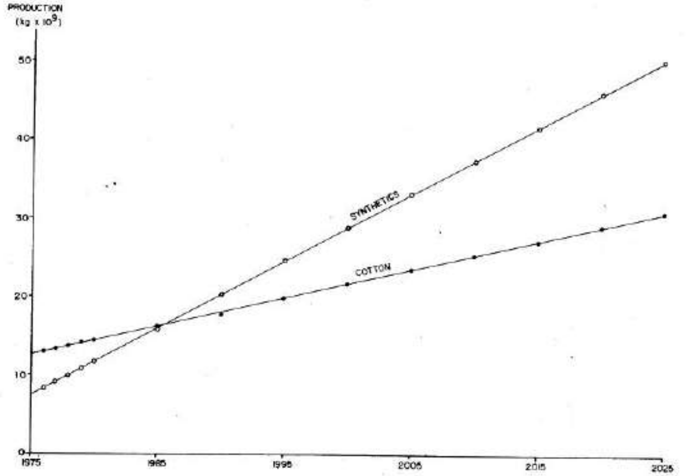


Fig. 11
Prediction of fibre-production figures to 2025

though the estimates for synthetic-fibre production, given for comparison, appear to indicate accelerated production rates. The two diagrams contain inconsistencies, particularly with reference to percentage shares of the market, but these are to be expected in view of the many subjective assumptions made. It is of interest to note, however, that the period of about 1984–86 should see the production of synthetic fibres rise for the first time above that of cotton, so that one aspect of the forecast can be checked in the not-too-distant future. It must be realized, of course, that the trends illustrated, based as they are on such speculative evidence, are open to considerable doubt and that prediction accuracy must diminish drastically as one attempts to look further forward in time. Nevertheless, it would appear that there is indeed a continued market for cotton in the foreseeable future, though one cannot be too optimistic about prospects for the fibre if current trends continue unchanged, as implied in developing the graphs.

After the time period shown, when synthetic fibres can presumably no longer be produced from oil, it is impossible to predict the future with any hope of accuracy. Other sources of polymer supply may well have been discovered, or new techniques may be able to duplicate artificially the desirable qualities of cotton so closely that its production becomes redundant. Conversely, of course, it may well have recovered its original supremacy and, as a result of developments in finishing treatments, may be able to imitate all the advantages of the synthetic fibres without suffering from any of their disadvantages.

As a final point, it is of interest to note the opinions of other authors concerning the future of cotton. As recently as 1972, Heitmiller[14] was suggesting that cotton would continue to lose ground to the synthetic fibres and that it could even be omitted from blends in the near future. A year later, Sharp[15] was predicting a continued increase in cotton production but a declining share of the market and suggesting that the growth rate of synthetic fibres would also decrease. In 1975, Koedam[16] was forecasting a viable future for cotton, and, in a later paper[17], he summarized the advantages of the fibre in comparison with synthetic fibres and pointed out that the latter were beginning to lose ground in world markets. At about the same time, an unbiased forecast[18] suggested that cotton would continue to maintain approximately its current position in the market, though Wooters[19] expected to see a significant rise in cotton's share of world fibre figures. Koedam[20] has recently reiterated his faith in cotton's future and pointed out that the plant is a valuable source of animal nutrition and thus unlikely to be displaced by other food crops, as well as providing high employment potential in the developing countries of the world. Mitchell[21], however, sounds a cautionary note, suggesting that economic factors may cause farmers to abandon cotton-growing if a more attractive crop becomes available as an alternative.

In contrast to this general air of increasing optimism, authors discussing the future of synthetic fibres tend to be more cautious. In 1973, Russell[22] reported the prevalent trend to increased production, but in the following year an uncertain outlook was evident[23], and Meeks and Winter[24] pointed out the heavy dependence of the synthetic-fibre industry on petrochemicals. Repeated problems were reported[25] in 1976, and, in the same year, Gaines[26] emphasized the need for alternative supply sources and the ability of political interference with oil supplies to upset fibre-production figures. Stultz[27] presented an outlook of guarded optimism but suggested that many problems loomed ahead that might well make optimism unfounded. A more recent report[28] suggests that this was indeed the case, since expected increases did not materialize, and the feeling is expressed that the synthetic-fibre industry may easily be facing a very critical future.

In all these various ways, therefore, we see the common message that cotton is likely to remain as a major world fibre on economic considerations alone. When this fact is added to the undeniable advantage of the material in aesthetic properties, it does seem that it will indeed not disappear in the foreseeable future. It may, however, be heavily dependent on such factors as new finishing treatments in order to survive the continuing challenge of synthetic fibres.

6. CONCLUSIONS

If the trends of the past few years continue unchanged, cotton is likely to remain as a reasonably important material for the next fifty years, though it may continue to lose ground to the synthetic fibres. Its percentage share of the world fibre market, however, should fall at a slower rate than has recently been evident. The major danger, perhaps, is the decline in agriculture, since the competitive ability of man-made fibres is likely to be curtailed drastically by diminishing reserves of natural resources. It may well be the aesthetic aspects of cotton that enable it to survive competition, and these, together with finishes that enhance its durability and easy-care behaviour, must be emphasized in research and publicity if continued survival of the fibre is to be assured. These predictions depend entirely on assumptions that cannot be justified to any degree of certainty, but they are felt to be sufficiently valid for some reliance to be placed on the forecasts derived.

ACKNOWLEDGEMENTS

The authors would like to express their grateful appreciation to Mrs. Janice Ainsworth for typing, to Mrs. Doreen Davies for producing the diagrams, and to the National Research Council of Canada for funding in support of the work discussed in this paper.

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3—THE LINK BETWEEN THE COTTON BREEDER, THE GROWER, AND THE CONSUMER

By A. Subramaniam

This paper deals with the link existing between the cotton breeder, grower, and consumer, whether for the textile industry or for potential new consumers of cottonseed products as food. After nearly 60 years of scientific, technological, and commercial activity, a vast volume of meaningful information has been accumulated. Cotton breeders have begun to achieve the development of new strains and hybrids that are equal or superior to existing varieties in relation to the needs of the grower and the textile demands of existing and newer machines, processes, and end-products. Recent research on producing glandless cotton with zero Gossypol content, apart from oil, without adverse effect on other fibre properties, offers exciting prospects for cotton as a competitive fibre for both clothing and food.

1. INTRODUCTION

W. Lawrence Balls[1], in his classic book 'Studies on Quality in Cotton', written in 1928, emphasized the need for forging links between production and utilization, and it is of interest to quote here his description 'The Spindle and Hoe', symbolizing the cotton consumer and producer.

> 'The dangling spindle with its whorl of clay is one of the oldest tools which mankind has invented. The hoe made out of a deer's antler, or from a dressed flint-stone lashed to its wooden haft by rawhide thongs, is another of our most venerable possessions. But these were handled separately, even in the dawn of tool-using; the spindle by the women, the hoe by the man; the spindle was more important to the nomads, the hoe belonged to the settlers on the soil. In our time, and for a century past, this separation has been emphasized and most especially emphasized for the workers in cotton. The hoe-users work in the sub-tropics, the spindle-users work in the damp northern lands. The hoe is still in the open air; the spindles are packed by thousands in serried ranks within factories from which the city's grime is barely excluded. The men who control the workers of the hoe must inevitably look on quite differently from those who direct the whirling spindles. Thus it happened when scientists brought the cotton industry within the orbit of their curiosity they soon found that the Hoe could not do its best for the Spindle unless the Spindle sent word and description of its need to the Hoe. The scientists had to examine both. . .

2. THE LINK

The development of an improved cotton variety is the result of systematic subjective study followed by quantitative and qualitative analysis of the cotton plant over the years. The studies made are of the yield, size of boll, earliness of maturity, percentage of lint, resistance to disease, damage from insects, size and shape of stalk and fruiting branches, resistance of bolls to storm damage, quality of seed strength and the attachment of fibres to seed, and other factors in the production phases of cotton. The breeder was also equally interested in lint length and its variability and had an eye for colour to suit the grader's requirement. Later, with the advent of fibre-testing instruments and more use being made of them, considerations of strength, fineness, and maturity gave him the necessary spurt to cross-breed and effect plant selection, and thus he was able to increase the yield and improve the fibre characteristics mentioned above.

Correlation studies in breeding a new strain of cotton have helped the breeder and the fibre and yarn technologists to associate the qualitative and quantitative characteristics, and thus they soon learned how the leaf shape affected the lint length, seed weight, and ginning percentage. The association between the quantitative characteristics of yield of seed cotton, yield of lint, ginning percentage, fibre length, weight, and maturity, and fibre strength has enabled the breeder to choose the over-all optimum values and at the same time avoid extremely high or low values of individual characteristics.

3. VARIETY

It has long been recognized that the spinning performance of a cotton depends upon certain fibre properties, such as length, strength, X-ray structure, and fineness. It has also been shown that a cotton of a particular variety of seed is the most important factor in determining the quality of lint produced, although environmental factors, such as climate, type of soil, temperature, and moisture during growth, can influence the quality of cotton to an important degree. In the past, the breeder used variety as an important factor to incorporate desirable combinations in new varieties, and the grower also found it profitable to grow superior varieties as the textile industry consumed cotton on the basis of its predictable spinning performance. This traditional idea of variety being used as one of the useful tools may have to be re-examined by the breeder, since the environmental effects on some species have much more influence than was originally believed. This could help in interpreting the interrelationship between various fibre properties and final yarn strength and appearance, which is a more complex matter.

4. ENVIRONMENT

The following example relating to the same variety and origin of seeds of a long-staple cotton grown in two different seasons and possibly in different environments of the same region for nearly three years has recorded a statistically very significant difference in fibre strength and fineness and a just-significant difference in length, as may be seen from figures given in Table I.

Table I

Season*	Length			Fineness	Strength
	Fibrograph Span Length			Micronaire Value	Pressley Strength Index†
	2.5%	50%	U.R.		
Winter (407)	1.314	0.602	45.8	3.39	40 904
Summer (539)	1.310	0.599	45.7	3.55	44 419

*Figures within brackets indicate the number of readings.
†$\frac{1}{8}$-in. (3.2-mm) gauge length.

5. VARIETAL AND ENVIRONMENTAL FACTORS

The example in Table I could be an exceptional case, since cotton is not normally grown in both winter and summer in the same region, but there are certain places in the Indian sub-continent where this is being done advantageously. It will be interesting to analyse the contribution of the fibre X-ray structure, perimeter, and fibre weight per unit length to this apparent change in fibre strength and fineness and its significance. This particular study may also throw light on the presence of small motes, i.e., aborted or immature seed, which appears in many of the newly developed hybrids, finds its way to the yarn, and impairs the appearance of the subsequent fabric. Thus it will be necessary for the breeder to know the effect of the environment on the properties of a cotton fibre, apart from having a knowledge of its hereditary basis, and to use plant-breeding techniques in developing new varieties. He must also use fibre technology in the improvement of fibre quality through breeding.

The breeder occupies a unique position between the grower and the spinner. It is his responsibility to develop the fibre that is best for both the grower and the spinner. He is intimately familiar with cotton growers' problems of climate, disease, insects, fertility, and other phases of production and at the same has a good knowledge of fibre properties dependent on variety, conditions of growth, ginning, etc.

6. MARKETING

In this connexion, one is not belittling the part played by the merchant, who is an important link between the grower and spinner and has a great influence on the price he decides for the cotton. It will be a great achievement in the interests of trade and industry when the marketing of cotton is done entirely on the basis of intrinsic fibre quality and not on the basis of supply and demand. Similar attempts were made in the 1970s in the U.S.A., and this approach was worth pursuing since it gave weight to various fibre properties, including trash and colour, and used the differentials to provide a base for the price quotation.

7. LONG-TERM AND IMMEDIATE OBJECTIVES

The breeder has to work on both long-term and immediate objectives by the very nature of his job. It could be said that he should develop a variety of maximum yield over a wide range of environment, that he should be tolerant of diseases, and that he should meet the basic textile-industry requirement. This could be a long-range cycle of from three to ten years. But his immediate problems will be to concentrate on the development of resistance to insect pests, early-maturity or short-season varieties (or both), the development of multi-adversity-resistant germplasm for maximum returns, the production of a fibre of a total fibre quality suitable for a range of counts, and lastly the attainment of good seed quality for both planting and crushing for oil. All the above factors require experts in different disciplines to guide the breeder and give him what he wants.

8. HYBRIDS

The development of hybrids has again opened a new vista for the breeder and he now has three possible approaches:

(*a*) to develop successful male-sterile female parents, usually as pairs of isogenic 'A' male-sterile and 'B' fertile lines;
(*b*) to develop promising fertility-restoring male-parents 'R' lines; and
(*c*) to initiate an extensive testing programme with fibre and textile technologists to identify the best combinations for a specific end-use.

There is a great need for a quick rapport in this area, because the actual performance of interspecific hybrids is rather disappointing so far with regard to the realization of a specific fibre property, although with respect to yield they are very satisfactory.

9. TRANSPLANTATION OF COTTON PLANTS

Where water-management stress exists, from a grower's angle particularly, the proposal is to transplant cotton plants after initially growing them under nursery conditions for the first 20–30 days and then to arrange this programme to coincide with the offset of the monsoon. This method is being experimented with in traditional rain-fed areas, and, if this results in increased yield, then there is an immense possibility of transformation in cotton cultivation and production.

10. THE RÔLE OF THE TEXTILE TECHNOLOGIST

The fibre technologist has to develop a rapid method of testing to analyse the contributions of the X-ray angle, fibre weight, perimeter size, and maturity ratio to yarn strength and appearance, and this must be transmitted to the breeder, since this is still an area where much research work is to be done.

The textile technologist has to convey to the breeder the requirements in relation to fibre properties of open-end spinning, which will be quite different from the demands of ring-spinning. Open-end spinning can accept lower Micronaire values in cotton and still produce a yarn that is better in appearance than ring-spun yarn because of the very nature of its structure. There are also other areas, such as trash, strength, and variable length properties, that could be advantageous in some respects to the breeder and grower in selecting those older varieties discarded as not suitable in earlier years. We may well see a full circle of cotton suitability from the time hand-spinning gave way to ring-spinning, with open-end spinning now accepting more or less the same quality of fibre as is suitable for hand-spinning except probably in fibre strength. This could be important for the grower, since it is expected that the U.S.A. will allot at least 35% of its cotton production to open-end spinning. In this connexion, it is pertinent to point out how breeders over the years must have concentrated on improving the fibre strength of long-staple cotton, and perhaps this could be one of the reasons for the neglect of short-staple cotton where high fibre strength is required. Again the spinner must take the blame for not telling the breeder that spinning technology after the introduction of top-arm drafting could have taken account of any deficiency in fibre length and strength, but he preferred to be silent in view of the high demands from his immediate customer, i.e., the weaver, installing high-speed looms, looking for high labour optimization, etc., and expecting high-strength yarn from the spinner. Ultimately the goal for the breeder, grower, and spinner is the requirement of the end-product and its fitness for its proper purpose from the point of view of both quality and economics.

11. GLANDLESS COTTON

Cottonseed oil accounts for one-tenth of the world's estimated output of edible vegetable oil, and it is superior to soya-bean oil in terms of stability, flavour, etc. Cottonseed meal's potential for human consumption became important when in 1959 Dr McMichael reported the development of cotton with no glands and essentially zero Gossypol content. Cottonseed meal, with its high protein content, is of immense value to the human race. Initially, the breeders had difficulty in achieving the required yield, good fibre properties, etc., but they overcame this by persistent selection of strains, and they are now able to produce glandless cotton equal in the production of various lengths and fibre properties to glandular cotton. But one of the immediate problems not yet overcome is that in some glandless cotton its pest-resistance is not wholly satisfactory. Secondly, rodents are attracted towards glandless cotton in the field. If these two problems can be solved by proper precautionary methods taken by growers, then glandless cotton will be a boon to mankind, particularly in developing countries. The cottonseed oil can also be used without the need for the liquid-cyclone process, and thus there will be lower processing and refining costs. The process of refining itself will have to be made economical, since it has not been fully evaluated, and here again the grower of glandless cotton should be convinced that he will obtain a fair return for his risk in producing glandless cotton with all its pest and rodent problems. Several glandless varieties are now in the experimental stage in India, since they are of great relevance to this region.

12. CONCLUSION

We have come a long way from the time when, exactly fifty years ago, W. Lawrence Balls visualized the ideal relationship between the cotton producer and the consumer. His words are more relevant than ever to-day, when man, with the aid of technology, is trying to reduce—in order to save time and money—the number of processes and areas of activity to achieve his objectives.

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4—A SURVEY OF RESEARCH ON COTTON PRODUCTION IN INDIA DURING THE LAST DECADE IN RELATION TO QUALITY AND SPECIFIC END-USES

By S. M. Betrabet, M. S. Parthasarathy, and V. Sundaram

Cotton-production research in India, with special reference to the improvement achieved in evolving high-quality cottons during the last decade, is reviewed. During the period 1968–78, 32 varieties were released in various staple-length categories from long- and extra-long-staple cottons (29.5 mm and above) to short-staple cottons (20 mm and below) for different cotton-growing tracts in the country, depending on their specific agro-climatic conditions. Notable among superior-quality cottons are MCU.5 (33 mm), Suvin (40 mm), comparable to Giza 45, Hybrid 4 (31 mm), the world's first commercially grown hybrid, and Varalaxmi (36 mm), yet another superior hybrid.

Studies on the blending of superior Indian cottons with polyester fibre have shown that some of the new varieties, such as Hybrid 4, Varalaxmi, Sujata, and Suvin, can successfully replace imported cottons in this quality category. Coarser varieties of Indian cottons could also be blended with natural fibres such as jute, wool, and ramie to produce fabrics for furnishing and blankets.

Investigations on the varietal response of Indian cottons to easy-care finishing treatments have revealed that there is considerable variation in the toughness retention between varieties of cottons after cross-linking. Furthermore, there are some coarser cottons even among the *G. arboreum* and *G. herbaceum* species that are suited to easy-care treatment, perhaps owing to factors such as their inherent circular cross-sectional shape and uniform fine structure.

1. INTRODUCTION

Although the pattern of cotton production in India has changed considerably during the last decade, there is a general impression, especially abroad, that India produces only short- and medium-staple cottons. This is mainly because only short-staple coarse varieties of cotton are exported. The object of this paper is to give a general idea of the progress made in improving the production and quality of cotton produced in India and also to examine how far some of the new strains are suited for specific end-uses, such as blending with other fibres and the production of easy-care fabrics.

2. COTTON-PRODUCTION RESEARCH

2.1 The Cotton Situation in India in the Post-independence Period

The area under cotton in 1946–47 was about 6 million hectares in the undivided Indian Sub-continent, and cotton production was about 3.7 million bales (each of 170 kg). When the country became independent in 1947, as a result of the partition of the Sub-continent, about 40% of the cotton crop, including most of the area growing superior-quality cotton, went over to Pakistan. On the other hand, 98% of the total mills still remained within the Indian Union. Since production in the Indian Union was only about 2.3 million bales in 1947–48, the textile industry was faced with an unprecedented shortage of cotton, especially good-quality cotton. As a result, foreign cottons had to be imported to the tune of over one million bales each year out of a total consumption of 3.9–4.3 million bales during the first five years after partition[1].

The problem of remedying the above situation was taken up seriously by the Government of India and the former Indian Central Cotton Committee. Cotton-extension schemes were launched in all cotton-growing states, and financial assistance was extended to the state governments. The main emphasis in increasing production under these schemes was the extension of cotton-growing areas and, in a limited manner, the raising of productivity by the application of fertilizers and adoption of improved agricultural practices. As a result, the area under cotton rose from 4.3 million hectares in 1947–48 to 5.9 million hectares in 1950–51, and then to 8.1 million hectares in 1955–56 at the end of the First Five-year-plan Period. The production has also increased from 3.1 million bales in 1950–51 to 4.2 million bales in 1955–56. The acreage under cotton remained nearly static during the next three years of the Second Five-year-plan Period and even dropped to about 7.6 million hectares during 1960–61 at the end of the Second Five-year Plan. Cotton production, however, improved to about 5.7 million bales.

With the beginning of the Third Five-year Plan, the keynote in cotton development was shifted from extension of the area cultivated to raising the yield per hectare. Schemes for intensive cultivation known as package programmes were launched in 1962–63. As a result, production rose to about 6.2 million bales in 1964–65, but vagaries of the weather led to a severe drop in production in 1965–66 by about one million bales.

2.2 Cotton Improvement since 1966

The tempo in cotton-development research in India can be said to have gained momentum mainly since 1966, when far-reaching policy decisions were taken by the Government of India on the organization of cotton research and development in the country. The Indian Central Cotton Committee, which until then was involved in both development and research on cotton, was abolished, and the research work was passed on to the Indian Council for Agricultural Research (ICAR). For continuing and expanding the work on development and marketing, a Directorate of Cotton Development was set up with its headquarters in Bombay.

The striking improvement in the staple length of Indian cottons can be attributed to the All-India Co-ordinated Cotton Improvement Project (AICCIP), launched by the ICAR in 1967 with a multi-disciplinary and multi-location approach. This project realized the need for the active collaboration of scientists from various disciplines involving cotton-breeding, agronomy, physiology, pathology, entomology, and technology in the development of any new variety of cotton. The AICCIP functions under the leadership of the Project Co-ordinator, currently stationed at the Regional Station of the Central Institute for Cotton Research at Coimbatore. Research is simultaneously carried out in different parts of the country and covers all the above aspects. In all, 30 centres located at Agricultural Universities and Central Research Institutions are involved in multi-location tests on promising varieties. Besides the development of better-quality cottons, new agronomic and plant-production techniques have also been developed to meet the varying needs of cottons cultivated in different parts of the country. The technological evaluation of the large number of samples under the AICCIP is carried out at the Cotton Technological Research Laboratory (CTRL), Bombay, and its nine regional units.

Though the AICCIP was able to function effectively in the development of newer varieties of cotton and in improving the over-all quality of Indian cottons soon after the AICCIP was launched, production in terms of quantity still did not improve to the desired degree, mainly owing to vagaries of the weather, the diffusion of financial assistance in package programmes over small areas spread over widely distributed locations, and the relegation of cotton to a position of lower priority than that of foodgrains by State Departments. Hence an Intensive Cotton District Programme (ICDP) was launched in 1971–72 with the objective of increasing production sizeably. The ICDP embodied a new approach of taking up whole districts for recommended package programmes and providing at subsidized rates costly inputs such as fertilizers, pesticides, etc., and also plant-protection equipment. As a result of the close co-ordination thus brought about between research on the one hand and extension work on the other, the average annual production during the five years after the launching of the ICDP (1971–76) was over one million bales more than the average during the preceding five years[2].

The acreage under cotton has at present stabilized around 7.6 million ha compared with about 7.9 million ha in 1965–66. Production, on the other hand, has increased from 5.1 million bales in 1965–66 to 7.1 million bales in 1974–75 and thus achieved an increase in yield from 108 kg/ha to 158 kg/ha.

2.3 Improvement in Cotton Quality

The improvement in cotton production has been accomplished simultaneously with an improvement in the quality of cotton produced, as may be seen from the figures for the production of cottons classified according to staple length summarized in Fig. 1. It may be noted that, before 1977–78, the mean fibre length was taken as the basis for the staple-length classification of cotton. In 1947–48, there was virtually no production of Indian cottons with a mean fibre length greater than 24 mm, and the bulk of the production of about 67% was in the medium and superior-medium group. However, by 1974–75, the production of long and superior-long cottons had risen to 37% of the total production, with

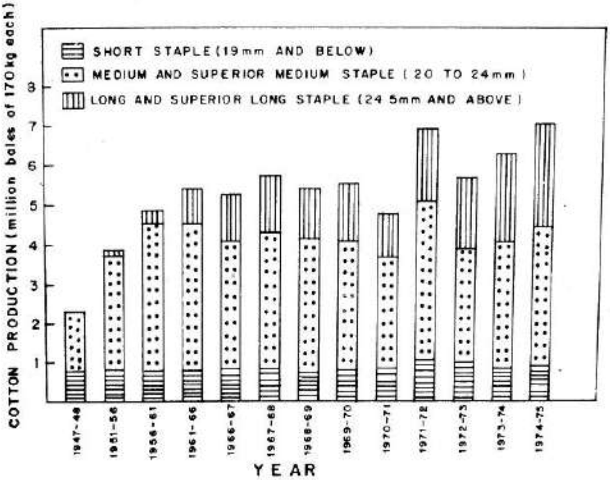

Fig. 1
Production of cotton in India according to staple length

50% of the production in the medium and superior-medium group. With regard to quantity, the production of short-staple cotton has remained around 0.8–0.9 million bales over the years, whereas the production of long- and superior-long-staple cottons rose from 1.2 million bales in 1966–67 to 2.6 million bales in 1974–75, and that of medium and superior-medium cottons from 3.3 million bales in 1966–67 to 3.6 million bales in 1974–75.

2.4 Varietal Improvement and Strains Released

The improvement in the quantity and quality of Indian cotton was achieved mainly owing to the release of new varieties and improvements in agronomic and cultivation practices. The traditional varieties of cotton cultivated in the country in the past belonged to the species *G. arboreum* and *G. herbaceum*, called *desi* cottons. The varieties belonging to these species have an inherently low yield and are shorter and coarser than varieties belonging to *G. hirsutum* (American Upland types) or *G. barbadense* (Egyptian types). In 1947–48, the proportion of Indian cottons belonging to *G. hirsutum* was hardly 3% of the over-all production, whereas to-day the cultivation of *hirsutum* cottons has risen to more than 50% of the over-all area. The area devoted to *barbadense*, negligible even in 1970, has also started rising steadily.

One further reason for the improvement in Indian cotton has been the introduction of several hybrid varieties. India has the distinction of making a commercial success of hybrid cottons for the first time anywhere in the world. The first hybrid variety, Hybrid 4, was released in Gujarat State in 1970, and a superior-quality hybrid, Varalaxmi, was released in Karnataka State in 1972. Hybrid 4 had spread to nearly 0.72 million ha in 1974–75, and Varalaxmi covered 0.14 million ha in 1975–76. Hybrid 4, covering 9% of the total acreage under cotton in the country accounted for over 15% of all the cotton produced in 1974–75. The two hybrids contributed 1.6 million bales that year. Recently, a new hybrid, JKHy.1, has been released in Madhya Pradesh for cultivation under mainly rain-fed conditions wherever protective irrigation is possible. JKHy.1 covered an area of 10 000 ha during 1978–79. Among the new promising hybrids under trial is CPH.2, a medium-staple hybrid for the southern part of India, suitable for spinning yarns of about 15 tex (40s cotton count).

The first attempt to introduce a *G. barbadense* variety, Sea Island Andrews, was made in India in 1957. However, it was Sujata, an Egyptian type, 34 mm in length and spinnable to 5.9 tex (100s cotton count), which, when released in 1969, made a real impact on the production of quality cotton in India. The improved variety Suvin, released in 1974, has replaced Sujata, and currently it covers 20 000 ha of tracts in the States of Andhra and Tamil Nadu.

As a result of the above efforts, 32 different varieties of cotton, including nine long- and superior-long-staple varieties, 11 medium-staple varieties, eight short-staple (A) varieties, and four short-staple (B) varieties, have been released between 1968 and 1978 for cultivation in various tracts of India. Since, in India, cotton is grown under diverse agro-climatic conditions of soil from fertile irrigated tracts to semi-arid unirrigated tracts, it has always posed a challenge to the ingenuity of scientists working on cotton in evolving varieties most suited for the different tracts in the country. Hence, when new strains are released for tracts for which they are suited, the appropriate agricultural practices are also specified.

Table I summarizes the fibre characteristics and spinning potential of some of the important improved varieties of cotton released during the period 1968–76. The classification by staple length in this table is based on the 2.5% span length adopted in 1977 by the Indian cotton trade and industry to correspond with the classification adopted by the U.S. Department of Agriculture. The 2.5%-span-length values will be generally higher than the mean fibre length by 10% or more. (The ranges of values of the mean fibre length and 2.5% span length adopted for the classification of cottons into different staple-length groups before 1977 and at present are given in the Appendix).

The wide spectrum of improved strains released during the period 1968–76 ranges from G.27 of 17-mm length, spinnable to a linear density below 59 tex (10s cotton count), to Suvin, with a length of 40 mm, spinnable to 4.9 tex (120s cotton count). The development and production of long- and superior-long-staple cottons exceeded the requirement of cotton in this category in 1974–75, and for the first time India exported about 200 000 bales of long-staple cotton.

It is estimated that the requirement at the end of the Sixth Five-year-plan Period, namely, 1982–83, will be about 8.3 million bales, consisting of 0.7 million bales of superior-long-staple, 1.3 million bales of long-staple, 3.1 million bales of superior-medium-staple, 2.3 million bales of medium-staple, and 0.9 million bales of short-staple cottons. The organizations involved in cotton research-and-development activities in the country will have to strive hard in the next five years to fulfil these targets.

Table I
The Characteristics of Major Varieties Released during 1968–78

S. No.	Variety	Year of Release	2.5% Span Length (mm)	Fineness (mtex)	Fineness Micronaire Value	Strength at Zero Gauge Length (gf/tex)	Strength at Zero Gauge Length (mN/tex)	Spinning Potential, Expressed as Linear Density or Count (tex)	Spinning Potential, Expressed as Linear Density or Count (count)
	Long- and Extra-long-staple (29.5 mm and above)								
1	Suvin	1974	40.0	142	3.6	53.6	526	4.9	120s
2	Varalaxmi (Hybrid)	1972	36.0	138	3.5	44.5	436	7.4	80s
3	Sujata	1969	34.0	169	4.3	52.0	510	5.9	100s
4	MCU.5	1968	33.0	130	3.3	43.0	422	9.8	60s
5	G. Cot. 100 (Vishnu)	1975	31.5	138	3.5	46.6	457	11.8	50s
6	MCU.8	1974	31.5	130	3.3	42.9	421	9.8	60s
7	Hybrid 4	1970	31.0	173	4.4	42.0	412	11.8	50s
	Medium-staple (25.0–29.0 mm)								
8	JK.Hy. 1	1976	28.5	165	4.2	44.0	432	12.8	46s
9	K.8	1971	28.0	169	4.3	51.5	505	16.4	36s
10	G. Cot. 10 (SRT. 1)	1975	27.0	173	4.4	49.0	480	14.8	40s
11	Khandwa.2	1971	26.5	161	4.1	44.5	436	16.4	36s
12	MCU.7	1972	26.5	161	4.1	42.3	415	17.4	34s
13	Krishna	1968	26.0	165	4.2	50.0	490	16.4	36s
	Short-staple (A) (20.5–24.5 mm)								
14	Jyoti	1973	24.5	157	4.0	49.3	484	19.7	30s
15	F.414	1976	24.0	165	4.2	47.7	468	19.7	30s
16	Bhagya (GS.23)	1972	24.0	142	3.6	42.9	421	17.4	34s
17	Sujay (3943)	1972	23.5	130	3.3	45.0	441	17.4	34s
	Short-staple (B) (20.0 mm and below)								
18	Lohit	1969	19.5	287	7.3	41.6	408	Above 59.0	(Below 10s)
19	L.D. 133	1978	17.5	276	7.0	41.3	405	98.4	6s
20	G.27	1969	17.0	299	7.6	46.1	452	Above 59.0	(Below 10s)

3. THE BLENDING OF INDIAN COTTONS WITH POLYESTER FIBRE

3.1 Introduction

Before the introduction of the *G. hirsutum* and *G. barbadense* varieties of Indian cotton, the bulk of cotton used for blending with man-made fibres such as viscose or polyester fibre used to be imported mainly from Egypt, Sudan, and the United States. With the setting up of a number of regenerated-staple-fibre-manufacturing companies in the country in the 1960s, research work was carried out at various centres on the suitability of *G. hirsutum* varieties of Indian cottons such as MCU.1 and CO.2, belonging mainly to the Madras Cambodia Uganda types, with viscose staple fibre. However, these cottons were still considered unsuitable for blending with polyester fibre. Later, with the evolution of superior *G. hirsutum* types such as MCU.5, hybrid cottons such as Hybrid 4, and Varalaxmi and *G. barbadense* varieties such as Sujata and Suvin, attention was also devoted to studying their suitability for blending with polyester and other fibres.

The spinning performance of some superior varieties of Indian cottons in blends with polyester fibre has been assessed in experiments conducted at CTRL, and the yarn quality has been compared with the quality of yarns from blends of imported cottons such as Egyptian Giza 45 and Sudan XG2VS with polyester fibre[3]. The cottons assessed were Suvin, Sujata, and Giza 45 for 7.4 tex (80s cotton count) and Hybrid 4, Varalaxmi, and Sudan XG2VS for 12 tex (50s cotton count). The cottons were blended after combing with polyester fibre in proportions of 75 : 25, 50 : 50, and 33 : 67 of cotton : polyester fibre, respectively. Since the studies were conducted at different times, the polyester fibres used were different and the blends were as follows:

(i) Suvin with polyester fibre of 1.2 den (1.33 dtex), normal tenacity (NT), spun to 7.4 tex (80s cotton count);
(ii) Sujata and Giza 45 with polyester fibre of 1.5 den (1.67 dtex) (NT), spun to 7.4 tex (80s cotton count);
(iii) Hybrid 4 and Sudan XG2VS with polyester fibre of 1.5 den (1.67 dtex) (NT), spun to 12 tex (50s cotton count); and
(iv) Hybrid 4, Varalaxmi, and Sudan XG2VS with polyester fibre of 1.5 den (1.67 dtex), high tenacity (HT), spun to 12 tex (50s cotton count).

In the above experiments, Giza 45 and Sudan XG2VS were the imported cottons (control) with which the selected Indian cottons were compared.

3.2 Fibre Properties

It may be seen from the fibre properties of the cottons chosen for the blending trials, given in Table II, that Suvin and Sudan XG2VS are nearly equal in length and longer than the other cottons. Among the Indian cottons, Suvin has

Table II

Fibre Properties of Cottons Used in the Blends with Polyester Fibre

Cotton	Suvin	Sujata	Varalaxmi	Hybrid 4	Giza 45	Sudan × G2VS
Baer Sorter						
Mean length (mm)	33.5	31.9	30.8	28.0	32.0	33.5
Effective length (mm)	42.0	36.8	39.8	35.2	38.0	41.1
Short fibre (%)	15.6	8.6	19.2	12.9	9.9	14.0
Stelometer						
Bundle tenacity						
At zero gauge length						
(gf/tex)	49.3	43.9	45.0	34.7	53.6	46.6
(mN/tex)	483.5	430.5	441.3	340.3	525.6	457.0
At 3-mm gauge length						
(gf/tex)	34.0	35.4	27.3	24.0	35.2	31.5
(mN/tex)	333.4	347.2	267.7	235.4	345.2	308.9
Fineness						
Linear density (mtex)	142	169	122	173	134	148
Micronaire value	(3.6)	(4.3)	(3.1)	(4.4)	(3.4)	(3.8)

the longest staple and is followed by Sujata, Varalaxmi, and Hybrid 4 in that order. Though Varalaxmi had a greater effective length and was finer than Sujata, it had a higher percentage of immature fibres and was also more neppy.

3.3 Lea CSP and Yarn Tenacity

The lea count–strength product (CSP) and yarn tenacity for 7.4-tex (80s cotton-count) yarns from the blends are plotted in Figures 2 and 3, respectively, and those for 12-tex (50s cotton-count) yarns are plotted in Figures 4 and 5. It can be seen from Fig. 2 and Fig. 3 that the curves depict the characteristic behaviour of yarn strengths for blends of dissimilar fibres such as cotton and polyester fibre, the CSP for blends being less than that for individual components. Though individually Sujata has a much lower yarn strength than Giza 45, the difference in lea CSP and single-yarn tenacity is considerably reduced when the proportion of polyester fibre in the blend is above 50%, the yarn strengths being more or less equal for a blend containing 67% polyester fibre. Suvin yarn is slightly weaker than Giza 45, but the blended yarns of Suvin with polyester fibre are all stronger than the polyester-fibre blends with Giza 45 owing to the lower linear density of the polyester fibre used in the blend with Suvin. One more distinct quality of the blends of Suvin with polyester fibre of 1.2 den (1.33 dtex) is that, compared with the blends of the other cottons with polyester fibre, no great fall in tenacity is noticed on blending, and the curve is flatter than the other two curves. This means that, with a choice of finer polyester fibre, a higher proportion of Suvin

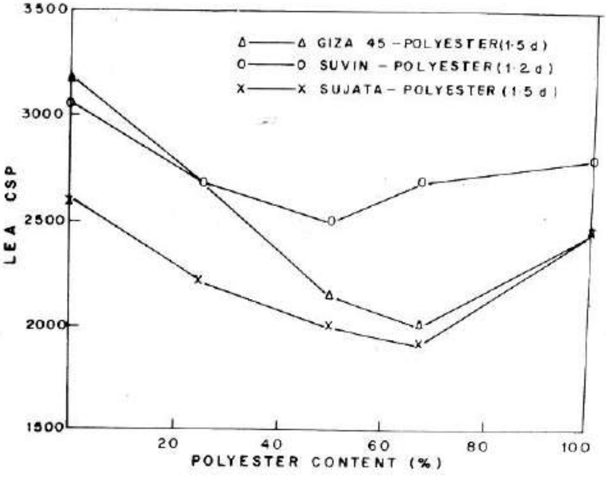

Fig. 2
Relation between lea CSP and blend proportion in 7.4-tex (80s-cotton-count yarns)

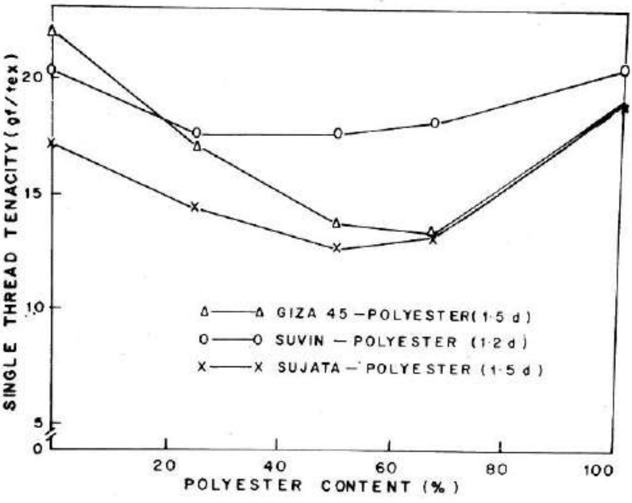

Fig. 3
Relation between single-thread tenacity and blend proportion in 7.4-tex (80s-cotton-count) yarns

could be used for acceptable levels of yarn strength.

Similar trends are noticed for blends of Hybrid 4, Varalaxmi, and Sudan with polyester fibre as for Sujata and Giza 45, and these are depicted in Figures 4 and 5. The maximum differences between the blended-fibre yarns are noticed when the polyester-fibre component is less than 50% of the blend composition. For blends with 67% of high-tenacity polyester fibre, the single-thread tenacities are nearly equal for both Sudan and Hybrid 4, and for the blends with Varalaxmi

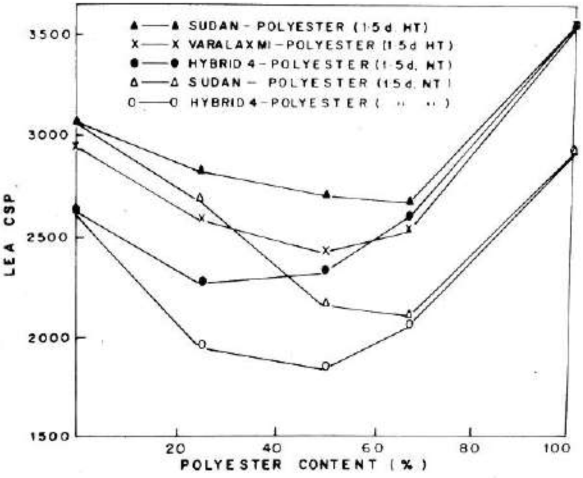

Fig. 4
Relation between lea CSP and blend proportion in 12-tex (50s-cotton-count) yarns

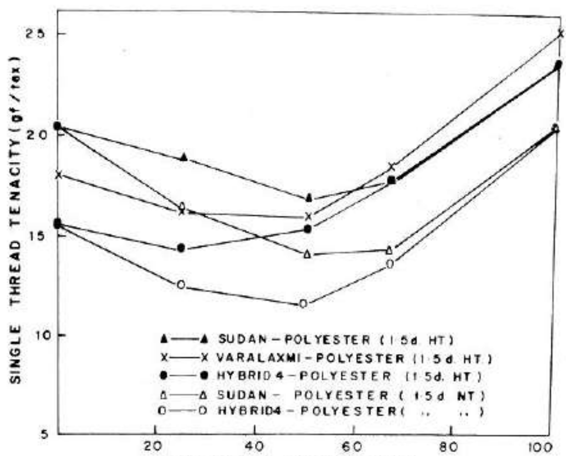

Fig. 5
Relation between single-thread tenacity and blend proportion in 12-tex (50s-cotton-count) yarns

the tenacities are higher, possibly owing to the higher tenacity of the polyester fibre used for blending with the cotton. For the blends with normal-tenacity polyester fibre, the Sudanese cotton gives stronger yarns throughout, but, as already stated, the difference between the blended-fibre yarns with Sudan and Hybrid 4 is substantially reduced when the polyester-fibre component forms 67% of the blend proportion.

3.4 Yarn Extension

The breaking elongation of the yarns is plotted in Figures 6 and 7 for the two yarn groups. As expected, the breaking elongation goes on increasing with an

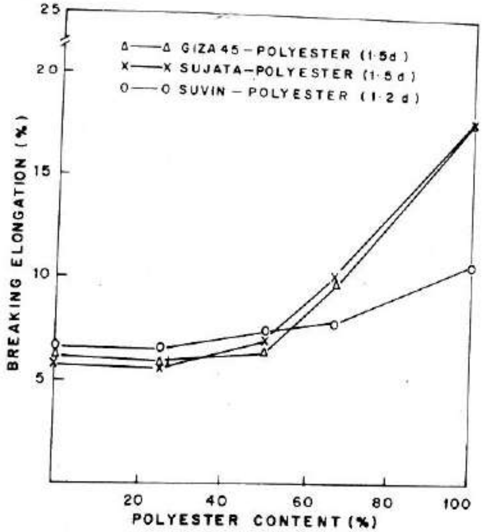

Fig. 6
Influence of polyester-fibre content on yarn breaking elongation (7.4-tex yarns)

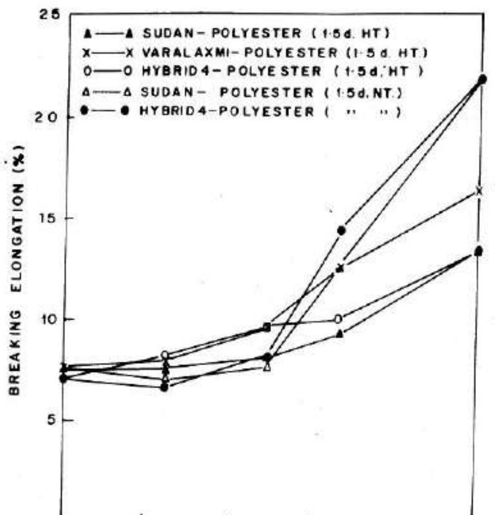

Fig. 7
Influence of polyester-fibre content on yarn breaking elongation (12-tex yarns)

increase in the proportion of polyester fibre. The breaking elongations are less for the high-tenacity polyester-fibre blends than for the blends with normal-tenacity polyester fibre and also for the 1.2-den (1.33-dtex) polyester-fibre blend (Fig. 6) than for the blend containing 1.5-den (1.67-dtex) polyester fibre. It may also be seen that, except for Suvin, the blends containing Indian cottons have generally given a higher breaking elongation than the blends containing imported cottons.

3.5 Yarn Unevenness and Imperfections

The unevenness and neps as measured by the Uster Evenness Tester for blends with 50% and 67% polyester fibre are given in Tables III and IV. The blended-fibre yarns from Sudan cotton are more even than those from Hybrid 4 and Varalaxmi, while between Giza 45 and the other two Indian cottons, Sujata and Suvin, no great difference in U% is noted. Among the 7.4-tex (80s cotton-count) yarns, Sujata gave the least neppy yarn and was followed by Suvin and Giza 45. However, in 12-tex (50s cotton-count) yarns, no great difference was observed between Sudan and Hybrid 4 in yarn neppiness, but Varalaxmi gave distinctly more neppy yarns.

Table III

Yarn Properties of 7.4-tex (80s) Polyester-fibre–Cotton Blended-fibre Yarns

Type of Polyester Fibre		1.2 den (1.33 dtex), 38 mm		1.5 den (1.67 dtex), 38 mm		1.5 den (1.67 dtex), 38 mm	
Cotton Used		Suvin		Sujata		Giza 45	
Blend proportion (Polyester fibre: cotton)		50:50	67:33	50:50	67:33	50:50	67:33
Lea CSP		2508	2688	2010	1921	2157	2019
Single-thread tenacity	(gf/tex)	17.8	18.2	12.9	13.4	13.9	13.6
	(mN/tex)	174.6	178.5	126.5	131.4	136.3	133.4
Elongation at break (%)		7.4	7.9	7.0	10.2	6.5	9.9
Uster unevenness (%)		16.7	16.4	15.5	15.3	16.1	15.1
Neps/100 m		42	39	14	25	97	76

3.6 Related Studies

In addition to the studies on the blending of Indian cottons with polyester fibre at CTRL, similar studies have also been carried out at other research centres in India as well as by the polyester-fibre manufacturers[4–6]. The conclusions reached in these studies are similar and can be summarized as follows.

(i) Cottons such as Hybrid 4 and MCU.5 can replace imported cottons for blends with polyester fibre for medium and fine yarns of 10–14.8 tex (40s–60s cotton count) for blend compositions containing up to 50% cotton.

Table IV

Yarn Properties of 11.9-tex (50s) Polyester-fibre–Cotton Blended-fibre Yarns

Type of Polyester Fibre	1.5 den (1.67 dtex) 38 mm (NT)				1.5 den (1.67 dtex) 38 mm (HT)				1.5 den (1.67 dtex) 38 mm (HT)	
Cotton Used	Sudan × G2VS		Hybrid 4		Sudan × G2VS		Hybrid 4		Varalaxmi	
Blend proportion (Polyester fibre: cotton)	50:50	67:33	50:50	67:33	50:50	67:33	50:50	67:33	50:50	67:33
Lea CSP	2174	2116	1850	2062	2725	2692	2335	2611	2366	2557
Single-thread tenacity (gf/tex)	14.2	14.4	11.7	13.7	17.0	17.9	15.4	17.8	16.0	18.5
(mN/tex)	139.3	141.2	114.7	134.4	166.7	175.5	151.0	174.6	156.9	181.4
Elongation at break (%)	7.9	12.8	8.4	14.5	8.2	9.6	9.8	10.2	9.9	12.8
Uster unevenness (%)	14.4	13.7	15.1	15.1	14.6	14.4	16.1	15.7	15.8	15.4
Neps/100 m	16	17	12	12	13	17	13	15	44	52

(ii) For finer yarns of about 7.4 tex (80s cotton count), cottons such as Suvin, Sujata, and Varalaxmi could be used without any deterioration in yarn tenacity.

(iii) In general, the Uster regularity of blended-fibre yarns from Indian cottons and polyester fibre are comparable with those from imported cottons such as Sudan cotton or Giza 45. However, the yarn appearance in certain cases, such as Varalaxmi or MCU.5, has been poorer owing to the higher nep content as a result of immaturity and the presence of motes.

4. THE BLENDING OF INDIAN COTTONS WITH OTHER NATURAL FIBRES

Apart from the blending of cotton with polyester fibre or other man-made fibres, where superior types of cotton are mainly used, the blending of cotton with other natural fibres such as jute, wool, or ramie offers interesting possibilities in the production of fabrics with diverse end-uses. The production of blended-fibre apparel fabrics containing cotton and wool has been in vogue, and such fabrics have been commercially produced. But the blending of cotton with jute or ramie has been practically ignored until recent times, mainly owing to the extreme differences in the length and fineness of the fibres and the impracticability of processing jute or ramie, as such, on the cotton-spinning system. A project was undertaken at CTRL to study the blending of jute, ramie, and wool with cotton, cotton-spinning machinery being used to investigate the quality of the yarns produced and their suitability for specific types of fabric. Under this scheme, the blending of cotton with jute was studied extensively.

Cotton was blended both with jute caddies and with jute waste, which have negligible economic value, and with jute stapled to about 25 mm[7]. The cottons used for blending with caddies for yarn of linear density 100 tex (6s cotton count) were mainly the short and coarse varieties, such as Shyamli and Wagad, with mean lengths around 20 mm and a Micronaire value of 6.0 and 6.5, whereas, for blending with jute staple for yarn of linear density 50 tex (12s cotton count), cottons such as Suyodhar and L 147, with mean lengths around 25 mm and a Micronaire value of 4.5, were used. The results indicated that jute could be blended up to about 20% without marked deterioration in yarn quality for the production of fabrics mainly intended for furnishings and upholstery materials. Attractive designs and colours are possible from such blends.

5. VARIETAL RESPONSE TO EASY-CARE FINISHING

5.1 Introduction

Cotton fabrics are increasingly being given a resin-finish cross-linking treatment to impart to them the easy-care properties of synthetic-fibre fabrics. However, it is well known that this treatment adversely affects the wear life and

Table V

Dimensional and Fine-structure Variations in Indian Cottons

Cotton Species	Length (mm)	Width (μm)	Average Cross-sectional Shape (75% mature)			Convolu-tions/cm	Rever-sals/cm	Convolution Angle (deg)	Spiral Angle (deg)	X-ray Angle (deg)
			Round	Elliptical	Flat					
G. arboreum	10–25	17–25	40.5	48.0	11.5	30–60	2–6	5.1–11.8	29.6–39.8	22.6–35.0
G. herbaceum	10–25	17–30	34.8	51.5	13.7	30–50	2–5	6.2–8.9	34.4–37.5	26.5–31.8
G. hirsutum	20–32	16–20	15.3	67.6	17.1	50–75	10–27	8.8–12.3	35.4–38.0	28.6–34.6
G. barbadense (Foreign)	35–45	14–18	18.2	65.3	16.5	30–55	12–20	3.9–8.5	28.2–35.0	22.8–30.5

tensile and tearing strengths of the cotton fabric. Attempts are therefore being made in many laboratories throughout the world to improve the strength retention and mechanical properties of cotton fabrics that are subjected to cross-linking treatments. One approach to overcoming this problem is to give some pre-treatment such as swelling and stretching to cotton to enhance its strength before cross-linking. The other approach is to identify cotton varieties that are inherently more suited for an easy-care finishing treatment. Both these approaches, particularly the latter, are being pursued at CTRL.

5.2 Dimensional and Structural Variation

Cotton fibres vary considerably in their gross morphology, namely, convolutions, cell-wall thickness, cross-sectional shape, etc., and in their fine structure, namely, fibrillar orientation, reversals, the packing density of microfibrils, etc., from variety to variety and species to species. The data amassed at CTRL on the dimensional and structural properties of Indian cottons[8,9] are summarized in Table V. It may be noted that *G. arboreum* and *G. herbaceum* cottons are not only shorter and coarser but also have fewer convolutions and fewer structural reversals per unit length than *G. hirsutum* and *G. barbadense* cottons. A critical study with regard to species of Indian cottons at maturity levels of 60 and 75% has revealed that *G. arboreum* and *G. herbaceum* cottons have a significantly higher percentage of fibres with a round cross-sectional shape than *G. hirsutum* and *G. barbadense* cottons.[10] There is a large variation in the convolution angle, spiral angle, and X-ray angle of cotton according to species. It has also been observed that the cell wall of *G. herbaceum* cotton is composed of finer micropores and smaller crystallities than the cell wall of *G. hirsutum* cotton.[11] The importance of these structural parameters needs no emphasis, since it is now well recognized that deterioration in the mechanical properties of easy-care fabrics is to a large extent due to the inherent heterogeneous structure of the cotton fibre and non-uniformity of distribution of cross-links. In view of this, Indian cottons representing all the four cultivable species offer excellent genetic material for study in depth of the behaviour of different varieties of cottons in their response to resin-finishing treatment.

5.3 Response to DMDHEU Treatment

In a recent investigation at CTRL, a large number of varieties of cottons cultivated in India were screened in yarn form after being given a standard cross-linking treatment with dimethylol-dihydroxy-ethylene urea (DMDHEU, about 0.8N). Fig. 8 summarizes the results of toughness retention of 34 varieties of Indian cottons subjected to DMDHEU treatment. Toughness is the most important single property of cotton that indicates the energy-absorbing capacity of the fibre, which influences the abrasion-resistance, tearing strength, and wear life of a cross-linked fabric. Cotton of medium strength (37.5–45.5 gf/tex, i.e., 367.8–446.2 mN/tex) with high elongation (over 8%) is more suited for an easy-

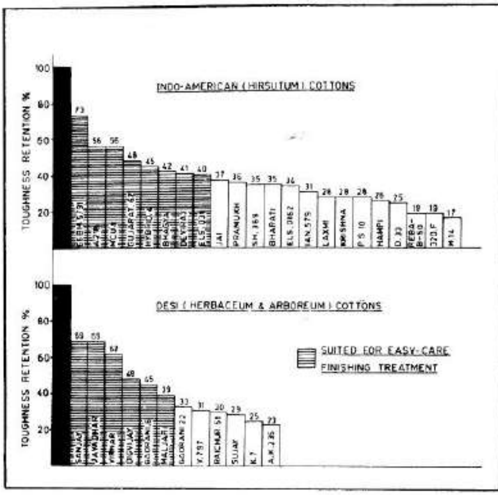

Fig. 8
Toughness retention of Indian-cotton yarns subjected to DMDHEU treatment

care finishing treatment than one with very high strength and low elongation. Furthermore, toughness retention of about 40% by a cotton after cross-linking may be considered as promising.

The wide variation in the toughness retention within *G. hirsutum* cottons after a cross-linking treatment is apparent from Fig. 8. For instance, cotton 66 BH5/91 has toughness retention of 73%, whereas the variety H.14 exhibits a poor toughness retention of about 17%. Similarly, of the *G. arboreum* and *G. herbaceum* cottons, Sanjay and Jayadhar exhibited very high toughness retention.

In an earlier study of cross-linked cottons in fibre form, it was observed that Sujata and Suvin, both belonging to the *G. barbadense* group, which have inherently high strength and high elongation, are also better suited to an easy-care finishing treatment[12].

Eight varieties of cotton that had shown promise while being examined in yarn form for easy-care properties were also tested further in fabric form. The fabrics produced from the eight cottons had an identical count and construction (linear density 19.8 tex, i.e., 30s cotton count, twist multiplier 4.2, 64 ends/in. (25 ends/cm) and 60 picks/in. (24 picks/cm). The fabrics were also given a standard DMDHEU treatment to obtain an add-on of about 3%. Fig. 9 illustrates the toughness retention and crease-recovery angle (CRA) of DMDHEU-treated fabrics. It may be noted that Hybrid 4, Digvijay, Deviraj, and Sanjay have high toughness retention and, with the exception of Hybrid 4, have CRA above the wash–wear level. Particular mention may be made of *desi* cottons like Sanjay and Digvijay, which have CRA above the durable-press level combined with high toughness retention. By giving less rigorous resin-finishing treatments to these varieties, it may be possible to obtain further improvement in their toughness

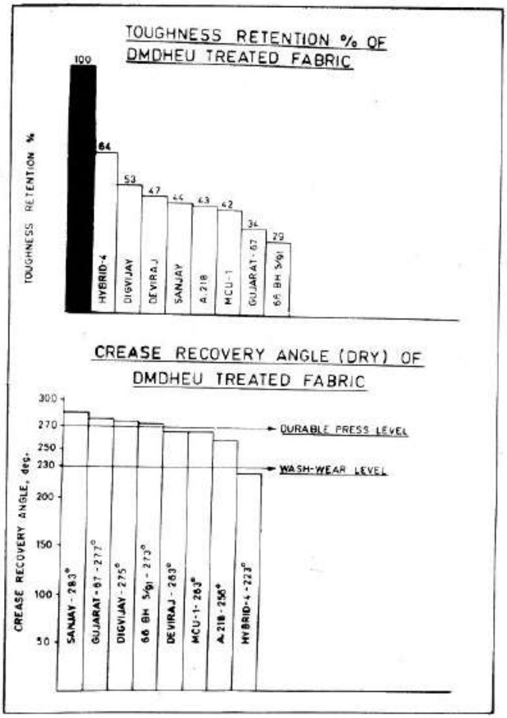

Fig. 9
Toughness retention of Indian-cotton fabrics subjected to DMDHEU treatment

retention while still retaining CRA at the wash–wear level. Many of the *G. arboreum* and *G. herbaceum* cottons have a high percentage of fibres of round cross-sectional shape, and, with due weight given to the so-called 'bilateral' structure of cotton proposed by Kassenbeck, it could be assumed that such cottons have a more homogeneous fine structure and are therefore better suited for easy-care finishing treatments.

The studies discussed above have demonstrated that there is a wide variation in the varietal response of cotton to easy-care finishing treatments. The present-day cotton breeder may, indeed, exploit this variability and attempt to introduce this new parameter in his breeding programme.

6. CONCLUDING REMARKS

The major trend in the development of cotton in India has been mainly linked to improvement in both cotton yield and quality by the introduction of several *G. hirsutum* varieties, such as MCU.5, MCU.8, SRT 1, and Khandwa, as well as hybrids such as Hybrid 4 and Varalaxmi. A limited number of *G. barbadense* varieties, such as Suvin, have also been introduced to fulfil the requirements of superior-long-staple cottons in the country. As a result, the production of Indian cottons has increased by nearly two million bales over the last decade, and this increase has been accompanied simultaneously by a remarkable improvement in cotton quality, the production of cotton of length over 25 mm having doubled during this period.

India is probably the only country in the world that is cultivating all the four major *Gossypium* species, i.e., *G. arboreum, G. herbaceum, G. hirsutum,* and *G. barbadense*. The wide genetic variation between varieties offers considerable scope to the breeder to evolve and to the technologist to choose the variety of cotton most suited for a particular end-use. Thus, some cottons belonging to the *desi* species, *G. arboreum* and *G. herbaceum*, though having low yield and poorer spinnability, have been found to be eminently suitable for easy-care finishing treatments owing to their uniform fibre structure, circular cross-section, and higher toughness characteristics. Some of them are inherently very coarse, which also makes them suitable for blending with other coarse natural fibres, such as jute, wool, and ramie. On the other hand, cottons belonging to the *G. hirsutum* and *G. barbadense* species, as well as hybrid cottons, have higher productivity and better spinnability and are also suitable for blending with synthetic fibres, such as polyester fibre.

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APPENDIX

Staple-length Classification in India before 1977 and at Present

Before 1977		Present	
Category	Staple length (Mean length) (range in mm)	Category	2.5% Span length (range in mm)
Short	19.0 and below	Short B	20.0 and below
Medium	20.0–21.5	Short A	20.5–24.5
Superior Medium	22.0–24.0	Medium	25.0–29.0
Long	24.5–26.0	Long	29.5–32.5
Superior Long	27.0 and above	Extra Long	33.0 and above

5—A STUDY OF HONEYDEW IN COTTON

By G. ALON, O. ELSNER, and M. OSTFELD

An attempt to improve the spinnability of sticky cotton, either by washing off or by decomposing the honeydew from the cotton under controlled conditions, is described.

Irrigation of cotton in the field did not wash off the sugars but distributed them more evenly over the lint. This was demonstrated by the replica test developed in the authors' laboratory. Although a more even sugar distribution might improve the spinning process, the investigation along these lines was discontinued for economic reasons.

A study of the decomposition of sugars by micro-organisms gave some contradictory results. In laboratory tests, the sugars were effectively decomposed by saccharomycetaceae. Sugar in mini-bales stored at 100% r.h. decomposed irrespective of the presence or absence of saccharomyces, whereas the sugar concentration in the same cotton stored under ordinary conditions did not change during the same period.

Spinning results showed that the best results were obtained by using the X–78 formula of North American Electro-Static Corporation. Spraying with a water and saccharomyces suspension improved the spinning process to some extent, most probably because of the more even spreading of the honeydew over the lint.

1. INTRODUCTION

In the last decade, the phenomenon of cotton sticking has been increasingly frequently discussed in the literature[1–13]. Sticky cotton originates in tropical and sub-tropical growing locations, such as the U.S.A., North Africa, the Middle East, and Asia. As many as eighteen different reasons for sticky cotton have been suggested, some of which are: honeydew, immature fibres, excessive wax, high moisture content, bacteria, fungi, seed-coat fragments, oil from cut seeds, defoliants, and liquids applied at the gin or at the mill. It is well known that sticky cotton affects processing efficiency and reduces yarn quality.

The study reported in this paper deals specifically with one cause, namely, honeydew deposited on the cotton as a result of the attack of the white fly (*bemisia tabaci*). It is known that the white fly attacks citrus trees, greenhouse plants, melon leaves, etc. After the harvesting of some of these crops at the end of the summer, the white fly may migrate to the cotton plant. The white fly sucks the sap from the cotton leaves and drops the excess sugars that it cannot digest on the leaves and the lint. In addition, the injured leaves may excrete honeydew.

Among the recommendations offered in the literature to overcome some of the negative effects of sticky cotton are:

(*a*) to blend small amounts of sticky cotton with non-sticky cotton;
(*b*) to minimize the effect by ageing the cotton (3–9 months); and
(*c*) to reduce the relative humidity during cotton processing and to raise the room temperature.

It is preferable to use a combination of all three methods.

The purpose of the study reported in this paper is to investigate ways and means of minimizing the sticking phenomenon during fibre processing.

Backe[1] assumes that during cotton storage the honeydew is digested by fungi, which develop accidentally. Roberts[10] found that honeydew consists of β-D fructose, α-D glucose, β-D glucose, glycerin, and some other unidentified materials. Hadwich[4] adds to this list sucrose and dextrine.

On taking all this information into consideration, it was decided to try to destroy or to wash away the honeydew from the lint.

2. EXPERIMENTAL PROCEDURE AND RESULTS

2.1 Irrigation

Initially, an attempt was made to irrigate a cotton field that had been attacked by the white fly. The field was irrigated in September after defoliation by using sprinklers for periods ranging from half an hour to seven hours.

From marked cotton plants, half of each open boll was hand-picked before irrigation, and the other half of the boll was hand-picked after irrigation when already dry.

The samples were analysed, after being hand-ginned, for sugar content, which was determined by using the modified Folin test[2]. For qualitative analysis, the replica test that was developed in the authors' laboratory was used. The test consisted in spreading a 2-g sample of cotton on a flat surface of about 25 cm^2. The sample was sprayed with about 1 cm^3 of Benedict solution. The sprayed cotton sample was covered by a piece of 10-cm $\times$ 10-cm No. 3 filter paper, slightly wetted with paraffin oil. The filter paper was pressed against the cotton sample by a glass plate. A 1-kg weight was placed on top of the glass plate for a few seconds, and the filter paper was then separated from the cotton and placed between two metal plates and heated in an oven at 100°C for 5 min.

The filter paper was visually judged for the colour of the stains developed (from pale yellow to orange) and for the size of the stains. (The paraffin oil prevented excessive spreading of sugars on the filter paper.)

It was found that the irrigation did not significantly reduce the sugar content of the cotton, but it did spread the honeydew more evenly on the lint, as shown by the replica test.

2.2 Honeydew Decomposition

2.2.1 Choice of Process for Effecting Decomposition

If it is true that during storage the sugars are destroyed by an uncontrollable development of micro-organisms, it should be possible to effect a similar decomposition of sugars by a controlled process. For this purpose, it was decided to use α-saccharase and sacchromycetaceae (saccharomyces is baking yeast).

2.2.2 *Sugar Decomposition in an Extract*

Two identical water extracts were prepared from cotton containing 1.3% honeydew. The extracts contained 0.025% reducing sugars.

Two suspensions were prepared, one containing 1% a-saccharase and the second containing 1% saccharomyces. The suspensions were activated at room temperature by adding 1% sugar.

The two extracts were inocculated by adding to one 2 cm^3 of a-saccharase suspension and to the second 2 cm^3 of saccharomyces suspension. The sugar content was measured as a function of time by using the Folin method.

The results are illustrated in Fig. 1.

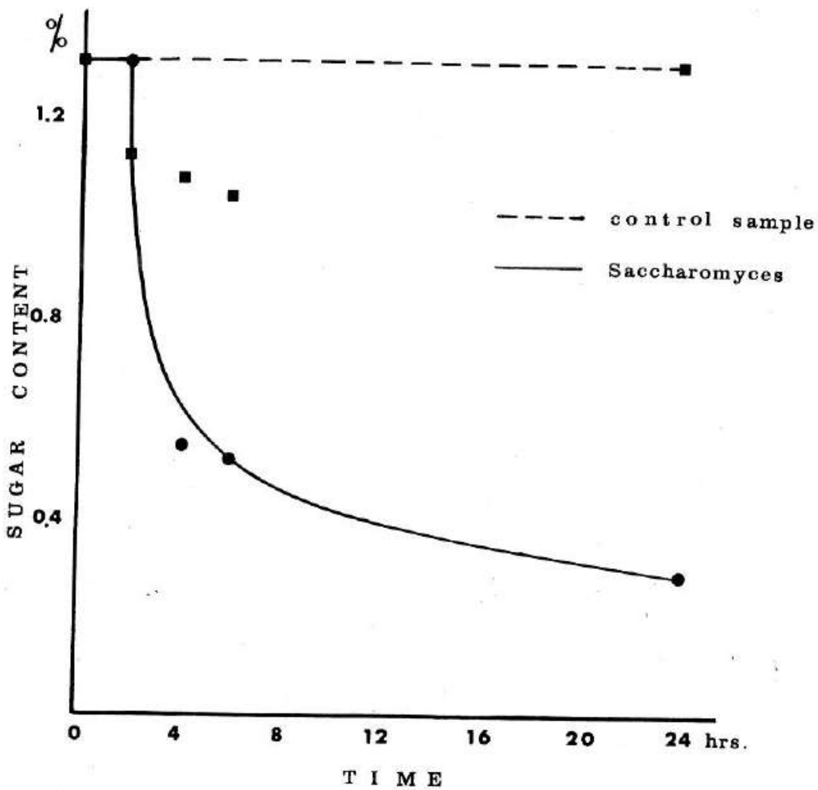

Fig. 1
Decomposition of sugars extracted from cotton by saccharomyces

It was found that only the saccharomyces were effective in decomposing the honeydew.

2.2.3 *Sugar Decomposition on the Lint*

An additional experiment involved an attempt to decompose honeydew directly on cotton lint.

In this experiment, a 1% saccharomyces suspension was sprayed on lint

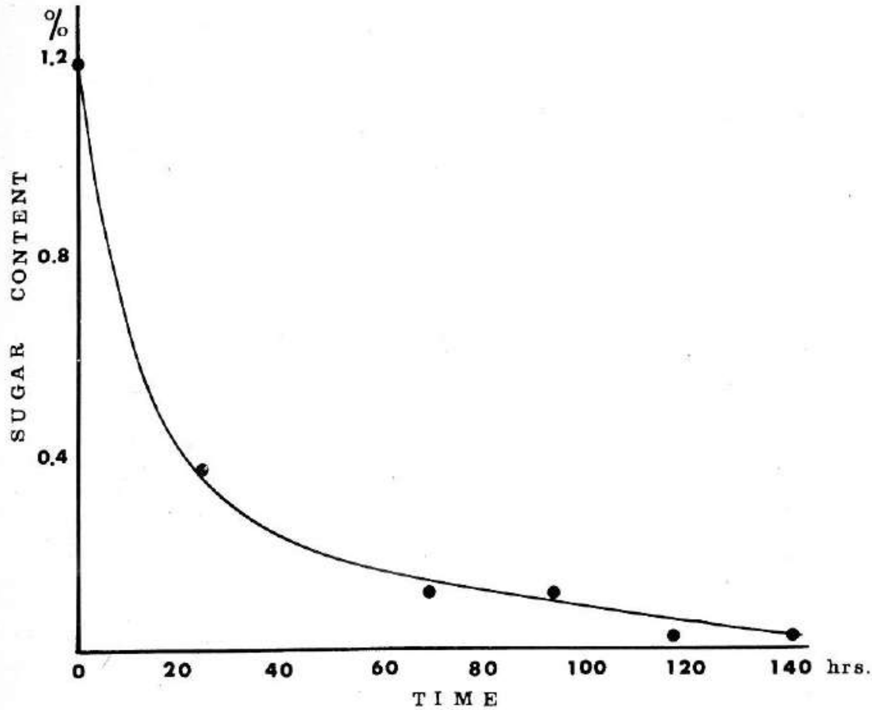

Fig. 2
Decomposition of honeydew deposits on cotton by 1% sacchromyces suspension

(20% liquid take-up). The lint was sealed in a plastics bag and stored at 25–30°C. The results obtained are illustrated in Fig. 2.

The results of this experiment clearly indicate that the saccharomyces disintegrate the honeydew effectively in a relatively short time.

2.3 Spinning Tests

2.3.1 Procedure

Samples of cotton, each of 10 kg, were processed in a spinning laboratory containing industrial equipment (Saco Lowell). The amount of waste at each cleaning point, the number of roller lappings, the silver and yarn properties, and the number of ends down were evaluated. The spinning tests were performed in an unconditioned laboratory with relative humidity ranging from 70 to 85% and at a room temperature ranging from 18 to 23°C. Such conditions are unfavourable for processing. They do, however, make the spinning test a very sensitive instrument for detecting the sticking phenomenon.

Samples A, B, and C, each of 30 kg, were divided into sub-samples of 10 kg each. The sub-samples were stored (picker laps), after being processed on the opening line, for periods ranging from one day to three weeks before further

Table I

Sample Pre-treatment

Sample	Method of Treatment	Cotton Type
M	Untreated sticky control sample	Middling $1\frac{1}{16}$ in. (27.0 mm) Acala SJ–2 1.1% sugar Pressley strength 90 000 lbf/in^2 (620.5 kPa) Micronaire value 4.7
A	Sprayed at feeder with tap water, 4% add-on	
B	Sprayed with saccharomyces suspension*, 4% add-on, 0.05% of saccharomyces of cotton weight	
C	Sprayed with saccharomyces suspension, 4% add-on, 0.1% of cotton weight	
X	Sprayed with Protect-o-coat formula X–78 of North American Electro-Static Corp., 0.2% add-on of cotton weight	
N	Untreated non-sticky control sample	Middling $1\frac{3}{32}$ in. (27.8 mm) Acala SJ–2 0.2% sugar Pressley strength 91 000 lbf/in^2 (627.4 kPa) Micronaire value 4.5

*Since cotton's moisture content is 6–7%, it is impracticable to add more than 4% additional moisture as compared with the 20% add-on in the laboratory honeydew-decomposition experiment.

processing. Regular sugar-content tests were performed for six weeks. The results indicate that no change in sugar concentration took place.

2.3.2 *Process Evaluation*

The spinning-test results clearly indicate that, although no change was found in the sugar content of the treated cottons, all treatments reduced the number of lap-ups at the drawing frame. The X–78 treatment solved the lapping problem, while enzyme or water treatment improved the situation to some extent.

It has to be noted that the drawing of sticky cotton, regardless of the type of treatment, could not have been performed on a drawing frame without an air-cleaning system unless the upper front roller was continuously cleaned with the aid of a felt brush in order to eliminate frequent lapping on the roller (this cleaning was not necessary with sample N).

It must also be mentioned that processing all the samples of sticky cotton increased the amount of waste at the drawing frame.

The amount of waste extracted from the cotton in the opening and carding processes was a little lower with cotton treated by X–78 then with the untreated sticky cotton (sample M) without affecting the cleanliness of the yarn.

All yarns spun from sticky cotton, regardless of the type of treatment, were trashier than the yarn spun from the non-sticky control sample (N).

Table II

Spinning-test Results

	Collected Waste Quantity (Opening + Picking + Carding) %	Neps in Card Web (neps/100 in^2)	Laps-up in Drawing			Uster Irregularity of Yarn $U\%$	End-breakage Ratio in Spinning (per 1000 spindle–hr)	Yarn Strength (Breaking Length)		Breaking Elongation	
			1st Passage	2nd Passage	Total			Mean Value (cN/tex = 1 km)	CV %	Mean Value %	CV %
M	4.31	48	19	5	24	16.2	77	15.6	18.0	5.9	11.5
A	4.02	74	10	3	13	13.9	66	15.3	14.3	6.1	10.7
B	4.21	65	13	1	14	16.8	74	15.2	12.5	6.3	11.2
C	4.17	72	6	0	6	15.8	168	15.5	11.5	6.4	9.6
X	3.75	69	1	0	1	15.3	35	15.2	12.3	5.7	9.1
N	4.08	50	0	0	0	12.7	23	16.8	10.4	5.9	16.0

Yarn linear density 40 tex. Twist 600 turns/m.

There are some indications that all treated cotton samples contained more neps in the card web than the sticky control sample M.

There are indications that the processing of sticky cottons (M) causes more ends down than that of regular cotton (N). There are also indications that treatment with X–78 reduces the number of ends down. For the other treatments, conflicting results were obtained. It should be stressed that these results are based on a limited number of spindle–hours.

During the processing of the cotton on the picker, tufts of cotton stuck to the calender roll. This was true for all samples of the sticky cotton, but it did not happen with the non-sticky control sample.

The sticking of cotton to rollers at the different stages of production revealed that the sticking occurs where there is a concentration of honeydew, whether on the lint or accumulated on the roller during the process.

2.3.4 Product Evaluation

A method was developed to evaluate visually the distribution of sugars on the fibres at the roving stage. A strand of roving was placed on a plate, and the roving was sprayed with a Benedict solution. The plate with the sprayed sample was sealed in a nylon bag and heated by immersing it in boiling water for 5 min. The evaluation was made according to the colour development in a similar manner to that of the replica test mentioned above.

It was found that the roving produced from the non-sticking control sample had a uniform green colour, whereas all treated cottons (A, B, C, and X) had a rather uniform yellow-to-orange colour. The sugar-indicating colours of the untreated sticky cotton (sample M) were unevenly interrupted by the green spots of the Benedict solution. This shows that there are local concentrations of honeydew in contrast to a rather even distribution of honeydew on the sample of the treated cotton.

Yarns of all samples and sub-samples were evaluated for regularity (Uster unevenness and imperfection count), strength, and elongation. All yarn samples spun from sticky cotton were more uneven than the yarns spun from the non-sticky control sample.

A significant loss of strength of all yarns spun from sticky cotton as compared with the yarn spun from the non-sticky control samples was found.

2.4 Storage

Parallel to the spinning tests, 800 g of cotton of each of the samples A, B, and C were pressed into miniature bales having a density similar to that of regular bales. The bales were stored in a hermetically closed chamber at 30°C. Open vessels containing water were placed next to the mini-bales. Sugar-content analysis was performed periodically for five weeks and showed no change in the sugar content of any of the samples. After six weeks, the samples were rechecked. The last analysis showed almost complete decomposition of the sugars for all three mini-bales.

Another highly sticky cotton sample was stored over a period of 18 months. This sample was not treated in any way in the laboratory and was stored in an unconditioned room, where it was kept loosely in a paper bag. No change in the sugar content occurred during this period.

3. DISCUSSION AND CONCLUSIONS

3.1 General Observations

The results of this study confirmed that sticky cotton reduces the process efficiency and yarn quality (more trash, laps up, ends down, irregular yarn, and strength loss).

The known tests for sugar determination are tedious and not suitable as standard tests for spinners. When the spinner detects sticky cotton, it is already too late to take any preventive measures. It should therefore be the growers' responsibility to report suspicions of sticky cotton. Preventive treatments should be carried out as soon as possible and preferably in the field with pest control. If this is not possible, the aim should be to treat the cotton as close as possible to the field in order to relieve the spinner from subsequent difficulties. The most logical place to treat the cotton would be at the gin.

In this study, two approaches were used:

(*a*) cotton irrigation;
(*b*) pre-treatment of the cotton.

For reasons of convenience, these experiments were carried out in the spinning laboratory rather than at the gin.

3.2 Irrigation

Close investigation of the nature of the sticking phenomenon clearly shows that laps up are caused by a concentration of honeydew on the lint or by its accumulation on the rolls. It can therefore be stated that the degree of sticking will depend on both the amount of free sugars on the lint and their distribution on it. The more even the distribution, the less the cotton will stick to the rolls. The dilution of sugars resulting from irrigation may thus ease the problem of sticking cotton. However, this solution is rather expensive and not always possible. Not all cottons are irrigated and, for some that are, irrigation techniques other than sprinkling (the dripping method) are used. The same effect could be achieved by picking the cotton after the first rain, but this solution is also not advisable, since it will lower the cotton grade and may cause other damage.

3.3 Sugar Decomposition

Results of the honeydew-extract treatment with saccharomyces indicate that this method is effective and may bring the sugar content of sticky cotton down to the normal level within a few hours.

It was also found that a 20% take-up of the saccharomyces suspension decomposes the honeydew directly on the lint to a normal level within 24 hr and completely after 4 days.

These two experiments encouraged the authors to apply this method to cotton to be processed in a semi-industrial spinning test.

The decision to investigate the saccharomyces was made since they can be active under both aerobic and anaerobic conditions. Under aerobic conditions, the sugars are decomposed by an oxidative process, whereas under anaerobic conditions fermentation takes place and the sugars decompose to alcohol and CO_2.

3.4 Spinning Test

The amount of liquid added to the cotton was limited to 4% in order to obtain fibres suitable for processing. With this limitation, the results were disappointing. The failure of enzymes to decompose the honeydew under these conditions may be due to the excessive osmotic pressure of the highly concentrated sugar solution on the lint. It is known that high osmotic pressure prevents the activity of micro-organisms. This was confirmed by two additional experiments, one with the mini-bales and the other with the untreated high-sugar-content cotton, which was tested over a period of eighteen months.

It was not surprising to find that untreated sticky cotton caused many processing difficulties. Although the enzyme treatment did not decrease the sugar concentration, it did improve the situation to some extent. This improvement can only be explained by the results obtained in the replica test, revealing a more even sugar distribution. The addition of 4% moisture to the fibre probably dissolved the solid honeydew and caused its migration. This migration was also encouraged by the fibre movement in the opening line.

For all types of cotton treatment, the best results were obtained by using X–78.

Another point of consideration is the increased number of neps in treated sticky cotton compared with untreated sticky cotton. This phenomenon may well be explained by the fact that, in the opening line and at the card, the treated fibres still contained excess moisture, which mean that the inter-fibre coefficient of friction was higher and fibre entanglement was therefore increased.

From this study, it is obvious that, in order to spin a yarn with the desired standard of cleanliness from sticky cotton, an additional cleaning process, which, of course, involves more waste, must be introduced.

Finally, it has to be stressed that this study was made under the following extreme conditions:

(*a*) cotton with a very high concentration of honeydew, which is rarely found, was used;

(*b*) the atmospheric conditions were unfavourable and extremely sensitive to the sticking phenomenon.

In addition it must be borne in mind that the results obtained in a spinning test on such small batches of cotton can give only indications, which should be verified by processing large batches of sticky cotton under actual mill conditions.

3.5 Storage

Much reference is made in the literature to the storage of cotton for periods of between three and nine months, which supposedly causes decomposition of sugars. This was not completely verified in the study reported above. During the first five weeks of storage, no change in sugar content was noted in the mini-bales. The sugar concentration dropped to 0.2% only after an additional six weeks. Contrary to these results, cotton containing 1.3% sugars stored loosely at room temperature showed no change in sugar content during the eighteen months of storage. Furthermore, the same cottons as were used for the preparation of the mini-bales (samples A, B, and C) were also used in the spinning experiments, and there the sugar content did not change during the three months of storage.

Since the drop in sugar concentration took place in both inocculated and non-inocculated cottons, the sugar decomposition cannot be ascribed solely to the saccharomyces' activity and may not be due to their activity at all.

It is highly possible that some other micro-organisms developed. The development of these micro-organisms requires incubation time and specific conditions, such as particularly high moisture. It may be further speculated that the development of micro-organisms is prevented by some inhibitors. In time, the inhibitors decompose and enable sugar-decomposing micro-organisms to develop.

Another possibility is that high moisture dilutes and spreads the sugars, which thereby reduces the osmotic pressure to a level at which the micro-organisms may become active. This point requires further investigation.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Israel Cotton Production and Marketing Board for sponsoring the study reported in this paper.

Many thanks are also due to Dr. M. Zeidman and the staff of the Chemistry, Spinning, and Testing laboratories.

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6—GENETICAL, PHYSIOLOGICAL, AND ECOLOGICAL INFLUENCES ON THE STRUCTURE AND TECHNOLOGICAL PROPERTIES OF COTTON FIBRES

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By studying genetical, physiological, and ecological influences, an attempt is made to explain the origin of some technological characteristics of cotton fibres. Changes in elongation and in strength observed on some allohexaploids could be explained by changes in fibre structure. The frequency distribution of the basal perimeter of fibre initials on the day of anthesis determines the frequency distribution of most fibre characteristics. The rôle of some essential elements, such as hormones and auxines, on the further fibre development is studied. Temperature has the most important influence on the fibre development. A constantly high temperature, 32°C, has a negative effect on primary- and secondary-wall formation. The rate of secondary-wall formation has an influence on the fibre strength that can be explained by a difference in the packing of the secondary wall.

1. INTRODUCTION

Since 1945, a close collaboration has existed between the geneticists in the stations of the former Belgian Congo (now Zaïre) and the Laboratory of Textile Technology of the University of Ghent. The various research programmes were set up with the co-operation of the Comité Cotonnier Congolais and INEAC.

Since 1958, new basic research programmes have been undertaken in the field of cotton, which have been more oriented to the factors influencing cotton-fibre strength[1–3]. These studies have revealed the importance of reversals, and a new programme, sponsored by the United States Department of Agriculture, was started in 1963 in order to find out the origin of the reversals[4–6]. It became clear that the existing research group needed the collaboration of laboratories specializing in cytology, morphology, and physiology. In 1968, the extended group started with a systematic study of the origin of fibre strength[7–21]. Funds for the research programmes were granted by the Belgian Foundation for Collective Basic Research. It was observed that cottons having comparable perimeter and maturity may nevertheless present important differences in some technological characteristics, such as strength.

The aim of this paper is to summarize the main findings of this research in order to contribute to a better understanding of the different elements acting on fibre properties. The genetical, the physiological, and the ecological influences are studied in succession. These influences are evaluated by studies of the technological characteristics of the fibres.

2. GENETICAL INFLUENCES

Allohexaploid cotton plants were obtained by crossing *Gossypium hirsutum* L. with different wild diploid species. In these hexaploids, a complete chromosome set of both parental species stand side by side. It is thus possible to observe the influence of a whole diploid genome on the fibre structure and technological characteristics of the cultivated amphidiploid.

Cotton breeders are also interested in these observations as an evaluation of potential introgression of useful characters from wild species. Indeed, earlier observations on hexaploids have already led to specification of the influence of some genomes on disease resistance, on the components of ginning out-turn, on certain forms of resistance to drought, and on the amino-acid balance of the kernels. It appears now that the same method could be applied to the improvement of technological characteristics[22, 23].

All these observations will permit prediction of the improvements that can be expected by direct introgression from diploid species within, of course, the limits of the remanent homology between the genomes.

The material investigated consists of:

two varieties of *G. hirsutum*, C2 and NC8, successive cultivars of the southern cotton belt of Zaïre, used here as controls;

ten allohexaploids from the collection of hybrids preserved in Gembloux (Belgium) and originated by crossing the two above-mentioned cultivars with ten different wild diploid species; the hexaploid combinations were created by colchicine treatment of the sterile triploid hybrids *G. hirsutum* × wild diploid species.

The results given in Tables I*a* and I*b* show very distinct differences in several fibre characteristics between the allohexaploids. They give evidence of important effects of the different genomes.

Factors improving the fibre length are produced by a series of diploid species: *G. anomalum* (2B1), *G. stocksii* (2E1), *G. areysianum* (2E3), and *G. longicalyx* (2F1).

Fibre-strength factors can be provided by many American diploids: *G. thurberi* (2D1), *G. harknessii* (2D2-2), *G. raimundii* (2D3), and *G. aridum* (2D4), subject to the acceptance of a rather considerable decrease in breaking elongation, and, except for *G. thurberi*, a certain decrease in length.

An improvement in both fibre strength and breaking elongation may be obtained from diploid species belonging to the E genomic group: *G. stocksii* (2E1) and *G. areysianum* (2E3). This fact is important and may be considered as a prospective means of improving fibre quality, provided that sufficient homology subsists between the E and the (AD) genomes so as to allow genic exchanges.

A reduction in the number of reversals, a character that improves fibre strength to some extent, is greatest in the hexaploids combining the E genome (*G. stocksii* and *G. areysianum*). It is also important in the hexaploid with *G. aridum* and satisfactory in the hexaploid with *G. thurberi*. *G. australe* induces a large number of reversals and a relatively low strength.

Table 1a

Test Results

Property		Cultivar C_2	Allohexaploids: $C_2 \times$ *G. anomalum* $2[(AD)_1B_1]$	$C_2 \times$ *G. sturtianum* $2[(AD)_1C_1]$	$C_2 \times$ *G. thurberi* $2[(AD)_1D_1]$	$C_2 \times$ *G. harknessii* $2[(AD)_1D_{2-2}]$	$C_2 \times$ *G. raimundii* $2[(AD)_1D_5]$
Fibre length (Suter–Webb Sorter)							
Upper quartile length	mm	28.40	27.70	21.00	20.60	17.03	18.00
Mean length	mm	18.50	20.10	13.80	16.40	11.52	12.40
Short-fibre content ($\leq$ 13 mm)	weight %	14.10	8.70	25.80	10.80	38.20	35.70
Coefficient of variation	%	55.40	47.70	61.00	35.70	66.65	66.30
Arealometer							
Fineness	mtex	116	180	228	181	186	165
Specific surface	mm^2/mm^3	519	454	394	427	471	487
Perimeter	μm	56.9	53.7	59.0	51.2	57.9	52.9
Maturity	%	65.4	80.1	83.4	87.4	71.9	76.2
Pressley bundle strength							
Force–weight ratio, zero gauge	(IP_0)	7.80	7.61	9.75	10.80	11.00	10.30
Force–weight ratio, 3-mm gauge	(IP_3)	5.11	5.01	6.39	6.64	5.82	6.85
$100IP_3/IP_0$		65.5	65.8	65.5	61.5	52.9	66.5
Extension	%	10.7	10.9	9.1	6.5	6.4	7.3
Individual-fibre strength (10-mm length)	gf	4.00	4.70	6.27	5.83	4.66	4.60
	mN	39.2	46.1	61.5	57.2	45.7	45.1
Coefficient of variation	%	52.9	30.3	37.1	37.4	33.9	39.1
Specific strength	kgf/mm^2	36.5	39.7	41.9	48.6	37.9	42.4
	MPa	358	389	411	477	372	416

Table Ia *(contd.)*

Test Results

Property		Cultivar C_2	Allohexaploids				
			C_2 × *G. anomalum* $2[(AD)_1B_1]$	C_2 × *G. sturtianum* $2[(AD)_1C_1]$	C_2 × *G. thurberi* $2[(AD)_1D_1]$	C_2 × *G. harknessii* $2[(AD)_1D_{2-2}]$	C_2 × *G. raimundii* $2[(AD)_1D_5]$
Elongation	%	9.66	10.27	8.37	6.81	5.35	7.47
Coefficient of variation	%	32.0	30.6	33.9	24.4	33.6	25.5
Reversals	number/cm	22.7	28.8	24.8	17.6	23.7	23.7
Degree of polymerization		3070	2815	3500	3545	3000	2915
Ribbon width (*d*)	μm	22.1	20.3	22.3	15.2	20.9	19.0
Standard deviation	μm	3.6	3.3	4.4	2.8	3.3	3.9
Coefficient of variation	%	16.3	16.5	19.8	18.6	15.6	20.4
Wall thickness (*e*)	μm	6.7	6.6	7.9	5.9	8.1	5.9
Standard deviation	μm	1.9	1.5	2.3	1.7	1.6	1.6
Coefficient of variation	%	28.2	23.4	28.8	28.6	19.8	27.9
Relative wall thickness (100*e*/*d*)	%	62.1	65.7	71.2	77.4	77.2	63.5
Standard deviation	%	15.3	12.4	13.5	12.6	11.0	13.9
Coefficient of variation	%	24.7	18.8	18.9	16.4	14.2	21.9

Table Ib

Test Results

Property		Cultivar	Allohexaploids				
		NC_8	NC_8 × *G. australe* 2 $(AD)_1C_3$	NC_8 × *G. aridum* 2 $(AD)_1D_4$	NC_8 × *G. stocksii* 2 $(AD)_1E_1$	NC_8 × *G. areysianum* 2 $(AD)_1E_3$	NC_8 × *G. longicalyx* 2 $(AD)_1F_1$
Fibre length (Suter–Webb Sorter)							
Upper quartile length	mm	24.54	16.9	20.7	25.4	24.58	24.7
Mean length	mm	16.55	13.5	14.1	16.0	16.80	15.4
Short-fibre content (≤ 13 mm)	weight %	17.46	23.9	27.6	17.5	18.64	21.5
Coefficient of variation	%	57.38	34.7	54.3	62.3	55.01	66.4
Arealometer							
Fineness	mtex	185	230	183	215	241	127
Specific surface	mm^2/mm^3	492	369	442	392	394	536
Perimeter	μm	60.3	56.4	53.5	55.8	63.1	45.2
Maturity	%	65.0	90.4	82.3	85.8	87.4	80.6
Pressley bundle strength							
Force–weight ratio, zero gauge	(IP_0)	6.67	6.88	11.60	8.83	9.70	10.70
Force–weight ratio, 3-mm gauge	(IP_3)	3.80	—	6.55	5.96	5.39	6.83
$100IP_3/IP_0$		56.1	—	56.5	67.5	55.5	63.8
Extension	%	11.7	—	7.4	12.4	13.7	8.6
Individual-fibre strength (10-mm length)	gf	4.40	4.55	5.76	7.34	7.26	10.70
	mN	43.1	44.6	56.5	72.0	71.2	104.9
Coefficient of variation	%	48.4	—	—	—	—	—
Specific strength	kgf/mm^2	35.9	29.8	47.6	51.7	45.3	44.5
	MPa	352	292	467	507	444	436

Table Ib (*contd.*)

Test Results

Property		Cultivar NC_8	Allohexaploids NC_8 × *G. australe* 2 $(AD)_1C_3$	NC_8 × *G. aridum* 2 $(AD)_1D_4$	NC_8 × *G. stocksii* 2 $(AD)_1E_1$	NC_8 × *G. areysianum* 2 $(AD)_1E_3$	NC_8 × *G. longicalyx* 2 $(AD)_1F_1$
Elongation	%	9.74	15.13	7.39	12.89	12.90	8.81
Coefficient of variation	%	39.0	—	—	—	—	—
Reversals	number/cm	20.3	33.4	11.1	5.0	9.8	23.7
Degree of polymerization		2795	2725	3430	3410	3409	3340
Ribbon width (*d*)	μm	22.3	—	—	—	—	—
Standard deviation	μm	3.8	—	—	—	—	—
Coefficient of variation	%	17.2	—	—	—	—	—
Wall thickness (*e*)	μm	7.7	—	—	—	—	—
Standard deviation	μm	2.3	—	—	—	—	—
Coefficient of variation	%	29.4	—	—	—	—	—
Relative wall thickness (100*e*/*d*)	%	65.8	—	—	—	—	—
Standard deviation	%	16.6	—	—	—	—	—
Coefficient of variation	%	23.8	—	—	—	—	—

An increase in the degree of cellulose polymerization, a factor also contributing to the fibre tensile strength, can be obtained from several diploid genomes: *G. thurberi*, *G. sturtianum* (2C1), *G. aridum*, *G. stocksii*, *G. areysianum*, and *G. longicalyx*.

Exceptional fibre fineness is produced in the hexaploid with *G. longicalyx*, combined with a fibre strength that is also exceptionally high and a high degree of polymerization. These characters of fineness and strength are superior to those found in *G. barbadense* cultivars and should certainly be much appreciated for certain textile performances.

An improvement in ginning out-turn could also be provided by *G. anomalum*, *G. sturtianum*, *G. australe* (2C3), *G. stocksii*, and *G. areysianum*.

Besides the analyses of their technological characteristics, the fibres of these allohexaploids were examined for their gross morphology and general outline. Two hexaploids, *G. hirsutum* NCx × *G. areysianum* and *G. hirsutum NC8* × *G. stocksii*, produced fibres having at the same time an improved strength and an improved breaking elongation. These fibres also exhibit unusual surface rugosity on plastic imprints or a negative replica, observed with an optical microscope. The microtopography of the fibre surface is generally studied by means of scanning electron photomicrographs of fully dehydrated, degassed, and metallized specimens. The following method, improved by one of the present authors (L.W.), although having a lower resolving power than the former, nevertheless permits a rapid and effective check to be made of surface structure*.

Native untreated fibres of *G. hirsutum* show a finely corrugated surface, with wrinkles 0.3–0.5 μm wide, mostly parallel to one another and obliquely oriented with regard to the fibre axis. They form a helical structure in the same direction (S or Z) as the major fibre twists and at an angle of 25–30° to the fibre axis (Fig. 1*a*). At a reversal level, the whole set of wrinkles changes and reverses its direction (Fig. 1*b*). Here and there, wide counter-wrinkles or folds 2.5μm wide are observed, and these more or less make a right angle with the former set of wrinkles (Fig. 1*c*). These two sets of wrinkles are limited to the outer skin of the fibre (formed by the cuticula, the primary wall, and, possibly, the S–1 or winding layer) and appear with the shrinkage of the fibre during its initial drying out.

These surface structures only partly disappear after the mercerization process. The almost cylindrical fibre retains smooth and small wrinkles, obliquely (Fig. 1*d*) or mainly longitudinally oriented (Fig. 1*e*). At a reversal level, these wrinkles are nevertheless conspicuous (Fig. 1*f*).

The fibres of the two hexaploids are broader and more cylindrical. They have thickened walls and fewer convolutions and reversals than the fibres of *G. hirsutum*. Even at a low magnification, their surfaces have a highly rugged

*A 3% formvar (polyvinylformol, Serva 21740) solution in chloroform is spread on a cover glass (24 mm × 46 mm). When the solvent is nearly evaporated, a bundle of fibres is placed on the still-plastic surface and firmly pressed by rolling a glass rod on it. After removal of the fibres by means of a tweezer, the cover glass is placed upside down on a slide and sealed on it by cement. The imprinted formvar film is then observed by Nomarski interference optic, at a high magnification and with a high numerical aperture immersion objective.

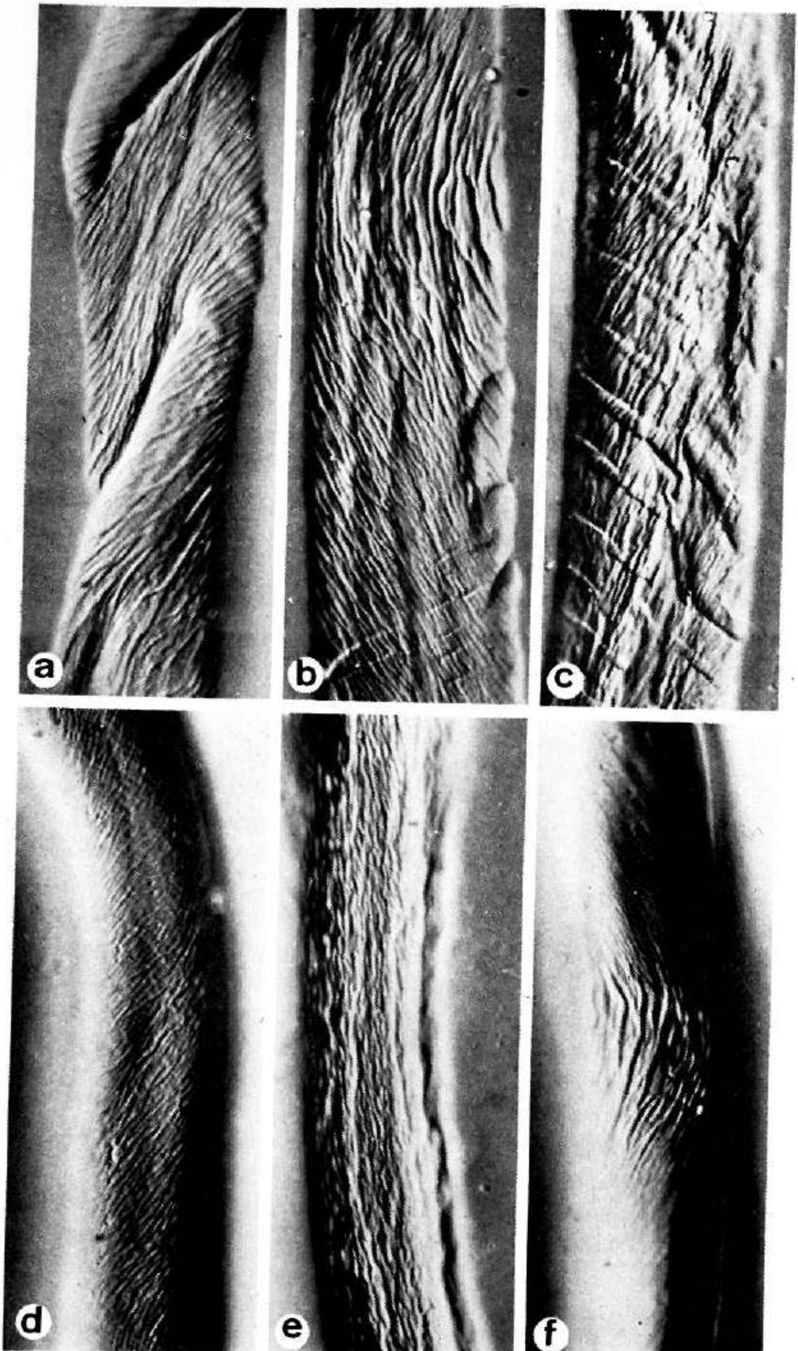

Fig. 1

Gossypium hirsutum v. B49: Formvar negative imprints of native untreated (*a–c*) and mercerized fibres (*d–f*); Normarski-interference optic (× 1340) (photograph by L. Waterkeyn) appearance, resembling a scale or wrung rope, with an irregular outline (Fig. 2*a*).

Careful observation at the highest magnification shows that the small wrinkles are locally obliterated by important rises and broad folds affecting the outer skin (Fig. 2*b, c, d*). This unique structure probably takes its origin from a considerable longitudinal contraction of the main body of the fibre during its first drying out. This contraction probably explains the high breaking elongation (Table I*b*). This feature seems to have been directly inherited from the diploid parents. The narrow and thick-walled fibres of the latter show, in fact, the same surface rugosities (Fig. 2*e, f, g*). On the other hand, the even higher breaking elongation of the hexaploids with *G. australe* is probably due to its high number of reversals or convolutions or both.

3. PHYSIOLOGICAL INFLUENCES

The physiological part of the study principally concerned the following physical parameters of the fibre: length, perimeter, and secondary-wall thickness. The aim was therefore to determine:

(i) the hormonal regulation of these properties, and
(ii) their relative importance in relation to the ultimate technological properties.

An important difficulty in evaluating modifications of fibre properties lies in the fact that, in most of the commercial varieties, they present an asymmetric frequency distribution. The non-normal frequency distribution of the fibre length is well known, but other essential characteristics, such as the perimeter, maturity, and reversal density, are also asymmetrically distributed. The asymmetric shape of the fibre-length frequency distribution is not determined by environmental factors and is not in the first instance due to variation between plants, or between bolls of the same plant, or even between seeds of the same boll, but rather to the level of the same seed.

The origin of the asymmetrical frequency distribution was studied by two temporary collaborators, Mrs. U. Kechagia[24] and Mr. Z. Michailidis[25]. They worked on three varieties, two *hirsutum* and one *barbadense*. All observations on seeds were made after considering nine equally distributed regions from chalaze to the micropyle pole. By careful observation they found that:

each of the seed regions presents the same asymmetric fibre-length frequency distribution as the total number of seeds;

in each seed region, a positive correlation exists between the perimeter measured at the base of the fibre initials and the final fibre perimeter;

a negative correlation exists between the fibre perimeter and the fibre length;

the skewness of the distribution of the basal perimeter of the fibre initials on the day of anthesis and of the length distribution of mature fibres

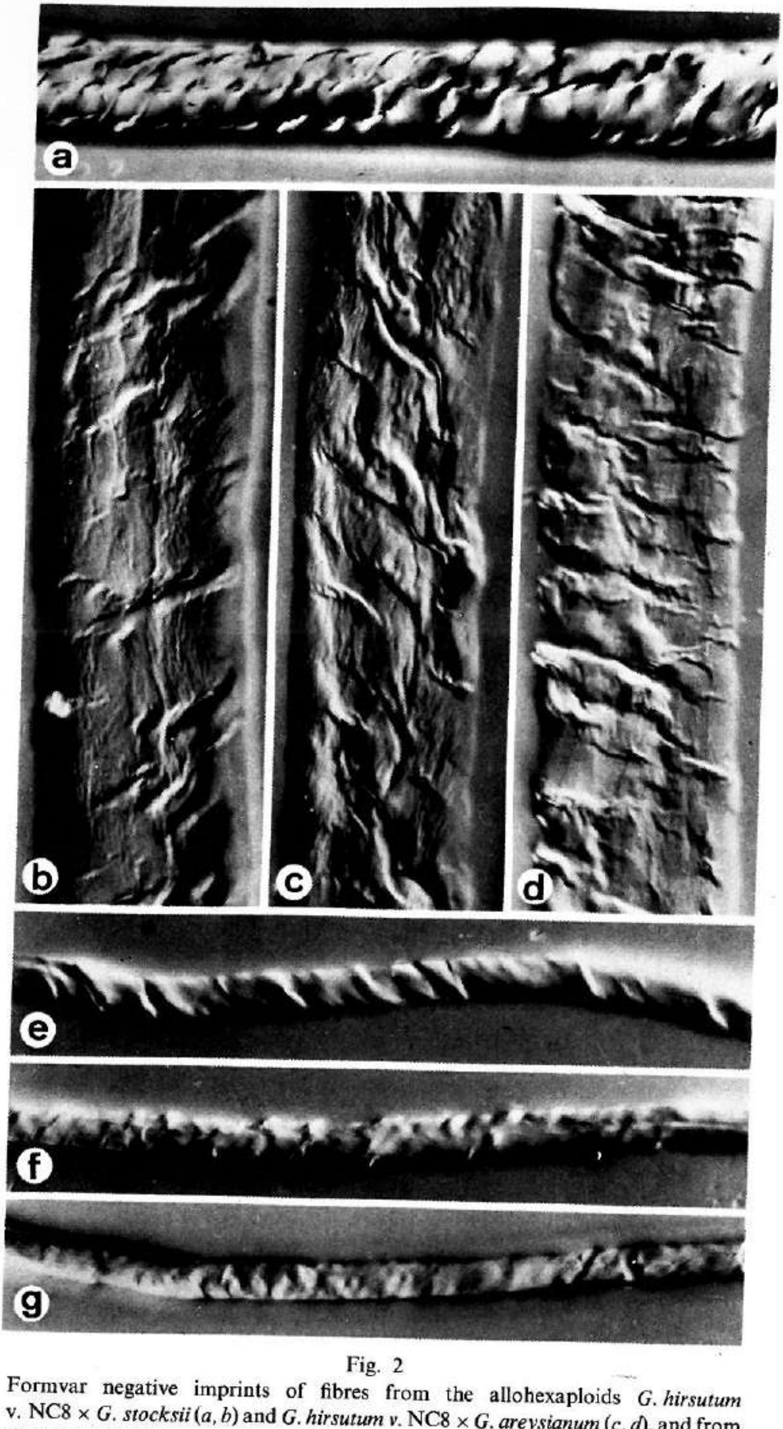

Fig. 2
Formvar negative imprints of fibres from the allohexaploids *G. hirsutum* v. NC8 × *G. stocksii* (*a, b*) and *G. hirsutum* v. NC8 × *G. areysianum* (*c, d*), and from the wild diploid parents *G. stocksii* (*e,f*) and *G. areysianum* (*g*) (*a, e–g*: × 535; *b–d*: × 1340) (photograph by L. Waterkeyn)

appears in standardized form approximately symmetrical about the origin;

the relation between the original basal perimeter and the elongation rate appears soon after the initiation.

It was concluded the distribution of the perimeter of the cells in each part of the ovule epidermis on the day of anthesis determines the shape of the final fibre-length distribution and in this way affects various technological properties to a certain extent.

Consequently, the eventual hormonal influence on the frequency distribution of the fibre characteristics should occur in a period preceding the elongation and ripening of the fibres. This period may start before anthesis. In research on hormonal influences, with the importance of the original perimeter of the initials taken into account, a study of the hormone action has to start even before fibre elongation commences. Hormones may, in principle, act upon the epidermic cells of the cotton ovules during three successive physiological periods:

Period I, before pollination: a variation in ovary dimensions at the time of anthesis is the probable consequence of variation in pre-anthesis hormonal regulation;

Period II, during the pollination–fertilization process (PF-process): this process, which is known to take more than 14 hours, probably means a rather invariable mechanism of hormonal control; and

Period III, during boll growth: epidermic cells are elongating and about 15–20 days after anthesis start secondary-wall formation.

It may be seen from the above that hormones can act upon the frequency distribution of fibre characteristics or, by a specific and separate influence, upon some fibre properties by a stimulation or an inhibition, or upon both.

In the present study, an attempt was made to identify both the hormones and the physiological period during which they were acting. They were performed on *in-situ* and *in-vitro* cultures of cotton fibre[26].

The *in-situ* tests showed that non-fertilized cotton bolls did not all shed in the first fifteen days after anthesis: a decreasing proportion of bolls were still growing at later dates, and about 4% reached a 30-day age. Their fibres were only about 2 mm long, but this nevertheless means a hundredfold elongation. However, the seeds remained very small (3 mm long and 1 mm wide) and showed evident atrophy of the inner integument and an empty nucellar space. The corresponding bolls could reach a diameter of 25 mm, and, during the first two days after anthesis, their growth rate was similar to that of normal fertilized bolls (Fig. 3). In fact, this initial growth rate can be extrapolated from the ovary-growth curve calculated for the five days before anthesis:

$$D_o = 3.617 + 0.62 \times 1.316^{(T + 6.198)},$$

where D_o = diameter of ovary or young boll expressed in mm, and T = number of

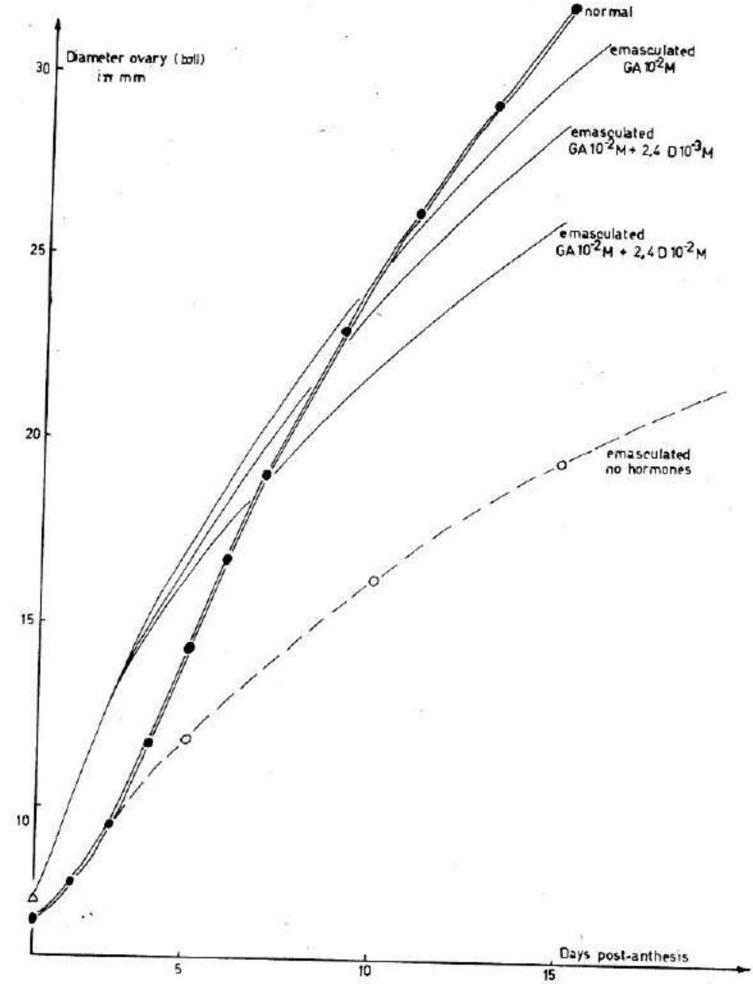

Fig. 3
Growth of emasculated bolls treated with hormones

days from anthesis, either before (negative values) or after (positive values).

The addition of 10^{-2}M GA$_3^*$ prevented complete boll-shedding while the addition of auxin alone had no effect on the shedding frequency.

These results point to the necessity of GA for the regulation of boll-shedding and an existing, but variable, growth capacity of bolls and fibres prepared during the pre-anthesis period. An additional growth capacity results from a successful PF-process.

Table II and Fig. 3 show how a single addition at the anthesis of GA_3 or $GA_3 + 2$, 4 D† results in a spectacular stimulation of boll and fibre growth.

*GA: Gibberelic acid.

†2, 4 D: 2,4 Dichlorophenoxy acetic acid.

Table II

Results of a Single Addition of Hormones to Emasculated Cotton Flowers

	Final Diameter of Boll (mm)	Seed Diameter (mm)	Halo Fibre Length (mm)	Mature Fibres (%)
F (fertilized)	34–39	6	30	78
NF (non-fertilized)*	25	1	2	—
NF + 10^{-2}MGA_3	31–35	1	10–15	2
NF + 10^{-2}MGA_3 + 10^{-3}M 2, 4 D	31–35	6	10–24	19

*30 days after anthesis on 4% of remaining bolls.

The variation of some results (e.g., halo fibre length) is probably closely linked to the already existing variability in growth capacity at anthesis. The auxin 2,4 D is clearly responsible for the major part of the additional growth capacity of the seeds and fibres. The frequency distribution of fibre perimeter was apparently the same as that in fertilized seeds, but the weight-biassed frequency distribution of fibre length and the frequency distribution of secondary-wall thickness were significantly different[27] (Fig. 4). Some exceptional seeds produced a few fully mature fibres, 30 mm long and with 80% maturity. Taking into account the fact that massive secondary-wall formation needs many more photosynthates than the primary-wall elongation, one can deduce from these results that the additional growth capacity of cotton bolls and fibres created by the PF-process is essentially due to the hormone auxin, which creates a high sink in the seeds.

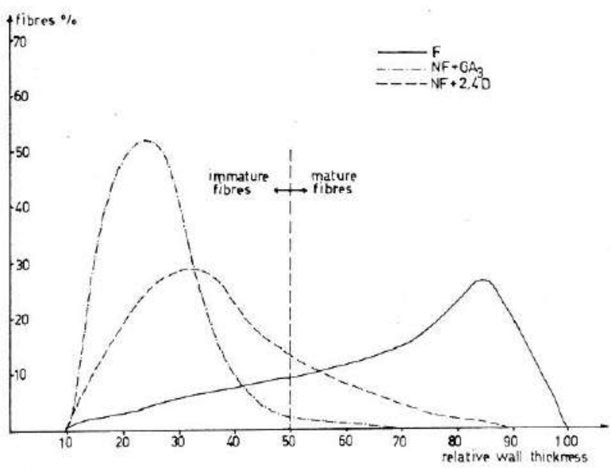

Fig. 4
Relative-wall-thickness distribution of cotton fibre: F and NF hormone-treated samples (from Kosmidou[27]).

These seeds presented a very thick inner integument, and the central space was filled with starch-containing cells.

An important cytological event noted during this period is the considerable size change shown by both the nucleus and nucleolus. From the day before anthesis to the third day after anthesis, the nucleus of each hair cell, and its nucleolus, undergo a spectacular increase of volume.

During this period, the diameter of the nucleus increases from 5–18 μm and the nucleolus increases its diameter from 1 to 8.5 μm. The nucleus retains this size until the end of the fibre differentiation (55 days). The nucleolus, on the other hand, shows first a rapid and then a slow decrease in its diameter during the same period (Fig. 5*a*–*f*). In addition, the nucleolar body forms one or more 'vacuoles' (Fig. 5*g*, *h*) and produces minute extrusions (arrowed in Fig. 5*c* and *d*)*. These morphological changes point to an important and rapid synthesis of nucleolar material (RNA) and increased metabolic activity of both nucleus and nucleolus.

In a recent publication[27], it was concluded that the hormone auxin (2, 4 D or NAA*) influenced the growth of the cotton-hair cell through the nucleolus: GA_3 should stimulate the 'input' (production) of nucleolar material, and auxin should stimulate 'output' (e.g., ribosome production).

Two days after anthesis, the size of the nucleolus was not different under F and NF conditions. But NF + high auxin concentrations (10^{-3}M 2, 4 D) resulted in a high initial, followed by a lower further fibre-elongation rate, compared with the F conditions. An overdose of 2, 4 D results in a slower boll growth (Fig. 3) and numerous atrophied seeds. One can deduce from these considerations that the plain fibre development depends on a precise auxin concentration in the young cotton bolls and that the fibre development may be already completely regulated by hormonal action at the beginning of the elongation period.

However, later auxin action on fibre development cannot be excluded: most of the results in the present paper were obtained with the stable 2, 4 D. With GA_3 + IAA†, only a few emasculated flowers showed a slightly better growth than occurred with GA_3 alone. Yet it is possible that this IAA, applied to the ovary wall, was metabolized before it reached the ovules. Ovules from five to fifteen days old, cultivated *in vitro*, produced repeatedly longer and more mature fibres in the presence of IAA or NAA. On the other hand, unfertilized ovules transferred at anthesis in auxin-containing medium showed a slow but steady fibre elongation, while the nucleoli remained large after 20 days' *invitro* culture. This points to a direct action of the auxin on the primary wall; the lack of 'output' of nucleolus material should mean a corresponding cessation of new ribosome production. Under normal conditions—fertilized ovules cultivated *in situ*—a major part of the whole-fibre development is probably the result of a high early ribosome production[28, 29]).

*The observations are performed in a bright field on FAA-fixed and pyronin–methyl-green-stained sections or on acrolein-fixed smears by means of phase or Nomarski-interference contrast.

*NAA: *a*-Naphtoxy acetic acid.
†IAA: Indol acetic acid.

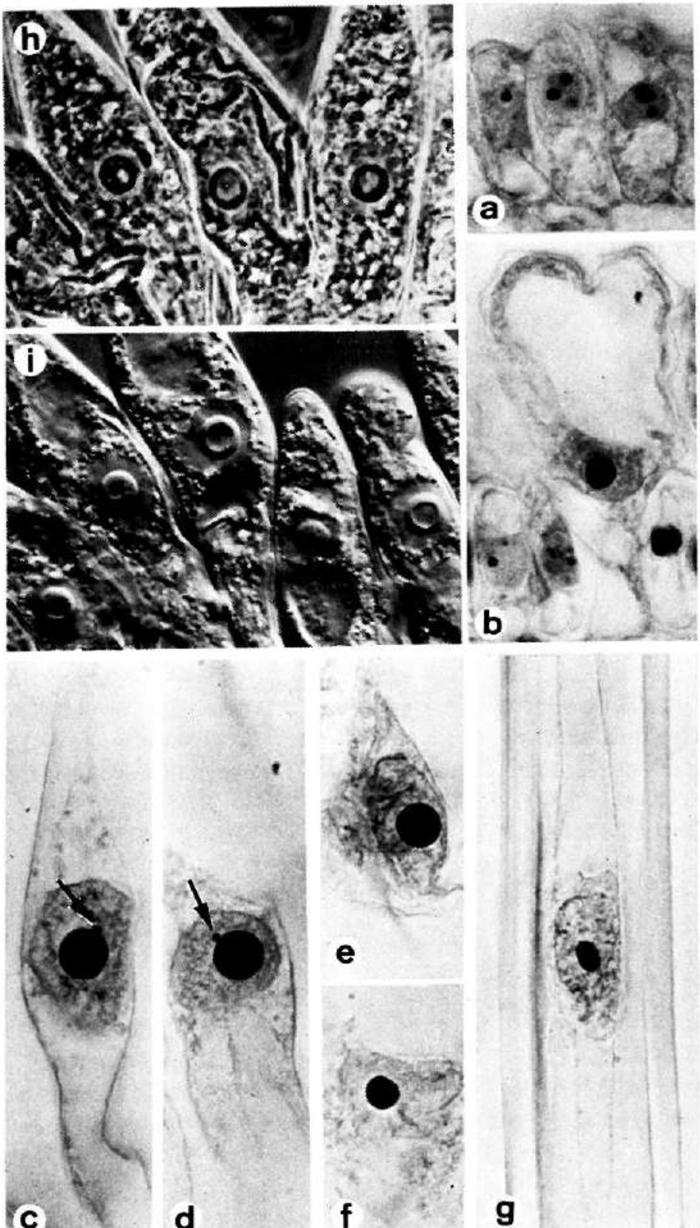

Fig. 5

G. hirsutum v. B49: (*a*)–(*g*) changes in nucleolar size during fibre differentiation: FAA-fixed and pyronin–methyl-green-strained fibres; (*a*) day before anthesis; (*b*) one day post-anthesis (p.a.); (*c*) three days p.a.; (*d*) five days p.a.; (*e*) ten days p.a.; (*f*) fifteen days p.a.; (*g*) 45 days p.a. (× 1280); (*h*) and (*i*) three-days-old acrolein-fixed fibres, observed respectively by phase-contrast and Nomarski-interference optics (× 940) (photograph by L. Waterkeyn)

4. ECOLOGICAL INFLUENCES

A range of different experiments was conducted in environmental cabinets with the aim of specifying the influence of climatic factors (temperature, relative humidity, light intensity) on the characteristics of cultivated cotton, mainly the fibre properties*.

The most interesting results revealed by these experiments concern the effect of temperature on the characteristics of the fibres produced.

Upland cotton plants (*G. hirsutum* L.) were grown in four different environmental cabinets regulated to give identical conditions except for one climatic parameter, the temperature.

Spectacular differences were observed in growth as well as in flowering, fructification, shedding, and production (Fig. 6).

Analyses of fibre characteristics revealed a particularly important effect of extreme temperatures on the development of the fibre (Table III).

A temperature maintained at a constantly high level appears to have a negative effect on the primary-wall formation of the fibre. At 32°C, a very marked reduction in length, perimeter, and secondary-wall thickness is observed. (Table IV).

The secondary wall is much reduced at the extreme temperatures, i.e., it is thin at 20°C and extremely thin or non-existent at 32°C. However, at these extreme temperatures, a few fibres reached a normal secondary-wall thickness. It thus appears that secondary-wall formation is not blocked but simply retarded. At the time of boll-opening, the majority of the fibres formed at 20 and 32°C have not yet reached normal thickness, the delays being more pronounced at 32°C than at 20°C.

It may be concluded that:

(i) constantly high temperatures reduce the length and perimeter of the fibres;

(ii) constantly low or constantly high temperatures decrease the rate of secondary-wall formation.

The latter conclusion led the group to study the importance of the rate of secondary-wall formation. Bolls of cotton plants of different varieties cultivated in a greenhouse were picked at different ages after anthesis. The surface area of the cellulose in the cross-section was determined in addition to the fibre tensile

*The experimental conditions were as follows:

cultivated material: cultivar B49 originating from Zaïre;

substrate: pots with standard earth mixture, water-saturated;

nutritive solution: CERA 2a (i.e., in g/1. :$KNO_3 \times 0.46$; $Ca(NO_3)_2 . 4H_2O \times 1.07$; $MgSO_4 . 7H_2O \times 0.84$; $KH_2PO_4 = 0.31$; at a rate of 0.5 1./week);

Light: 24 TL tubes of 120 W each, giving 40 000 lux directly under the glass pane separating the light source from the growth chamber;

photoperiodism: 12 hr day, 12 hr night;

air moisture: 60% r.h.;

temperatures: 20°C, 24°C, 28°C, 32°C.

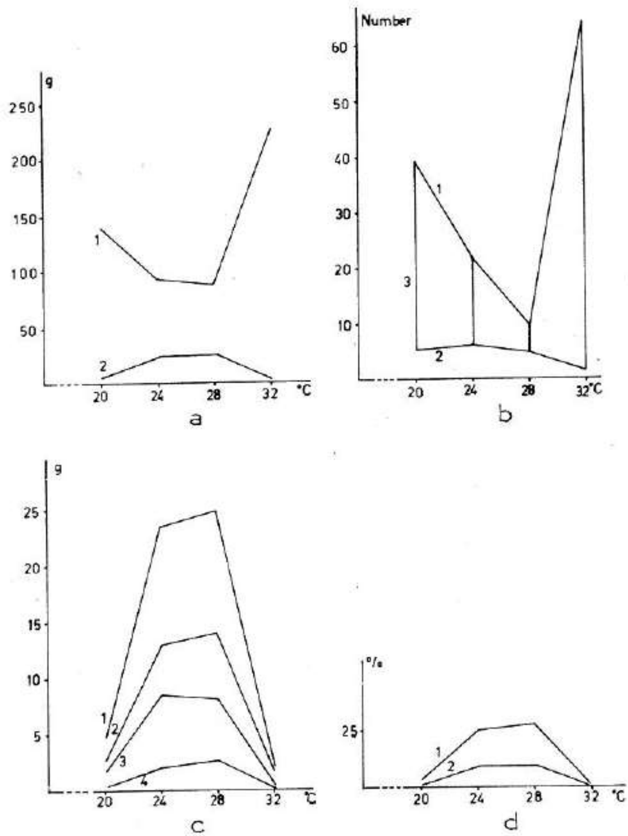

Fig. 6

Influence of temperature on the characteristics of cultivated cotton

(*a*) (1) Whole-plant mass
(2) Cotton-seed mass

(*b*) (1) Number of flowers/plant
(2) Number of bolls/plant
(3) Shedding

(*c*) (1) Cotton-seed mass/plant
(2) Delinted-seed mass/plant
(3) Fibre mass/plant
(4) Fuzz mass/plant

(*d*) (1) Ratio: cotton-seed mass/plant mass
(2) Ratio: fibre mass/plant mass

strength. Table V gives some of the results obtained.

Rapidly formed walls in 30–35-days-old bolls have, for the same or even a greater thickness, a lower strength than slowly formed ones.

The calculated apparent wall density, which is different from the cellulose

Table III

Primary-wall Development: Length and Perimeter*

Temperarature, T (°C)	Length, l (mm)	Ribbon Width, W (μm)	Fibre Perimeter, P (μm)
20	26.7	23.3	57.4
24	26.6	22.3	62.0
28	29.9	22.5	69.4
32	25.5	21.1	48.8

*The length is measured on 500 individual fibres and the ribbon width by means of a projection microscope with a magnification of 500 ×. The perimeter (P) is calculated by means of the mathematical formula:

$$P = 2W + e(\pi - 2),$$

where e is the wall thickness. These results were compared with those of perimeters measured on cross-sections. The correlation coefficient between the two sets of results is higher than 0.9.

Table IV

Secondary-wall Development: Thickness, Cross-sectional Area and Volume*

Temperature (°C)	Thickness (μm)	Cross-sectional Area (μm^2)	Volume (mm^3/1000)
20	9.5	201.8	5.39
24	15.3	290.5	7.73
28	21.2	382.6	11.44
32	5.8	115.1	8.94

*The wall thickness is measured on a projection microscope at a magnification of 500 ×. The surface of the wall section of a fibre that is not collapsed is calculated by the formula:

$$S = \pi e(D - e),$$

e being the wall thickness and D the diameter derived from the perimeter. The volume is the product of the length and section, the fibre being considered in the case as a perfect cylinder.

density, points in the direction that quickly formed walls have a lower density than slowly formed ones. This can be a consequence of a looser packing of the cellulose chains or fibrils.

Furthermore, it has been noted that the density and compactness of the wall may be directly and irreversibly modified during the initial drying process, when the original cylindrical hair cell collapses and becomes a twisted ribbon (Fig. 7*a*) with a kidney-like section. In such sections, a bilateral structure has been observed after enzymatic degradation or by electron-beam analysis[30–32]. The effect of this heterogeneity on the entire fibre was recently analysed by the present authors.

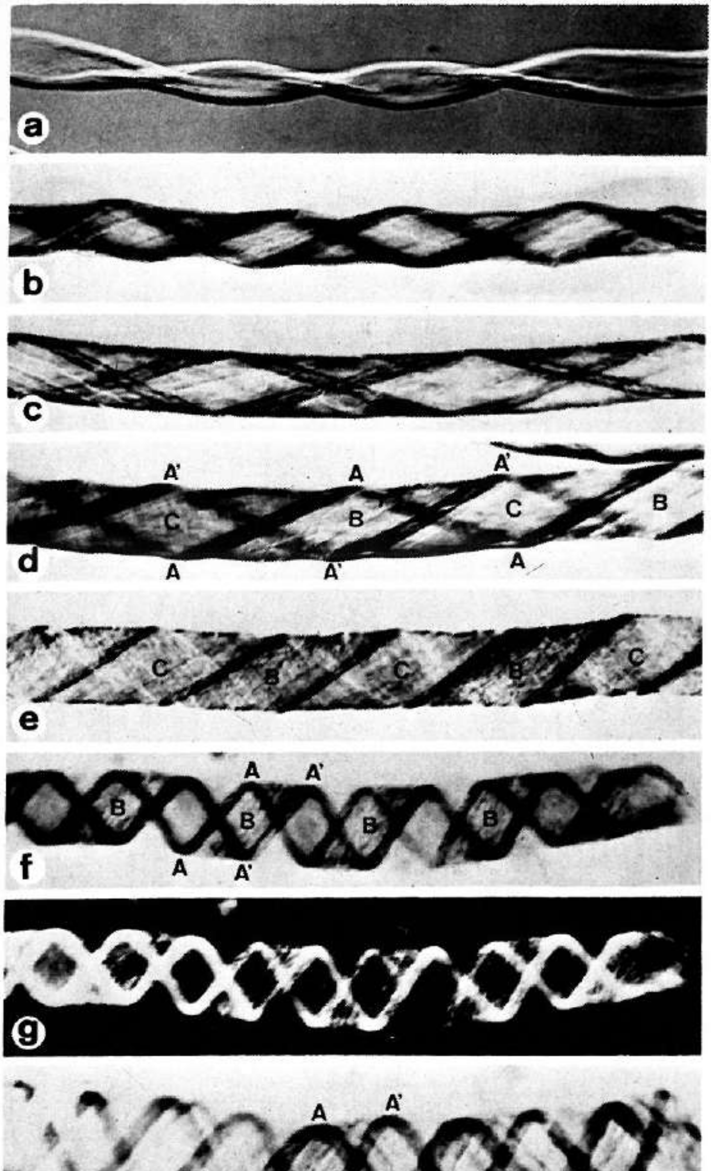

Fig. 7

G. hirsutum v. B.49: degrading patterns shown by native fibres after periodic acid oxidation (see text): (*a*) untreated fibre in bright field; (*b*)–(*f*), (*h*) polarized light in dark compensation; (*g*) polarized light in dark compensation with fibre between crossed polaroids (× 335) (photograph by L. Waterkeyn)

Table V

Importance of Rate of Wall Formation

Variety	Age (days)	Section (μm^2)	Strength (gf)	Strength (mN)
Del Cerro	35	323	4.61	45.2
	50	280	6.98	68.5
3080	30	267	3.77	37.0
	35	267	5.91	58.0
Coker	30	249	3.74	36.7
	40	184	4.26	41.8

Dry fibres are first treated by oxidizing or degrading agents (such as periodic acid, sodium periodate, cellulase, or gamma rays). Placed in alkaline solutions, they shorten, twist, and show a very individual swelling pattern. In polarized light, the uncollapsed fibre presents two opposite helicoidal lines, indicating the demarcation between two alternating helicoidal ribbons (Fig. 7*b–e*). These lines, A and A′, formed by highly crystalline cellulose, correspond to the two opposite folds of the fibre that was previously collapsed. They twist in the same direction as the convolutions and change their direction at the reversal level. The two ribbons B and C correspond, respectively, to the convex (or dorsal) and the concave (or ventral) side of the dry fibre and are formed by less-resistant cellulose. After drastic action by the degrading agents, the ventral ribbon fades out first and is followed by the dorsal one, the helicoidal twisted uprights being the most-resistant parts of the wall (Fig. 7*f, g, h*).

Never-dried mature fibres give a different swelling pattern after the same treatment. They swell regularly or show a typical ballooning pattern and vanish immediately.

It must be admitted that, during the first loss of water and collapse of the fibre, anisotropic tensions are created in the cell wall. They irreversibly affect the density, the crystallinity, and the accessibility of the cellulose chains. The heterogeneous structure thus created is no doubt responsible for some mechanical and technological characteristics of the cotton fibre.

5. CONCLUSIONS

From this study, the following conclusions may be reached:

Each wild-cotton type could bring about specific changes in the technological characteristics of the cultivated cottons. Of the large number of hexaploids that have already been obtained and analysed, the most important feature is the increase in the strength and breaking elongation obtained with *G. stocksii* and *G. areysianum*. Both allohexaploids have at the same time a very typical highly rugged surface, giving the fibre the aspect of a scaly or wrung rope. In the long run, the group hopes to set up an exhaustive list of the different characteristics that could be introduced by each of the different diploids of the *Gossypium* genus into the cultivated varieties.

The appreciation of the fibre properties of a cotton cultivar depends strongly on the shape of their asymmetrical distribution on the seedcoat. The frequency distribution of the base perimeter of the fibre initials is fixed at anthesis and may determine the distribution of most other fibre characteristics.

The phytohormones gibberelic acid and auxin influence the fibre physical properties, such as length and maturity, and hence the over-all technological properties. The exact expression of the influence, however, is differentiated along the pattern of the asymmetric frequency distribution of these properties: auxin will stimulate more fibres to develop fully. This process involves spectacular changes in the nucleolus behaviour. The properties *per se* do not seem to be influenced by these hormones: neither GA_3 nor 2, 4 D has a specific influence on a particular property. The major part, if not the whole, of the hormonal action on the over-all fibre properties occurs during the development of the flower bud and in the first days after the ovule fertilization.

The temperature has an important effect on the fibre characteristics. A constantly high temperature, 32°C, has a negative effect on the primary-wall formation, and the perimeter and length are reduced. Constantly high and constantly low temperatures have a negative effect on the secondary-wall formation. The thickest walls are formed at 28°C.

The rate of wall formation has an influence upon the packing of the cellulose or fibrils and through this on the strength.

The initial drying process has a certain effect on the cellulose density and accessibility and could be responsible for the mechanical and technological properties of native cottons.

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7—THE CHARACTERIZATION OF SOME INDIAN COTTON VARIETIES WITH THE HELP OF ELECTRON MICROSCOPY AND X-RAY DIFFRACTION AND THE CORRELATION OF THEIR STRUCTURE WITH THEIR MECHANICAL PROPERTIES

By V. B. GUPTA, A. V. MOHARIR and B. C. PANDA

An investigation is described in which, out of a large number of pure and recently developed hybrid varieties of Indian cottons, eleven varieties were selected with a view to investigating how their mechanical properties were correlated with their structure and thereby evaluating the rôles of X-ray diffraction and electron microscopy as techniques for possible screening of the varieties.

The samples were first characterized for staple length, fineness, maturity coefficient, moisture absorption, number of convolutions, and convolution angle. The X-ray-diffraction technique was used to measure crystallinity and crystallite orientation. The fibrillar geometry was studied with the help of scanning and transmission electron microscopy. The mechanical properties of single fibres were determined at room temperature on an Instron Tensile Tester, and the bundle strength was obtained by using Pressley's Method. In two cases, the birefringence of the fibres is also reported.

The structural dependence of mechanical properties is discussed in terms of correlation coefficients. Whereas the strength and modulus increase with increasing orientation, the elongation at break decreases. The strength also shows good correlation with the maturity index. Moisture absorption appears to depend on the degree of crystallinity. The results indicate that the crystallite orientation provides a reasonable index for varietal characterization. However, it must preferably be combined with other characterization techniques for varietal screening.

An exact method for determining Hermans orientation factor for the crystallites is used and shows good correlation with the orientation factor based on Hermans's method. After combining observations on X-ray orientation with those on optical orientation for two varieties, some comments are made on the possible deformation mechanisms in cotton when it is subjected to a tensile force.

The longitudinal periodicity along the length of the microfibril, obtained on a transmission electron microscope with certain varieties of cotton, suggests that the elementary fibrils may themselves be helically disposed in the microfibril. This observation, however, needs confirmation by extending the study to a larger number of samples. Elementary fibrils of width close to or less than 2 nm are revealed in some cotton varieties.

1. INTRODUCTION

1.1 Scope of Investigation

This paper is concerned with three aspects of cotton, namely, (i) its structure, (ii) its mechanical properties, and (iii) the correlation between structure and mechanical properties. It will therefore be advisable to summarize the available information on these three aspects at this stage to put the subject in its correct perspective. There has been a great deal of work done in these areas for over three decades, and fortunately excellent reviews[1-3] are available in addition to the information contained in some standard books[4-8]. Only that information which is most relevant to the present work and is used later for discussion of results will therefore be briefly presented. The references to original papers are too numerous to be included here, and only a limited number are given.

1.2 The Structure of Cotton

The cotton fibre, as used, has a ribbon-like shape with frequent twists or convolutions. The molecular chains were previously thought to be rigid, but it is now believed[4,9] that the inherent flexibility of the cellulose backbone is similar to that of typical synthetic fibres. It is also accepted[1] that the molecular chains aggregate in extended, and not folded, form into elementary fibrils, which, in turn, combine to form a microfibril. A close correlation is reported between the molecular chain length and the maturity index[10]. The fibrils are believed to be from 4 to 10 nm wide and lengthwise can most likely attain a macroscopic dimension[1-3]. However, it is stated[11] that the lattice coherence along the elementary fibril is intercepted at irregularly spaced intervals with an average distance of about 50 nm, so that the fibril contains a sequence of slightly mismatched crystal blocks with the same axial orientation of the cellulose chains but differing from each other in the orientation of the *a*- and *c*-axes. The microfibrils are deposited in a characteristic helical fashion in concentric cylindrical growth layers. Owing to physical coalescence resulting from a reduction in surface free energy, fibrils can occur in bundles of larger diameter. These macrofibrils, having widths around 100 nm, are quite well interconnected[12]. The helix angle was thought to vary for different types, varieties, and strains of cotton; however, recent studies have shown that the angle is constant throughout the cross-section and along the length for all cottons and that apparent variations are due to the superposition of the convolutions and the helical angles[1,2]. Although the helical angle of the fibrils with respect to the fibre axis is constant over the full length of the fibre, the sense of the helix reverses many times—from 30 to 100 times in the fibre, the reversal frequency being primarily a varietal characteristic[6] but also dependent on the environmental growth conditions. The crystallite orientation has been shown to be high at the reversal points[13].

It is generally believed[2] that, though one-third of the total molecules constitute the amorphous phase, cotton is essentially crystalline, and the disorder is mainly due to the fact that small crystalline units are imperfectly packed together. The structure is considered to be paracrystalline.

During drying from a swollen cellular tube to the collapsed-fibre form, inbuilt strains and stresses are locked-in in the fibres. In fact, the asymmetry of mechanical strains during drying is thought to be responsible for the typical convoluted structure of the fibre[2].

The brief description given above clearly indicates the complexity of the structure and morphology of the cotton fibre.

1.3 The Mechanical Properties of Cotton

The mechanical properties of textile fibres are perhaps their most important asset, and hence there is a considerable need to map them experimentally and to calculate them theoretically. The discussion of mechanical properties involves two objectives: (i) an adequate description of the behaviour, and (ii) an explanation of the behaviour in molecular terms. The first aspect, the development of a suitable approach, which offers an adequate description of the mechanical properties of cotton fibres, will be considered in this section; the second will be discussed in Section 1.4.

The load–elongation or stress–strain curve of the cotton fibre is close to that of a glassy solid, except perhaps that the elongation at break is relatively large compared with that of a typical glassy solid. An adequate description of its mechanical properties at low strains is therefore achieved by assuming that it is an anisotropic Hookean solid when the generalized Hooke's law offers a reasonable description of its elastic behaviour. Treloar[14] calculated the Young's modulus along the fibre axis for the cellulose crystal and observed that it was not too far from the observed modulus. It was later pointed out that the experimental dynamic modulus could exceed the calculated crystal modulus[15]. Treloar had not taken hydrogen-bonding into consideration in his calculations and stated that the low theoretical value could be due to neglect of these forces. A very elaborate calculation of the various elastic constants of cellulose crystal followed[16], and it was shown that, even if hydrogen-bonding was taken into account, the calculated modulus was almost identical to that obtained by Treloar.

The above treatment assumed that the fibre was elastic, and at low strains this is, no doubt, a reasonable assumption. The next step is to recognize that the fibre is viscoelastic and then to seek an adequate representation of its behaviour. In this area, work on cotton is sparse, obviously because of the lack of any significant thermal transitions in the temperature range of interest. Dynamic mechanical experiments, which are useful in characterizing linear viscoelastic behaviour, do not yield very interesting information because there are no loss-peaks. The viscoelastic behaviour, both linear and non-linear, can be studied with the help of creep and stress-relaxation experiments. Such experiments are difficult with cotton but have been reported[8]. Creep and creep-recovery studies on single fibres of cotton have demonstrated that the elongation and recovery from strain show considerable time-dependence. It was noted, however, that mechanical conditioning, i.e., subjecting the fibre to loading and unloading cycles before performing the actual experiment, tends to establish the 'elastic state'.

The upper limit of the tensile strength of cellulose[8] is over 1000 gf/tex (9.8 N/tex). This value is much higher than any observed value. It is interesting to note that, for a fibre that is not wholly crystalline, the experimental modulus can exceed the crystal modulus, but the measured strength is much lower than the crystal strength.

In the fracture of cotton under tensile loading, the dominant feature is the splitting of the structure along its length, which is associated with the marked fibrillar nature of the fibre[4]. The splitting occurs between fibrils and the break adjacent to a reversal, and, according to Hearle[4], the splitting will be due to the untwisting effects. Eventually a tear develops along the fibre to join up the split, which follows the helical path of the fibrils around the fibre.

In cotton fibres, the interaction between the chain molecules will be strong, and hence the elasticity of cotton will be expected to be dominated by changes in internal energy[8]. Stöckmann[9], on the basis of elaborate experimental results, discounts this by showing that the deformation of cotton, like that of rubber, is dominated by entropy effects. This observation, however, is difficult to reconcile with the structure and properties of cotton.

This brief account points out that our understanding of the mechanical properties of cotton is rather limited, and a proper approach to its description is yet to be formulated.

1.4 Structure–Property Correlation in Cotton

That the mechanical properties of textile fibres are dependent on their structure is well known. However, the relationships are often complex, and the field is full of controversies even after many years of research.

The stiffness or initial modulus, which represents the resistance offered by the fibre to initial deformation, has been shown to be highly dependent on orientation in synthetic fibres[17]. Crystallinity, crystal size, and the links between crystalline units are also important. The molecular weight has no measurable effect on stiffness. In cotton fibres too, orientation appears to offer high correlation with Young's modulus in the fibre-axis direction[1–3]. Good correlations have been reported with birefringence and crystallite orientation[1–3]. However, Preston[18] pointed out that 'it is a pity that micellar inclination was determined from the refractive indices of cotton fibres, using a Becke-line method. This can give the refractive indices, and therefore the orientation, only in the outermost skin of the fibre. . . .' It has recently been shown[19] that mature fibres have a higher elastic modulus than less mature fibres. As stated in the previous section, the measured modulus of a cotton fibre can approach, and at high frequencies even exceed, the theoretically calculated modulus of cellulose crystal. This may be taken to imply that, unlike what happens in synthetic fibres, the crystallites take part in the deformation even at low strains during the room-temperature measurement of modulus.

The strength of cotton is perhaps its most widely measured property. Fibre tenacity is closely related to the X-ray-orientation angle; the higher the angle, the lower is the tenacity[1-3]. This angle has been shown to measure a composite of the convolution angle and the spiral angle[20]. However, the scatter in strength–orientation correlations is considerable. The highest correlations are observed for zero-gauge-length measurements of bundle strength[21,22]. There is a decrease in the degree of correlation with increasing test length, which indicates that the strength of cotton fibres is determined partly by the orientation and partly by the presence of weak places along the fibre length. The decrease of tenacity with an increasing number of reversals was particularly great for highly oriented samples. Cotton fibres broken under a variety of conditions and then examined in a scanning electron microscope showed that many fractures occurred adjacent to the reversal zone and not through it, which indicated that the reversal zone itself is strong, but, because of its existence in the fibre, it is a source of weakness in that it is a cause of fracture in the regions adjacent to it[1,2]. The strength of cotton has been shown to be related to its molecular weight; the higher the molecular weight, the higher is the strength. Paracrystalline-lattice distortion also adversely affects strength[23].

The extension at break for cotton is correlated with the X-ray angle[1-3]; the larger the angle, the greater is the extension at break. It is well known that crystals are elastic only up to relatively low elongations, beyond which various plasticity effects become operative[7]. Thus the extensibility of cotton derives partly from the alignment of the fibrils in the direction of stretch and partly from their deformation.

2. EXPERIMENTAL

2.1 Samples

The cotton-fibre varieties that were studied are listed in Table I. The various sets of samples were obtained from different parts of India from the crop grown during 1975; the breeders provided ginned samples.

The fibres were purified in a way[24-27] that effectively removed the non-fibrous impurities without altering the structural features of cotton cellulose. Whereas most of the investigations were made on purified fibres, some electron-microscopy and water-absorption studies were also made on unpurified cotton.

2.2 Characterization

2.2.1 Physical Characterization

2.2.1.1 Staple Length, Fineness, and Maturity Coefficient The fibre staple lengths were evaluated by using the Balls Sorter[28]; the linear density and fibre maturity were determined with the Micronaire apparatus[28].

Table I

Name and Species of Cotton Samples Tested*

Serial No.	Name	Species
1	B–1007	*Gossypium hirsutum*
2	H–14	*G. hirsutum*
3	H–4	*G. hirsutum*
4	Varalaxmi	*G. hirsutum*
5	Laxmi	*G. hirsutum*
6	V–797	*G. herbaceum*
7	D–33	*G. hirsutum*
8	Digvijay	*G. herbaceum*
9	Deviraj	*G. hirsutum*
10	SRT–1G	
	Cot 10	*G. hirsutum*
11	Acala 4–42	*G. hirsutum*

* In addition to the varieties listed, electron-microscopy studies were also made on the Rex variety, belonging to the *G. hirsutum* species.

2.2.1.2 Number of Convolutions and Convolution Angles The number of convolutions over the entire length of the fibre was measured[28] for 60 fibres of each variety in an optical microscope, and the convolution angle, θ', was obtained by using the expression

$$\tan\theta' = (\pi/2)(\overline{D/C}),$$

where D is the ribbon width and C the pitch of the convolution, $(\overline{D/C})$ representing the average value of D/C.

2.2.1.3 Moisture Absorption Moisture absorption was determined for both unpurified and purified samples with a Marconi TF 933–A moisture meter. Twenty observations were made for each variety, and the average values are reported only for unpurified samples.

2.2.2 Fine-structure Characterization

2.2.2.1 Degree of Crystallinity A well-parallelized bundle of fibres was mounted on the sample-rotation holder of a Philips Universal Flat Plate X-ray Camera. The sample was rotated to give a randomized scattering pattern. The radial intensity distribution of the pattern was recorded with the help of a Joyce–Loebel Microdensitometer. The intensity scan for a standard amorphous cellulose sample was taken from the literature[29]. The method suggested by Farrow and Preston[30] for polyethylene terephthalate fibre was then used to compute the degree of crystallinity. The amorphous-scattering curve was constructed below the scattering curve for the sample by proportionately reducing the scattering curve for the completely amorphous sample until it matched the observed intensity minimum between the crystalline peaks. The degree of crystallinity (X) was then given by:

$$X = C/(C + A),$$

where C is the integrated area corresponding to the crystalline phase and A the area corresponding to the amorphous part.

2.2.2.2 Crystallite Orientation A well-parallelized bundle of fibres, as in the previous case, was mounted on the X-ray Camera, and the flat-plate pattern of the oriented fibre was recorded. The Microdensitometer was used for radial scans at various azimuthal angles, and, from these scans, the azimuthal-intensity curves for the (002) and combined (101) and ($10\bar{1}$) planes were constructed. From the latter, (101) and ($10\bar{1}$) plane-intensity curves were then separately resolved. The scans were normalized to equal peak intensity and, from the curves for (002) reflexion, the 40, 50, and 75% X-ray angles were determined. It may be remarked that, whereas the use of the 40 and 50% X-ray angles is quite common, the 75% angle has also been used previously in a particular investigation[20].

From the intensity scans, the Hermans orientation factor for the various cotton varieties was also computed. If θ is the angle made by the molecular chain with the fibre axis, the Hermans orientation factor, f_c, is defined as

$$f_c = 1 - \frac{3}{2}\overline{\sin^2\theta},$$

Where $\overline{\sin^2\theta}$ is the average value of $\sin^2\theta$. The following two approaches were used to evaluate $\overline{\sin^2\theta}$.

(i) *Hermans's Approach :* If α is the angle between the plane normal and the equator, then, according to Hermans[31]:

$$\overline{\sin^2\theta} = \overline{\sin^2\alpha_{002}} + \overline{\sin^2\alpha_{101,10\bar{1}}}$$

and the Hermans orientation factor by Hermans's method, f_{cH}, is thus obtained from suitable integration of the intensity curves.

(ii) *Wilchinsky's Approach:* Wilchinsky[32] proposed an exact equation for calculating $\overline{\sin^2\theta}$ for a monoclinic until cell by using two equatorial planes. For cotton, we may therefore write:

$$\overline{\sin^2\theta} = \frac{(1 - 2\sin^2\rho_{002})\overline{\cos^2\phi_{10\bar{1}}} - (1 - 2\sin^2\rho_{10\bar{1}})\overline{\cos^2\phi_{002}}}{\sin^2\rho_{10\bar{1}} - \sin^2\rho_{002}},$$

where ϕ represents the angle between the plane normal and the fibre axis and ρ the angle between the plane normal and the c-axis of the unit cell. For cellulose I, this equation reduces to:

$$\overline{\sin^2\theta} = 1.868\overline{\cos^2\phi_{10\bar{1}}} + 0.134\overline{\cos^2\phi_{002}},$$

where $\overline{\cos^2\phi}$ can be calculated in the usual manner, and from this the Hermans orientation factor involving the use of Wilchinsky's expression, f_{cW}, can be computed.

2.2.2.3 Birefringence Birefringence was measured by using the Becke-line method, the liquids used[5] being liquid paraffin and α-bromonaphthalene. Ten readings were taken for each sample. Since the variability was large, data for only those two samples in which the spread is not too great are presented.

2.2.2.4 Transmission Electron Microscopy The two-stage-replica technique was employed to study the surface morphology of the fibres[33]. A primary impression of the purified and unpurified cotton was taken on cellulose acetate replicating tape softened with acetone. On drying, the cotton fibres were carefully extracted. The impression was shadowed with platinum–carbon. Finally, a film of carbon was evaporated onto this. The replicating tape was next dissolved in acetone, and the replica was mounted on copper grids for observation in a Philips EM300 Transmission Electron Microscope.

In another series of experiments, cotton samples cut into small pieces and digested in 2% sodium hydroxide for sixteen days were subjected to ultrasonic disintegration. The slurry from the supernatant liquid was mounted on a formvar film supported on a copper grid. After being dried, the slurry was negatively stained with phosphotungstic acid (pH 7), and the specimen was ready for observation.

2.2.2.5 Scanning Electron Microscopy The purified cotton fibres were straight-mounted on an aluminium stub and then coated with silver. The fibres were examined in a Cambridge S4–10 Scanning Electron Microscope at 10 kV.

2.2.3 Tensile Testing of Single Fibres

The load–elongation curves of single fibres were recorded on an Instron 1112 Table-model Tensile Tester fitted with pneumatic jaws. The gauge length was kept at 1 cm and the strain rate maintained at 50%/min. The initial modulus, tenacity, extension at break, and toughness were computed by the usual method. For each variety, over 100 observations were made; the mean value of tenacity represents an average of over 150 observations.

2.2.4 Pressley Strength Test

The bundle strength was determined[28] on a Pressley strength tester with zero gauge length. Ten observations were made for each variety. The Pressley index in lbf/mg was converted to gf/tex by multiplying the lbf/mg value by a factor of 5.36.

3. RESULTS

3.1 Physical Characteristics

The physical characteristics of the cotton fibre varieties tested are shown in Table II. These include the mean fibre length, linear density, maturity coefficient, number of convolutions, convolution angle, and moisture absorption.

Table II

Some Physical Characteristics of Samples Tested

Serial No.	Variety	Mean Fibre Length (cm)	Linear Density (mtex)	Maturity Coeffi-cient	Number of Convo-lutions per cm	Convolu-tion Angle (deg)	Moisture Regain (%)
1	B–1007	2.775	168.80	0.75	80	13°34′	6.410
2	H–14	2.490	164.84	0.74	80	13°50′	6.995
3	H–4	2.773	156.84	0.75	100	16°47′	6.720
4	Varalaxmi	3.006	119.88	0.66	100	15°52′	7.055
5	Laxmi	2.456	148.85	0.72	70	10°54′	6.945
6	V–797	2.310	179.82	0.76	60	11°40′	6.765
7	D–33	2.466	156.84	0.74	90	14°40′	6.365
8	Digvijay	2.202	176.82	0.76	60	10°31′	6.810
9	Deviraj	2.773	110.89	0.63	80	12°4′	6.265
10	SRT–IG Cot 10	2.500	180.82	0.77	90	13°50′	5.875
11	Acala 4–42	2.400	157.80	—	—	—	—

Table III

Some Fine-structure Characteristics of Samples Tested

Serial No.	Variety	Degree of Crystalli-nity	Crystallite Orientation				
			X-ray Angle			Hermans Orientation Factor	
			40%	50%	75%	f_{cH}	f_{cW}
1	B–1007	0.685	38.7	34.0	22.5	0.592	0.615
2	H–14	—	35.5	31.5	20.0	0.598	0.623
3	H–4	0.68	45.0	39.2	27.5	0.519	0.550
4	Varalaxmi	0.67	43.5	36.2	25.5	0.552	0.609
5	Laxmi	0.61	34.7	29.5	19.5	0.606	0.641
6	V–797	0.73	43.5	37.5	24.0	0.547	0.591
7	D–33	0.72	43.0	36.5	23.5	0.576	0.648
8	Digvijay	0.64	35.5	30.0	18.7	0.599	0.650
9	Deviraj	—	46.0	41.5	27.5	0.542	0.606
10	SRT–1G Cot 10	0.68	35.5	31.0	20.5	0.571	0.604
11	Acala 4–42	0.71	37.5	33.0	21.5	0.591	0.623

3.2 Fine-structure Characteristics

The data on degree of crystallinity and crystallite orientation are presented in Table III. The birefringence values of two varieties will be given in Section 4.

The electron micrographs will be reproduced later in Section 4.

3.3 Mechanical Characteristics

The mechanical data are presented in Table IV. These include the initial modulus, tenacity, extension at break, toughness, and bundle strength.

4. DISCUSSION

4.1 Introduction

The results presented in the previous section show that the cotton varieties included in this investigation cover a wide range of physical and fine-structure characteristics and mechanical properties. The dependence of mechanical properties on physical and fine-structure parameters will now be critically examined and discussed. Some of this discussion will be based on the ideas that have evolved over the years to explain the mechanical properties of synthetic fibres. Some findings on fibrillar geometry will also be presented. In addition, the various representations of crystallite orientation will be assessed.

4.2 Initial Modulus

4.2.1 Relation to Orientation

The initial modulus is correlated with the crystallite orientation, i.e., it gives a correlation coefficient of -0.5 with the 50% X-ray angle. The dependence of the initial modulus on the molecular and crystallite orientation has also been observed by other authors[1–3]. However, the initial modulus of cotton has not been as extensively studied as its strength, for example. This is unfortunate, since an analysis of initial-modulus results can perhaps lead to some knowledge about the deformation mechanisms in the fibre and also throw some light on the rôle of various structural parameters in determining mechanical properties. The present initial-modulus results, though on a rather limited number of varieties, will be analysed to ascertain if such an approach is possible.

The initial modulus is measured at very low strains, since linearity of the stress–strain curves is observed in fibres only below 0.5% strain[17]. It will be interesting and useful to be able to understand how deformation takes place in the fibre at such low strains and what is the nature of the deforming unit. There are two ways in which this problem can be approached. It may be assumed, firstly, that the fibre has a distinct two-phase structure and, secondly, that the two phases cannot be clearly distinguished and the fibre has therefore to be treated as having a single phase. Both these approaches will be considered.

In a two-phase system, it will be generally expected that the value of the initial modulus will reflect the property of the most compliant part of the fibre system, and this is believed to be the amorphous part. In fact, in synthetic fibres, it has been amply demonstrated[34] that the amorphous regions dominate their mechanical properties. Some knowledge of the state of amorphous regions can be obtained by combining the X-ray data with optical-birefringence data[34]. The

Table IV

Mechanical Properties of Samples Tested*

Serial No.	Variety	Young's Modulus Average (gf/tex)	Young's Modulus CV%	Tenacity Average (gf/tex)	Tenacity CV%	Elongation % Average (%)	Elongation % CV%	Bundle Strength (gf/tex)	Toughness Index (gf/tex)
1	B–1007	383.01 (3.76)	34	22.65 (0.22)	29	6.93	29	48.24 (0.47)	0.92 (0.90×10^{-2})
2	H–14	508.31 (4.98)	31	24.76 (0.24)	34	5.98	26	49.31 (0.48)	0.71 ($0.70[10^{-2}$)
3	H–4	504.55 (4.95)	45	26.87 (0.26)	30	7.94	31	47.70 (0.47)	1.13 (1.11×10^{-2})
4	Varalaxmi	573.92 (5.63)	47	33.02 (0.32)	28	9.77	36	48.24 (0.47)	1.74 (1.71×10^{-2})
5	Laxmi	483.72 (4.75)	37	23.91 (0.23)	25	6.37	31	47.70 (0.47)	0.82 (0.80×10^{-2})
6	V–797	488.39 (4.79)	34	22.52 (0.22)	34	5.00	29	48.78 (0.48)	0.62 (0.61×10^{-2})
7	D–33	423.27 (4.15)	38	25.61 (0.25)	34	6.99	34	51.46 (0.50)	0.98 (0.96×10^{-2})
8	Digvijay	484.84 (4.75)	39	28.60 (0.28)	43	5.68	37	52.53 (0.52)	0.76 (0.75×10^{-2})
9	Deviraj	310.28 (3.04)	28	27.86 (0.27)	30	11.72	50	44.49 (0.44)	1.93 (1.89×10^{-2})
10	SRT–1G Cot 10	511.11 (5.01)	39	24.33 (0.24)	33	5.40	30	52.53 (0.52)	0.78 (0.76×10^{-2})
11	Acala 4–42	476.05 (4.67)	34	21.06 (0.21)	36	6.07	31	49.85 (0.49)	0.85 (0.83×10^{-2})

*The values in brackets are in N/tex.

birefringence, Δn, of a fibre may be expressed[31] as

$$\Delta n = \Delta n_{max}(1 - \tfrac{3}{2}\overline{\sin^2\theta}),$$

where Δn_{max} is the maximum theoretical birefringence and θ represents the angle between a molecule in the fibre and the fibre axis. The expression within the brackets is the Hermans orientation factor for the molecules, f_{mol}. It has been shown that, to a first approximation, the average molecular orientation may be related to the crystallite and amorphous orientation in terms of the following relation[34]:

$$f_{mol} = Xf_c + (1 - X)f_a,$$

where X is the degree of crystallinity and f_c and f_a are the Hermans orientation factors for the crystalline and amorphous regions, respectively. The assumption in this expression is that the two phases can be considered as being distinctly separate.

The maximum birefringence of the cellulose I crystal has been estimated[3] as 0.063. However, the value of Δn_{max} has also been obtained by extrapolation of the birefringence–X-ray-angle curve to zero X-ray angle and comes out[35] to be 0.071. For the two cotton fibres for which birefringence values are shown in Table V, the various orientation factors can be calculated and are also shown in Table V. It is interesting to note that the average molecular orientation comes out to be higher than or almost equal to the crystallite orientation and that the orientation of the molecules in the amorphous regions is higher than their orientation in the crystalline regions. Both Meredith[18] and Hermans[31] have also shown that the optical-orientation and crystallite-orientation factors are quite close in various cottons, which thus indicates that the amorphous orientation can be high. It must, of course, be emphasized that the equation used to calculate f_a may not be strictly true, but perhaps a more rigorous treatment would not substantially alter the results. In synthetic fibres in general, the crystallite orientation is much higher than the amorphous orientation[34]. This is taken to mean either that the molecules in the amorphous regions are not as highly oriented or that the number of straight molecules connecting the crystallites is rather small. The results for cotton presented in Table V would therefore imply

Table V

The Birefringence and Hermans Orientation Factors for Two Varieties

Variety	Δn	$\Delta n_{max} = 0.063$			$\Delta n_{max} = 0.071$		
		f_{mol}	f_c	f_a	f_{mol}	f_c	f_a
Varalaxmi	0.051	0.81	0.552	1.0*	0.72	0.552	1*
V–797	0.038	0.60	0.547	0.75	0.54	0.547	0.6

*Approximate values.

that the amorphous regions in cotton, if they can be considered as a separate phase, are in an oriented state and their orientation is as high as, if not higher than, the orientation of the crystalline phase. If one takes into account the structural features of cotton listed earlier, this is not surprising, since in any system in which the crystallites are laid down in an oriented manner, it is unlikely that this highly ordered phase can be 'out-of-step' with the less-ordered phase. The main implication of this approach is that the degree of crystallinity may not be a very important factor in determining the fibre modulus for two reasons. Firstly, the amorphous regions will be in the glassy state and therefore rigid. Secondly, they have high orientation. The axial modulus of this oriented amorphous phase will therefore be close to that of the crystalline phase. This also applies to synthetic fibres whose amorphous regions are in a glassy state and oriented.

We may now consider the fibre as a one-phase system. With this assumption, the present data can be subjected to further analysis in terms of two orientation-dependent models given, respectively, by Hearle[15] and Moseley[36].

4.2.2 *Hearle's Model*

Assuming that the fibril deforms at constant volume, Hearle has developed the following equation for the elastic modulus, E, of a fibre:

$$E = E_f(\cos^2\beta - \sigma\sin^2\beta)^2 + K(1-2\sigma)^2,$$

where E_f = the elastic modulus of the crystalline fibre,
β = the helix angle,
σ = Poisson's ratio for the fibre, and
K = the bulk modulus.

If $\sigma = 0.5$, i.e., if it is assumed that the fibre also deforms at constant volume, this equation reduces to:

$$E = E_f(\cos^2\beta - \tfrac{1}{2}\sin^2\beta)^2,$$

or we may write:

$$E = E_f \cdot f^2,$$

where f is the Hermans orientation factor. By using this simple equation, the values of E_f for different varieties can be calculated; this was done in the case at present under consideration by taking $f = f_{cH}$.

4.2.3 *Moseley's Model*

Assuming a one-phase structure, Moseley[36] showed that:

$$\bar{S}_{33} = S_{11} \cdot \overline{\sin^2\theta},$$

where $\bar{S}_{33}$ is the average compliance of the fibre along the fibre axis, S_{11} the transverse compliance of the unit, and θ the angle between the axis of symmetry of the unit and the fibre axis. Though the relation was originally proposed for sonic compliance, it was shown[17] that it also holds for compliance at low frequencies for certain fibres. The equation may be rewritten as:

$$E = E_t/\overline{\sin^2\theta},$$

where E is the longitudinal modulus of the fibre and E_t the transverse modulus of the unit. Again, by using $\overline{\sin^2\theta}$ values obtained from the Hermans orientation factor, f_{cH}, and the experimental modulus values (E), E_t was calculated.

4.2.4 *Consideration of the Two Models*

The values of the longitudinal and transverse moduli of the deforming unit obtained from the above two treatments, together with the experimental-modulus values, are shown in Fig. 1. It may be seen that the calculated moduli of the deforming unit for different varieties are very different, and broadly speaking

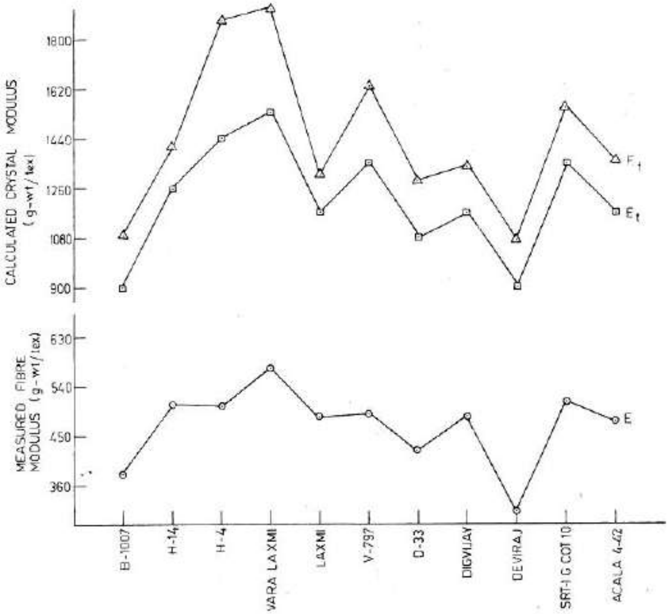

Fig. 1
The measured fibre modulus (E) and the calculated moduli of the deforming unit: longitudinal (E_f) and transverse (E_t) (g-wt/tex is equivalent to gf/tex).

they follow a pattern that is similar to that followed by the measured modulus. It may be pointed out in passing that Jawson *et al.*[16] have observed that all the elastic constants of cellulose crystal except the axial modulus depend on the inter-chain hydrogen bond, and the lateral Young's moduli are found to be surprisingly high.

The above analysis implies that, if these single-phase orientation-dependent models are applicable to cotton, two factors must be considered. It is generally believed that the deforming unit in all cotton fibres has the sâme elastic constants, and the modulus is primarily dependent on the average orientation of the units. Since the orientation-dependent models lead to different values for the modulus of the deforming unit for different varieties, it is possible that the units themselves have different stiffnesses, this obviously being a genetic feature. The intrinsic stiffness of the unit will then contribute to the fibre modulus in addition to the orientation effects.

It may be recalled that the theoretical modulus of crystalline cellulose can be achieved or even exceeded under dynamic conditions of loading [15,16]. Thus the deformation of cotton, even at low strains, could involve the deformation of crystallites in a dynamic test. While on this point, it may also be stated that the cylindrical growth layers would act as an assembly of parallel springs, and the deformation of such a system in a tensile test necessitates the constancy of strain in the system; the load will therefore be shared in such a manner that the stiffest layer carries the highest load. The non-uniform distribution of stresses within the fibre can be one possible cause of the discrepancy between the theoretical and experimental moduli.

It may, however, be noted that the modulus values of the different varieties of cotton shown in Table IV are rather low. In the present investigation, the test is essentially quasi-static, and, as Hearle[15] has pointed out, under these conditions both fibrillar slip and the removal of some fine buckling of fibrils can contribute to the low modulus. In addition, the imperfections in the paracrystalline structure can also contribute to the low modulus at these relatively low speeds of testing.

4.3 Tenacity of Single Fibres and Bundle Strength

The strength of cotton fibres, being an extremely important property, has been extensively studied, and the main factors that determine strength have been shown[1–3] to be the molecular weight, orientation, and number of reversals. The molecular weight is perhaps reflected to some extent in the maturity coefficient of the fibre[10]. Orientation includes crystalline and molecular orientation and is also affected by the spiral angle and the frequency and angle of convolutions[20]. The number of reversals is thought to be a varietal characteristic[6], and owing to differences in reversal frequency in a fibre, the strength shows dependence on the gauge length of the test specimen.

It may be seen from Table IV that the bundle-strength values for all cotton varieties are higher than the single-fibre-tenacity values. These differences essentially arise from the difference in the gauge lengths in the two cases: zero gauge length for the bundle-strength measurement and 1 cm for tenacity measurements.

Bundle strength shows good correlation with X-ray orientation, e.g., with the 75% X-ray angle, the correlation coefficient is -0.65. It also shows good correlation with the maturity coefficient ($r = 0.72$). Thus an increase in molecular weight and crystallite orientation leads to an increase in the bundle strength of cotton.

The single-fibre-tenacity results do not show significant correlation with orientation. There can be two reasons for this. First, as various authors have shown[21, 22], as the gauge length increases, the correlation with orientation goes on decreasing, and the reversal frequency begins to become the more important factor. Secondly, the linear density of individual fibres was not measured in the investigation described in this paper. As Patel and Patil[37] have pointed out, if the average fineness is taken, the breaking-tenacity values show more scatter. The same authors have also shown that the breaking load of fibres increases with increasing linear density up to the average linear density of the cotton. Beyond this, however, the breaking load levels off; consequently, values were obtained for the breaking tenacity that were lower than the average. It thus appears that the distribution of linear density may influence the results considerably.

There are two orientation-dependent models for tenacity or strength. The first one gives the following expression[1, 2] for the tenacity, T, of a fibre:

$$T = T_k \exp(-K \mathrm{Sin}^2\theta_c),$$

where T_k is the tenacity of unconvoluted fibre and k is a constant approximately equal to 7. The second is a phenomenological model[34] according to which the logarithm of tenacity is linearly related to the Hermans orientation factor. In the present case, both these models do not work, which shows that factors other than orientation may be important.

The present results indicate that, whereas the bundle strength is correlated with the orientation, the tenacity of single fibres is perhaps mainly determined by the reversal frequency. Since the latter parameter has not been measured, no comments can be made on its rôle.

The breaking of fibres ultimately involves the rupture of molecules. As was noted earlier, in cotton fibres, fracture cross-sections show that tensile failure is started by splitting between fibrils, i.e., hydrogen bonds are overcome. Mark[6] has pointed outs that, in cellulosic fibres, overcoming hydrogen bonds provides the measured strength values: once hydrogen bonds are overcome, the stress can concentrate on fibrils close to the reversals and breakage occurs.

The results of tests on single fibres show that the structural-dependence of tenacity is considerably different from that of modulus. Whereas, for tenacity, reversal points and stress concentrations play an important rôle, for the modulus these factors may not be so important. The fact that theoretical modulus values have been achieved or exceeded but not the theoretical tenacity values may in part be explained on this basis.

4.4 Extension at Break and Toughness

The extension at break shows a high correlation with the toughness ($r = 0.98$), indicating that the structural parameters that control these two properties may be similar. The extension at break correlates with the 75% X-ray angle ($r = 0.74$), the linear density ($r = -0.93$), and the maturity coefficient ($r = -0.92$). The toughness shows good correlation with the 75% X-ray angle ($r = 0.72$). Thus the main factors that make elongation high are: low crystallite orientation, low linear density, and low maturity coefficient. The toughness is mainly determined by the elongation of the cotton fibre.

The extension at break also shows high correlation with the mean fibre length ($r = 0.771$).

During a tensile test, the crystallites align towards the stretch direction. Some preliminary studies, reported recently[38], show that, as the fibre is stressed, the crystallite orientation improves. The stress–strain behaviour is stated to be Hookean, but the rate of increase of the Hermans orientation factor is irregular and does not increase linearly with strain. The author concludes that 'increase in stress seems to pull the cellulose network in a haphazard way'. The stress–strain curve of cotton is not linear; in general, it first shows slight strain-softening followed by strain-hardening at a later stage. Thus the rate of change of the Hermans orientation factor would not be expected to show linear dependence on strain. This type of work should, however, throw interesting light on the deformation mechanisms in cotton.

4.5 Fibrillar Geometry

As stated earlier, the authors have studied the surface morphology of both purified and unpurified cotton by a two-stage replica technique in a transmission electron microscope capable of giving high resolution. In the available literature[5, 39], several micrographs of fibre surfaces have been reproduced, and most of them reveal the ridges that are said to arise during the drying of cotton fibres. However, the fibrillar architecture of the primary wall is sometimes clearly visible between the ridges, particularly at the edges of the fibre, e.g., in plate 66 of O'Connor's book[39]. The present authors have also observed this for several of the cotton varieties for which results are reported in this paper.

In two varieties of cotton, H–14 and Rex, both purified, the scanning electron micrographs of the fibre surface clearly reveal the macrofibrils (Figures 2 and 3). This shows that an examination of the surface of cotton can reveal fibrillar geometry.

In the preparation of the replicas of fibre surfaces in the investigation at present under discussion[33], the shadowing was done with platinum–carbon, which has a very fine grain size; a resolution of 2 nm has already been reported for carbon replicas with this shadowing system[40]. Carbon deposition was done with simultaneous rotation of the specimen at 100 rev/min, the specimen being kept inclined at 20–30° to the vertical.

The micrograph shown in Fig. 4 is taken from a paper by Hearle and Simmens[41] in which the elementary fibrils are clearly shown to be joining together to form a larger fibril.

Fig. 5 is a surface replica of variety H–14 showing fibrillar architecture of the primary wall with longitudinal periodicity along the length of the microfib-

Fig. 2

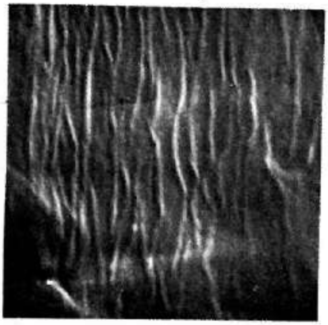

Fig. 3

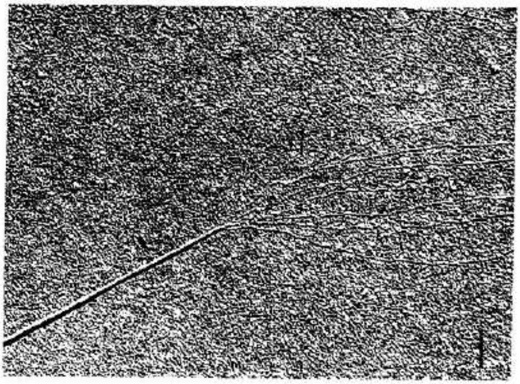

Fig. 4

Fig. 2 Scanning electron micrograph of H–14 purified cotton (× 2440).
Fig. 3 Scanning electron micrograph of Rex purified cotton (× 5640).
Fig. 4 Cotton micrograph showing splitting into finer units (photograph taken by Mr. S. C. Simmens and reproduced from reference 41 by courtesy of Professor J. W. S. Hearle 1 cm = 200 nm).

rils. In another variety, Rex (Fig. 6), the microfibrils can be clearly seen. An enlargement of a small area of this micrograph is shown in Fig. 7, and the transverse straitions show up clearly. Similar features shown by another variety, cotton B–1007, are clearly evident from Fig. 8.

The present authors have recently come across an electron micrograph of negatively stained cellulose microfibril that shows[42] a longitudinal periodicity of less than 10 nm. The cellulose was precipitated from a 0.2% cellulose solution in cuprammonium hydroxide. The periodicity was attributed to a double layer of spirally constituted microfibrils. Such features have been seen in at least three cotton varieties studied by the authors.

A possible interpretation of the above results is that the macro- or microfibril consists of several elementary fibrils, which are helically disposed.

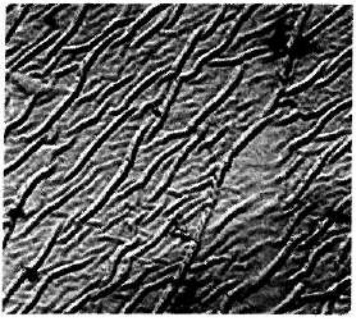

Fig. 5

Fig. 6

Fig. 7

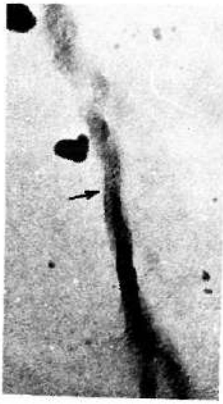

Fig. 8

Fig. 5 Surface replica of H–14 variety (unpurified), showing fibrillar architecture of the primary wall (× 13735).

Fig. 6 Surface replica of Rex (purified), showing microfibrillar impressions (× 13735).

Fig. 7 A magnified view of the microfibrils in Fig. 6, showing the transverse striations (× 26760).

Fig. 8 The transverse striations in a microfibril in B–1007 (purified) cotton (× 66 868).

The longitudinal periodicity observed in the surface replica is then a measure of the pitch of the helix. It is not claimed that this is a universal feature or indeed the only possible interpretation. It is realized that this observation needs further confirmation from studies on a larger number of samples. The possible effects of these morphological features on the mechanical properties of cotton need to be investigated.

The second part of the investigation on the electron microscope involved looking at fragmented fibre samples. In the various varieties that were examined in this way, a wide distribution of fibril sizes was noticed, and it was interesting to observe clear indications of fibrils having a diameter of less than or close to 2 nm.

Fig. 9
NaOH-digested, ultrasonically fragmented PTA-stained, PtC-shadowed H-14 (purified) cotton (the fibril width is 1.97 nm).

One such photograph is reproduced here as an example (Fig. 9). The effect of fibril-size distribution on mechanical properties is also worth investigating, and attempts in this direction are in progress.

4.6 Some Other Correlations

In this section, some of the correlations that have not been discussed previously will be considered.

The mean fibre length is correlated with the fineness ($r = 0.687$); the longer fibres are finer. There is a high correlation between the number of convolutions and the convolution angle ($r = 0.906$).

Moisture absorption is correlated with crystallinity ($r = -0.41$); the higher the degree of crystallinity, the lower is the moisture absorption. The X-ray angle is correlated with the convolution angle ($r = 0.511$). The various representations of crystallite orientation give reasonable correlations among themselves, as shown in Table VI. It is interesting to note that f_{cW}, Hermans orientation factor calculated on the basis of Wilchinsky's approach, gives good correlation with f_{cH} ($r = 0.831$) but does not correlate so well with X-ray angles. Since the calculation of f_{cW} does not involve any approximation, the following comments can be made. The good correlation between the 40% X-ray angle and fibre properties may be due to the fact that the crystallites that come within the 40% X-ray angle are relatively more important in contributing to mechanical properties. In the present case, mechanical properties do not show as good a correlation with the Hermans orientation factors as they do with X-ray angles. Meredith, however, found[43] that tensile strength showed a higher correlation

Table VI

Correlation Coefficients between Orientation Parameters

Parameter	40% Angle	50% Angle	75% Angle	f_{cH}	f_{cW}
40% Angle	1				
50% Angle	0.975	1			
75% Angle	0.961	0.964	1		
f_{cH}	−0.872	−0.863	−0.916	1	
f_{cW}	−0.555	−0.597	−0.689	0.831	1

with the orientation factor than with the 40% X-ray angle, although the difference in the values of the correlation coefficients was not high. A critical examination of various aspects of these correlations may provide useful information.

5. CONCLUSIONS

From an extensive investigation of the structure and mechanical properties of eleven varieties of cotton, it has been shown that the mechanical properties exhibit considerable dependence on orientation. Thus the crystallite orientation would appear to be a reasonable index for varietal screening, especially in terms of the X-ray angle.

The modulus results suggest that the deforming unit may be the crystallite itself and that the intrinsic stiffness of these units may be different in different varieties.

The electron-microscopical studies indicate that the elementary fibrils may be helically disposed in the microfibrils. Elementary fibrils of width close to 2 nm have been shown to exist.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. Satish Kumar and Dr. N. D. Ray of the Textile Technology Department, Indian Institute of Technology, Delhi, for considerable assistance with the experimental work and analysis of results.

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8—VARIETAL BEHAVIOUR IN SAW-GINNING IN RELATION TO FEEDING AND THE AMOUNT OF SEED COTTON

By G. PAULY

The aim of the study reported in this paper was to observe the performance of several cotton varieties during twenty saw-ginning tests in relation to the amount of seed cotton to be ginned and the rate of feeding. A strong relation exists between the ginning out-turn, the amount of fibre ginned per saw and per hour, and the size of the sample. The out-turned amount ginned increase with the size of the sample. A relationship was also found between the amount of fibre ginned per saw/per hour and the rate of feeding of seed cotton. The ginning out-turn decreases with an increase in the feed-rate for the varieties having large fuzzy seeds.

These observations allow one to define the ease of ginning of a given variety, the optimum weight of the sample to be ginned (25 kg), and the optimum feed rate of seed cotton into the gin stand.

1. INTRODUCTION

The principal ginning characteristics of a variety depend on two types of factor:

agricultural factors: climatology, pedology, and cultural practices; and mechanical factors, directly linked to the ginning conditions: the ginning rate, the setting of the seed board, the cleaning level, and the seed-cotton moisture content.

The ginning of the seed cotton from different variety tests on the twenty-saw gin at the I.R.C.T. Station at Bebedjia, Chad, allowed two of these mechanical factors to be studied more closely:

(*a*) the size of the seed-cotton sample; and
(*b*) the ginning rate determined by the feed-rate of seed cotton into the gin breast.

The amounts of seed cotton to be ginned for a particular variety being very variable and depending on the variety tested (from 5 to about 40 kg), it was not always possible to compare the main ginning characteristics obtained for each test.

The conclusions of this study will contribute to the improvement of commercial ginning and will allow certain results obtained on the twenty-saw gin to be interpreted according to the varieties ginned.

2. MATERIALS

The influence of the size of the cotton-seed sample and of the feed-rate of cotton seed on the main ginning characteristics was studied on four varieties (BJA 592, MK 73, Pan 575, and F 280 glandless) and three varieties (BJA 592, MK 73, and F 280 glandless), respectively.

Three reasons led to this choice of varieties:

the varieties are grown on a fairly large scale (BJA 592) or on multiplication schemes (MK 73, Pan 575, and F 280);

each variety taken from isolated plots of from multiplication plots of the I.R.C.T. Station at Bebedjia presented a sufficient amount of seed cotton to enable the different ginning tests to be carried out and to be replicated; and

each variety had particular ginning and technological characteristics:

BJA 592: average lint percentage and length; high seed index and linter percentage;

MK 73: fairly good lint percentage; good length; average seed index and linter percentage;

F 280: good lint percentage; medium length; high seed index and linter percentage;

Pan 575: fairly good lint percentage; long length; medium seed index; low to very low linter percentage.

All the ginning tests were made on the twenty-saw gin at Bebedjia. The ginning tests to determine the effect of the amount of seed cotton were made with the control lever on position 3 for varieties BJA 592, MK 73, and F 280 and on position 4 for variety Pan 575.

For the ginning tests to determine the effect of the seed-cotton feed-rate, control of the speed of the feed rollers at the base of the feed box and control of the position of the counterweight locked to the feed-control assembly allowed the experiments to be repeated without too many divergences.

3. METHODS

For each variety, homogeneous blending was effected by mixing the whole of the seed cotton.

The ginning test was repeated twice, three times, or four times according to the variety. The results and the curves obtained in this study for one type of ginning test are averages for these replications. After each ginning test, the gin stand was thoroughly cleaned.

For each ginning test, the following characteristics were determined:

the time needed for ginning, measured in hundredths of a minute, corresponding to the duration of the rotation of the seed roller in the feed breast;

the lint percentage;

the seed percentage;

the mote percentage;

the visible-waste percentage;

the invisible-waste percentage;

the weight of the seed roller corresponding to the weight of the seeds remaining in the feed breast at the end of ginning, the seed board being shut when the last seed cotton left the feed box; and

the number of revolutions of the saw shaft (in revolutions per minute).

In the ginning tests made to determine the effect of the feed-rate, the feed-rate of the seed cotton (kg/min) corresponding to the different position of the control lever was determined according to the formula:

$$\text{feed rate (kg/min)} = \frac{\text{mass (kg) of seed cotton of the sample} - 2\text{ kg}}{\text{duration of ginning}}$$

where 2 kg was the amount of seed cotton taken out of the sample to fill the breast at the beginning of each ginning test.

On the other hand, observations on the roll (shape, tightness, rotation speed) and measurements on the seeds (linter percentage) and of the regularity of the seed-cotton feed-rate were made during the whole series of experiments.

4. RESULTS AND INTERPRETATION

4.1 Ginning Test Made to Determine the Amount of Seed Cotton Ginned

4.1.1 Mass of Samples Tested

Samples of 2.5, 5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, and 50 kg of seed cotton were prepared and ginned in the same feeding position.

4.1.2 Remarks Common to the Four Varieties

The number of saw-shaft revolutions remained more or less constant for a particular variety, i.e., about 680 for F 280 and Mk 73, 685 for BJA 592, and 675 for Pan 575.

The mote percentage was very homogeneous for a particular variety; a slight increase was observed from 25 kg onwards. It was slightly higher for Pan 575 than for the three other varieties.

The visible-waste percentage remained constant for each variety. It was higher for F 280 and Pan 575 (0.60%) than for the varieties BJA 592 (0.45%) and MK 73 (0.35%).

The invisible-waste percentage remained more or less constant for each variety during the whole test, except for the large amounts of seed cotton, for which a slight increase was observed; it was the same for BJA 592, F 280, and MK 73 and lower for Pan 575.

4.1.3 Ginning Out-turn

The lint percentage increased with the amount of seed cotton, the relation being a regular sigmoid curve, the upper curvature of which was attained at the level of 15–17 kg for Pan 575, 17.5–20 kg for BJA 592, and 25 kg for MK 73 and F 280 (see Fig. 1). The plateau of the curve rose slightly between 20 and 50 kg.

The lint percentage was narrowly linked to the amount of seed cotton between 7.5 and 20 kg and varied little for the large samples, whichever variety was used.

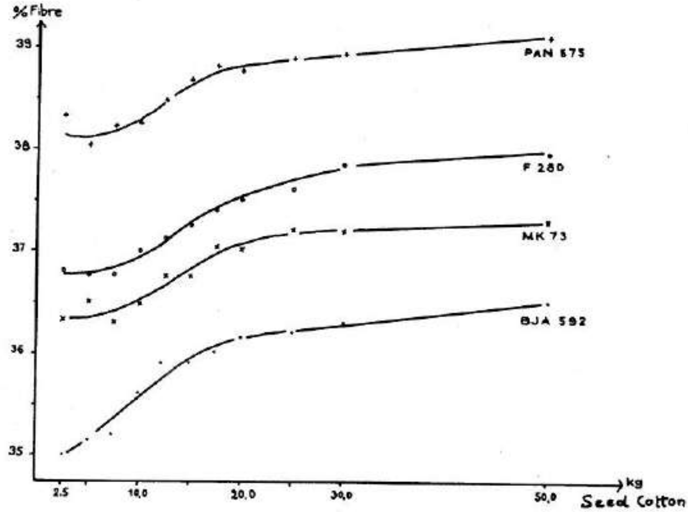

Fig. 1
Relation between amount of seed cotton and ginning out-turn

Table I

Variation of the Lint Percentage with the Amount of Seed Cotton

Variety	Ginning Out-turn at 7.5 kg	20 kg	50 kg	Variations between 7.5 and 20 kg	20 and 50 kg	Total Variation
BJA 592	35.22	36.15	36.50	0.93	0.35	1.28
F 280	36.77	37.49	37.96	0.72	0.47	1.19
MK 73	36.31	37.01	37.28	0.70	0.27	0.97
Pan 575	38.22	38.76	39.09	0.54	0.33	0.87

The ginning out-turn varied about 1% between a small and a large amount of seed cotton (Table I). However, varietal differences were observed. The varieties BJA 592 and F 280 had total variations that were greater than those for MK 73 and Pan 575.

4.1.4 *Fibre Output per Saw per House (s/hr)*

Two types of curves were observed, which corresponded to two different varietal behaviours in ginning (see Fig. 2). For varieties BJA 592 and F 280, the curve rose uniformly between 2.5 and 15 kg and attained a peak around 15 kg, after which it fell between 15 and 20 kg and became asymptotic, with a slight fall from 20 to 50 kg onwards. In spite of fibre outputs (s/hr) that were not very different between 10 and 50 kg, this curve and the asymptote can be explained.

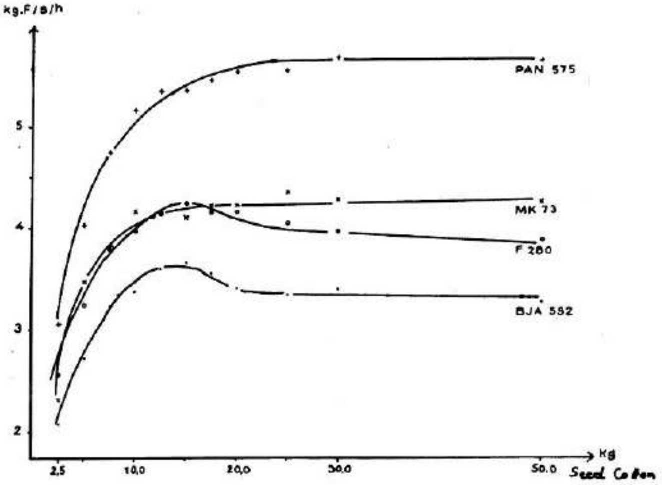

Fig. 2
Relation between amount of seed cotton and fibre output per saw per hour

Up to 15 kg of seed cotton, the regular increase in the fibre output (s/hr) was linked to the formation of the roll in the breast. Below 10 kg, the roll could not form and kept turning for a long time after the end of the feeding of seed cotton. This was the cause of the low values recorded. Between 10 and 15 kg, the roll was a little tight and turned regularly; an equilibrium developed between the number of seeds evacuated and the seed cotton that fed the roll. From 15 kg upwards, obstruction of the roll by the incoming seed cotton was noted as well as a distinct tightening of the roll, which released the seeds less easily through the open seed board; the roll increased in volume and bore on the automatic feed control; the feed rate decreased slightly, which caused a drop in the fibre output, whereas the lint percentage increased.

BJA 592 and F 280 have seeds with a high seed index (between 11 and 11.5 g) and with a high linter percentage, which prevented a normal evacuation of the seeds of the roll through the seed board when the amount of seed cotton to be ginned was important.

For varieties MK 73 and Pan 575, the curve rose between 2.5 and 15 kg; it became asymptotic up to 50 kg.

Up to 15 kg, the same kind of curve was observed as for varieties BJA 592 and F 280. From 15 kg of seed cotton upwards, the fibre output (s/hr) remained more or less constant, which corresponded to an equilibrium between the feed rate of seed cotton in the feed breast and the release of the seeds from the roll, whatever the size of the sample was.

An average seed index (8.5–9.5 g), and above all low-fuzzed seeds (MK 73) or almost naked seeds (Pan 575), allowed easier evacuation of the seeds through the seed board.

4.1.5 Mass of the Roll

The mass of the roll increased rapidly between 7.5 and 17.5 kg and remained more or less constant up to 50 kg (Fig. 3). Between 2.5 and 7.5 kg, the small quantities of seed cotton used prevented the formation of the roll even though the seed board was closed. From 7.5 to 17.5 kg and beyond, formation of the seed roll in the feed breast was observed; it turned regularly and tightened as the amount of seed cotton increased. From 17 kg onwards, the size of the sample was sufficient to ensure a tightness and weight of the roll that remained more or less constant. An equilibrium developed between the evacuation of the seeds and the feeding of the seed cotton. Ginning was steady and seemed optimal for the constant feed-rate of seed cotton corresponding to position 3 or 4 of the control lever.

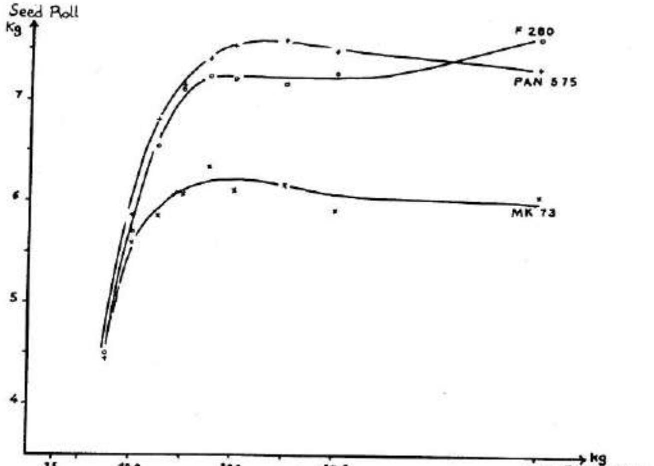

Fig. 3
Relation between amount of seed cotton and mass of seed roll

4.2 Ginning Test in relation to the Feed-rate of Seed Cotton

4.2.1 Size of Samples

All the samples of seed cotton were of mass 20 kg. The main observations on ginning are given in Table II.

4.2.2 Remarks Common to the Three Varieties

The number of saw-shaft revolutions decreased with the feed-rate; this was

Table II

Main Observations on Ginning

Variety	BJA 592	F 280	MK 73
Feed-rate (kg/min)	2.90	3.20	3.50
	Well-formed roll, not very tight, turning regularly; easy evacuation of the seeds, normal linter percentage; regular and sufficient feeding of seed cotton.	as for BJA 592	as for BJA 592
Feed-rate (kg/min)	3.50	3.80	4.40
	Well-formed roll, but tight; accumulation of the seeds in the roll, difficult evacuation of the seeds at the end of ginning quick stop of the roll presence of seed cotton not ginned.	Well-formed roll, rather tight, turning regularly; normal evacuation of the seeds; feeding of the seed cotton slightly controlled by the volume of the roll.	Well-formed roll, rather tight, turning normally; easy evacuation of the seeds; regular feeding of seeds, regular feeding of seed cotton.
Feed-rate (kg/min)	Above 4.00	Above 4.50	4.95–7.10
	Very tight roll, very bulky, turning very badly, often stopping, blocked above 4.50; no evacuation of the seeds; stopping of the feeding by autoregulation; at the end of the ginning, rapid stopping of the roll, presence of much seed cotton not ginned (about 2.6% of fibre).	Very hard and tight roll, turning very badly, often stopping; difficult evacuation of the seeds; stopping of the feeding by autoregulation; at the end of ginning, rapid stopping of the roll by blocking, presence of much seed cotton not ginned (about 0.8% of fibre).	Tight to rather tight roll, but turning regularly; normal evacuation of the seeds, normal linter percentage; feeding reduced by autoregulation, but never stopped.

linked to the increase in the weight and the tightness of the seed roll, that is to say, to the increase in the friction forces in the feed breast.

The mote percentage decreased slightly with the feed-rate; less good cleaning of the motes of the fibre was observed, the saws being overloaded with fibre.

The visible-waste percentage decreased with the feed-rate, the seed cotton being increasingly less well cleaned; when too much seed cotton entered at one time, the different cleaning levels of the gin were less efficient.

Results for the invisible-waste percentage varied according to the variety.

The mass of the seed roll increased rapidly with the feed-rate (see Fig. 4). For MK 73, a plateau was observed, which proved to be an equilibrium in the roll between the incoming seed cotton and the evacuated seeds; it was not so far varieties BJA 592 and F 280.

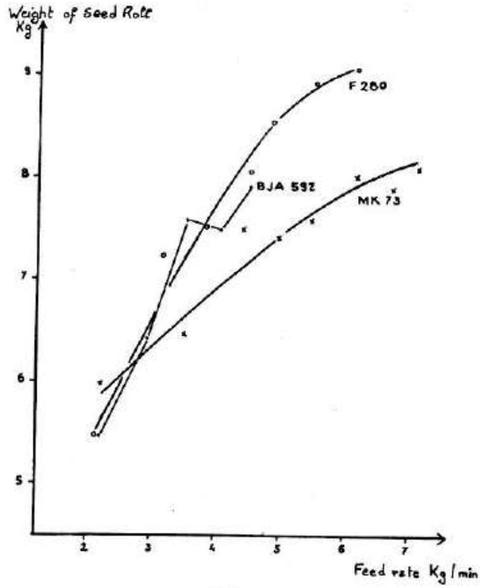

Fig. 4
Relation between feed-rate of seed cotton and mass of seed roll

4.2.3 *Ginning Out-turn*

For BJA 592 and F 280, the lint percentage followed a falling curve (Fig. 5) the maximum of which corresponded to low or average feed-rates (2–3 kg/min). The decrease in lint percentage (more considerable for BJA 592) recorded for high feed-rates (above 4 kg/min) was related to the presence of an increasing amount of seed cotton in the roll at the end of ginning, which was often precipitated by the blocking of the roll.

For MK 73, the lint percentage remained more or less constant with the feed-rate, with $r = 0.164$ and the regression lines $0.015x + 37.005$.

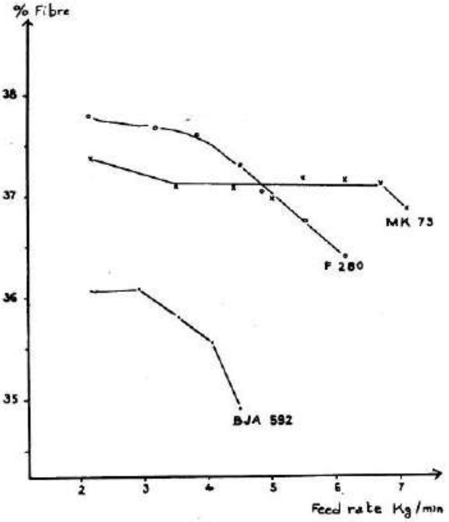

Fig. 5
Relation between feed-rate of seed cotton and ginning out-turn

4.2.4 Fibre Output per Saw per Hour (s/hr)

This increased regularly with the feed-rate; all the varieties showed a linear relation, the lines almost merging (Fig. 6). However, differences in varietal behaviour were observed; the rise in the seed-cotton feed-rate led to an increase in the volume and density of the roll. For MK 73, no stopping of the roll in the breast during ginning was observed, the low-fuzzed seeds being normally evacuated. For BJA 592 and F 280, the seeds with a high linter percentage accumulated in the roll at the same time as the seed cotton in spite of automatic regulation of the feeding, leading to frequent blocking of the rolls towards the end of ginning. The output fell sharply with BJA 592 when the feed-rate was 4.5 kg/min and with F 280 when the feed-rate was 6 kg/min because of the complete stoppage of the roll in the breast in the course of ginning.

4.2.6 Technological Characteristics

No effect of the feed-rate on the principal characteristics of the fibre was observed.

5. CORRELATIONS

5.1 Parameters Calculated

In certain cases, these studies were completed with the calculation of correlations:

the correlation coefficient, *r*, for linear relations; and
the correlation ratio or non-linear correlation ratio, *n*, measuring the

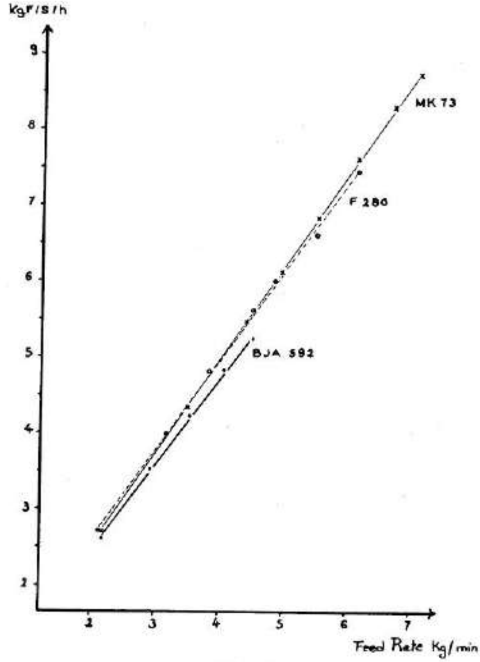

Fig. 6
Relation between feed-rate of seed cotton and fibre output per saw per hour

degree of dependence of the variables considered whatever the form of the relation between them.

5.2 Ginning Test to Determine the Effect of the Amount of Seed Cotton

The lint percentage rose linearly with the amount of seed cotton between 7.5 and 20 kg.

The lower value for r for Pan 575 resulted from the difference in the varietal behaviour. The upper curvature of the sigmoid occurred around 17.5 kg instead of 20 kg as for the other varieties.

Table III

Variety	r	Significance Level at 1%	Regression Line
BJA 592	0.934	Significant	$0.067x+34.89$
F 280	0.848	Significant	$0.057x+36.38$
MK 73	0.873	Significant	$0.059x+35.91$
Pan 575	0.701	Significant	$0.052x+37.81$

Table IV

Variety	Lint Percentage	Output per Saw per Hour
F 280	0.860	0.810
MK 73	0.618	0.944

The non-linear correlation ratio showed that the lint percentage and the fibre out put per saw per hour are closely linked to the amount of seed cotton.

5.3 Ginning Test to Determine the Effect of the Seed-cotton Feed-rate

The feed-rate was governed by the control lever (Fig. 7). From position 4 onwards, the relation between the feed-rate of seed cotton per minute and the position of the control lever was perfectly linear: $r = 0.999$ for BJA 592, 0.995 for F 280, and 0.998 for MK 73. The half-lines corresponding to these varieties were roughly parallel but did not merge. Consequently, the position was not a reliable datum, for different feed-rates for a particular position were observed according to varieties. The feed-rate of seed cotton was used to compare the varieties between themselves.

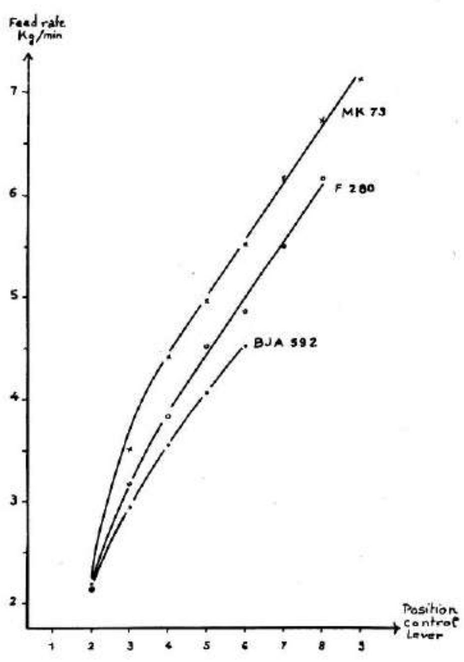

Fig. 7
Relation between position of control lever and feed-rate of seed cotton

6. CONCLUSIONS

6.1 Principal Observations

The two types of study reported in this paper showed:

the great influence of the size of the sample of seed cotton on the lint percentage and on the fibre output per saw per hour, above all for samples of average size (from 7.5 to 20 kg); these two characteristics increased with the size of the sample;

the strong influence of the feed-rate of cotton seed in the breast on the fibre output per saw per hour, which increased regularly and linearly for F 280 and MK 73; BJA 592 showed a fall in the fibre output per saw per hour when the feed-rates were rather high.

the variation of the lint percentage was in inverse relation to the feed-rate for the varieties with seeds of a large size and with a high linter percentage; it seemed independent of the feed-rate for variety MK 73, which has seeds of an average size and of a low fuzz grade.

These observations allowed the ease of ginning of a variety, the optimal size of sample for the ginning tests, and the optimal feed-rate of seed cotton to be defined, as explained below.

6.2 The Ease of Ginning of a Variety

The behaviour of the roll when the feed-rate was high and the amount of seed cotton to be ginned were both important, and the output per saw per hour allowed four types of variety to be distinguished:

the varieties that were very easily ginned (type Pan 575): very high output (s/hr), especially with a high feed-rate; seeds of an average size and almost bare;

the varieties that were easily ginned (type MK 73); high output (s/hr), particularly when the feed-rate of seed cotton was high; seeds of an average size and of an average linter percentage;

the varieties that were not very easily ginned (type F 280); average output (s/hr), but falling at a high feed-rate because the roll became bulky and tight and turned with difficulty;

the varieties that were difficult to gin (type BJA 592); average output (s/hr), but falling at an average-to-high feed rate; large seeds, high linter percentage, producing a bulky and tight roll.

6.3 An Optimal Size of Sample for the Ginning Tests

The study of the group of varieties showed that the lint percentage varied distinctly less with the size of the sample from 20 kg onwards; from that amount of seed cotton, the curve presented a plateau that was rising slightly. For the varieties that were easy to gin (type Pan 575), the size of the sample could be reduced to 15 kg.

The different results obtained with the same variety in regional variety tests at farms and experiment stations were not homogeneous between themselves because they corresponded to a very variable amount of seed cotton from one variety test to another and particularly to amounts between 7.5 and 20 kg, between which the lint percentage rose linearly.

If, at the level of regional variety tests, it was not possible to control the size of the sample at the time of ginning, the variety tests being very heterogeneous in yield, the control tests of industrial ginning will have to take into consideration samples that are larger than 25 kg. While remaining within acceptable limits for experimentation, the more large sample are used, the greater will be the lint percentage, and a comparison of the results of ginning on commercial gins and on laboratory gins will be possible.

6.4 The Optimal Feed-rate of Seed Cotton

Too high a feed-rate led to a drop in lint percentage that is more or less important according to the type of variety. For the varieties that are difficult to gin, a drop in output (s/hr) was also observed. Thus it is possible to improve commercial ginning by acting on the quality and on the costs of ginning. There seemed to be no influence of the feed-rate on the quality of the fibre with laboratory ginning; however, with commercial ginning, there could be an influence on the main technological characteirstics and, above all, on the aspects of the fibre (preparation) and its grade.

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9—NIGERIAN COTTON: ITS PRODUCTION, CHARACTERISTICS, AND UTILIZATION

By S. C. O. UGBOLUE and P. O. ADEGBILE

This paper emphasizes the fact that Nigeria is one of the major cotton producers in Africa and a member country of the International Institute for Cotton. A critical account of the production of cotton in the country is given. It is pointed out that indigenous African cotton has been grown in Nigeria for generations, the most successful type being the Ishan variety (*G. barbadense*). The characteristics of Nigerian cotton are discussed in relation to the breeding programme in Samaru. To satisfy a large and increasing domestic market, several suggestions are made.

1. INTRODUCTION

Cotton is one of the world's most vital and economically important agricultural crops. Millions of people are dependent on it as their main source of clothing and as an important food source. It provides employment to millions of individuals in many nations of the world. Nigeria is one such nation, being an important cotton-producing and textile-manufacturing country in Africa and a member country of the International Institute for Cotton.

2. CLASSIFICATION OF COTTON

Cotton belongs to the botanical genus *Gossypium*, which includes the cultivated cottons and is a member of the sub-tribe *Hibisceae* in the natural order of *Malvaceae*. Recent studies on cotton from different parts of the world indicate that the independent origins of American (New World) and Asiatic and African (Old World) cottons have remained distinct. The New World, American, cottons have 26 chromosomes; Old World, Asiatic and African, cottons have only thirteen.

Four species of *Gossypium* account for practically all the world's supply of cultivated cotton. These species, which were independently developed and cultivated by different tropical peoples in both the Old and New Worlds, are as follows:

(i) *G. hirsutum* These varieties, of Central American origin, are the most important varieties of cotton in world commerce, constituting 87% of the world's production. Their maximum height is 1.8 m.

(ii) *G. barbadense* Believed to have originated in Peru this species includes the famous Sea Island and Pima S–2 cottons and some of the Egyptian varieties. Their height is between 1.8 and 4.6 m. The Nigerian Ishan variety, referred to as *G. vitifolium*[2] in 1857, belongs to this group.

(iii) *G. arboreum* This includes the tree cottons found in Nigeria and the native cottons of India and Pakistan. It grows as tall as 4.6–6.1 m.
(iv) *G. herbaceum* This average 1.2–1.8 m in height, is low-yielding, and has short fibres; it is similar to the Nigerian Meko variety grown in the Abeokuta area.

3. THE PRODUCTION OF COTTON

3.1 The World Situation

Cotton continues to be the most important single fibre used in the textile industry. Its production and consumption throughout the world are given in Table I. It is evident that the consumption of cotton is still greater than the combined consumption of all other fibres. In fact, cotton's share of 52.7% in world fibre consumption[3] in 1975 remained comparable to the level attained three years earlier: 53% in 1972.

Table I

World Cotton Production and Consumption

Year	Production ($kg \times 10^{-6}$)	Mill Consumption ($kg \times 10^{-6}$)	Percentage Share in World Fibre Consumption
1950	6 600	7 068	71.1
1960	10 129	10 360	68.4
1970	11 450	12 058	55.4
1975	13 624	13 012	52.7

3.2 The Status of Cotton in Nigeria

It is estimated that the total cotton area in Nigeria is 0.6 million ha. The output of cotton within an area is generally determined by the quantity and quality of resources used for its production, together with the techniques of production used. Most Nigerian farmers are small-scale farmers, who use predominantly locally made farm implements and no mechanization, every operation being manually done. Cotton-breeding and detailed studies on growing and husbandry are specialist fields for agronomists and scientists in two locations: the Institute for Agricultural Research, Ahmadu Bello University, Samaru, Zaria, and the Moor Plantation, University of Ife, Ibadan campus. Cotton yields[4] are as high as 1500 kg/ha in the research stations, sprayed fields record an average of 631 kg/ha, and local farmers produce about 200 kg/ha. A report[5] of a study group on cotton and other fibres concluded that there should be increased production mainly by increasing yields through the adoption of improved farming practices rather than by further expansion of the cotton area.

The prime commercial product of the cotton plant is lint, which is removed and separated from the remainder of the seed in the ginning process. Ginning is done, on behalf of the Nigerian Cotton Board, in several ginneries sited in various locations throughout the cotton-growing areas. The ginneries are owned and managed by Cotton and Agricultural Processors Ltd, Zaria (formerly the British Cotton Growing Association Nigeria, Ltd.) and the administration and marketing of cotton resources in the Country remain the responsibility of the Nigerian Cotton Board.

Table II shows the total production and consumption of cotton in Nigeria.

Table II

Nigeria: Cotton Production and Consumption*

Season	Production	Consumption	Exports	Imports
1972–73	40.00	30.92	5.56	—
1973–74	25.47	41.84	1.46	8.19
1974–75	52.10	45.48	—	20.00
1975–76	60.66	45.48	—	3.64
1976–77	82.96	32.57	19.37	—
1977–78 (estimated)	36.38	61.85	18.19	—

*Figures provided by Market Research Department, Nigerian Cotton Board[6]. All are in kg $\times 10^6$.

Factors responsible for the fluctuation in production were adverse climatic conditions, the worst being the long drought that swept across the Sahelian areas of West Africa, including Nigeria. The bumper harvest of 1976–77 was a response to an increase in producer price[7], shown in Table III, and in acreage under cultivation, good weather, greater inputs in agriculture, and extension services, as well as the deliberate and successful efforts of the Federal and State Governments in establishing agricultural projects in Funtua, Gombe, and Gusua. The estimated production for 1977–78 shows a decrease from the previous year and is attributed to late planting and erratic rainfall.

Table III

Nigeria: Producer Prices for Cotton*

Season	Producer Price per Ton of Seed Cotton (Naira)	Equivalent Producer Price (U.S. Dollars)
1973–74	134.40	214.40
1974–75	201.60	322.56
1975–76	308.00	492.80
1976–77	330.00	528.00
1977–78	330.00	528.00

*Figures given by Adamu[7].

4. UTILIZATION

Nigeria has a large domestic market for cotton and until recently exported an appreciable quantity to other countries, as shown in Table IV. The average cotton production for the period shown in Table II is 49.60×10^6 kg, which is approximately 0.66 kg per capita (based on a population of 75 millions) compared with 14.4 kg per capita for U.S.A. (based on 1977–78 production figures and a population of 200 millions). There are over 120 textile mills, 35 of which are fully integrated to produce apparel and furnishing fabrics, both dyed and printed. The Federal Ministry of Industries[7] estimates that the textile mills in Nigeria require 64.3×10^6 kg of cotton lint annually. Local spinners and handloom weavers producing traditional cloths also consume some cotton. To meet the increasing domestic demand and make some contribution to export earnings, it would be necessary to increase cotton production in Nigeria. Detailed examination of the production pattern, however, indicates that little or no cotton is currently being produced in the former traditional cotton belts in Idoma land in Benue State and the northern parts of Bendel State. The ginneries at Keffi, Lokoja, and Oshogbo are grossly under-utilized. Current effort in establishing the Ayangba Agricultural Development Project in Benue State should accelerate cotton production in this area.

Table IV

Nigeria: Exports of Cotton by Country of Destination (Average 1966–70; Annual 1970–74)*

Country of Destination \ Year	Average 1966–70	1971	1972	1973	1974	1975
Belgium	4.18	1.32	0.22	0.22	†	†
France	2.2	†	†	†	0	0
Federal Republic of Germany	0.44	†	†	0.11	†	0
Hong Kong	3.08	0.44	†	1.32	0	0
Republic of Korea	0	0	0	0	0.22	0
Netherlands	3.96	0.44	0.44	0.66	0	0
U.K.	3.08	0.22	0.22	0.22	0	†

*All Figures are kg $\times 10^6$.

†Fewer than 500 bales (i.e., less than 0.11×10^6 kg).

5. CHARACTERISTICS OF NIGERIAN COTTON

Studies of the structure of the cotton fibre have been presented by Ugbolue[8]. Equipped with improved knowledge of the structure and properties of the cotton fibre, the manufacturer can face the challenges posed to cotton by the man-made fibres. For cotton to retain a leading rôle in a competitive world, much greater attention will therefore have to be paid to the changes, not only in consumer demand but also in the industry that is serving that market. Nigerian cotton has achieved a reputation for being easily carded to 40s cotton count (14.8 tex) and as a very good mixer with other cottons or man-made staple fibres or both.

Indigenous African cotton has been grown in Nigeria for generations, the most successful being the Ishan (*G. barbadense*) with a staple length of $1\frac{1}{8}$ in. (28.6 mm). In 1912, P. H. Lamb[2] introduced the best available improved Allen seed from Uganda and thus laid the foundation for the successful Nigerian Allen variety, which is an American-cotton type (*G. hirsutum*). In the breeding programme for the cotton crop in Nigeria, selection within the Nigerian Allen variety (*G. hirsutum*) has produced a series of improved varieties, which have been brought into general cultivation through a system of seed multiplication and distribution. The multiline Allen 260 was constituted in 1957–58, and Allen 26J was introduced in 1960–61. Plant hairiness and glands were retained in Nigerian commercial cottons to make them less susceptible to attack by flea beetles.

Improved varieties were subsequently introduced as Samaru 69, Samaru 71, and Samaru 72, and a much-improved variety, Samaru 77, is now at the multiplication stage. Table V gives a summary of the characteristics of cotton varieties grown in Nigeria. Research is also continuing in Samaru for even better varieties.

Table V

Characteristics of Cotton Varieties in Nigeria

Variety	Samaru 26G	Samaru 26J		Samaru 71	Samaru 72
Property \ Season	1956–57	From 1957–58 to 1968–69	1970–72	1971–72	
Effective length (mm)	27.78	29.44	20.52	29.4	31.4
Fibre bundle strength* (tenacity)					
(gf/tex)	18.2	18.8	20.5	21.0	22.6
(mN/tex)	178	184	201	206	222
Micronaire value	3.2	3.2	3.2	3.3	3.3

*Determined on Stelometer.

6. CONCLUSIONS

The evidence therefore suggests that much has been accomplished in the cotton-fibre breeding programme in Nigeria. However, to maintain a viable future for cotton and keep it competitive as a major textile fibre the following guidelines would have significant impact:

(i) research must be directed mainly towards the needs of the average farmer, but progressive farmers willing and able to pay for some inputs and farmers' co-operatives, where mechanization is possible, should be encouraged;

(ii) cotton research must have a strong bias towards practical questions answerable in the short term—to define and reduce the risks of cotton-growing and eliminate wide fluctuations in yield over which the farmer has no control;

(iii) the reasons for every scientific farming recommendation must be explained to the farmer by the agricultural extension worker;

(iv) research must be intensified on cotton with emphasis on improved processability, utilization, and the application of chemical finishes to enhance durability, performance, and service;

(v) there is a need to stabilize cotton prices and maintain an adequate stockpile to ensure constancy of supply to the industry; and

(vi) Nigeria must continue to participate effectively in those international bodies that are interested in maintaining the viability of the cotton fibre.

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10—THE IMPORTANCE OF THE COTTON TEST FOR THE PRODUCER, THE MERCHANT, AND THE INDUSTRY

By F. Hadwich

The importance of the systematic determination of fibre properties in assessing the spinnability of cotton is pointed out, and the different types of test available are discussed and classified. Requirements for tests and for the instruments used in making them are set out. Tests for various fibre properties—the Micronaire value, fibre tenacity, fibre length and fibre-length distribution, maturity, colour, non-lint content, neppiness, and moisture content—are considered in turn. The accuracy of the test values obtained is discussed, and details are given of international round tests, international standard specifications, and international calibration cottons. A discussion of control limits completes the paper, and finally proposals are made for the future direction of work on cotton-fibre tests.

1. INTRODUCTION

In the past, the evaluation of cotton was generally done by the classer, that is to say, by the eye and the hand. The properties evaluated (or appraised) are primarily grade, colour, and staple length. However, a good classer will also include in his appraisal the following aspects: the uniformity of fibre lengths, especially the proportion of short fibres, the breaking strength, and, particularly, the character of the cotton, which may be reduced by 'overheating' of the cotton before ginning, by 'overcleaning', by severe cold, by insect infestation, or by some other cause. The spinning properties of a cotton may be lowered by all of these influences.

Nowadays, when machinery for the processing of cotton is geared to ever-increasing speeds, when the competitive pressure from man-made fibres is by no means diminished, and when demands on the final product (yarn, woven fabrics, knitwear) constantly increase—at a time when new and important properties are bestowed on the fibre and cotton products by new finishing techniques—an appraisal by a classer is simply no longer sufficient in most cases. Rather it is necessary that additional properties of the cotton be determined numerically.

In this way, the spinner is placed in a position to select and use the 'right' or 'optimal' cotton for spinning an attractively priced yarn possessing all the required properties, such as strength, elongation, and uniformity. In this connexion, the following four factors have to be primarily considered:

the intended yarn or the intended final product;
the available equipment by which the cotton is to be processed, as well as the finishing process to be applied;
experience in the spinning of cotton of different qualities and the finishing

of the products made from it; and
the price of cotton.

Only the experienced spinning-mill manager can decide which cotton is to be considered as 'optimal' according to these four factors and can then reasonably specify his demands with regard to classing results and test values. This decision has to be made for each spinning lot.

To ascertain the spinnability of a cotton, two procedures are available: the spinning test and the cotton-fibre test (i.e., the cotton test).

2. THE SPINNING TEST

In the spinning test, a representative sample of a cotton lot is spun under constant conditions into a yarn of given fineness (yarn count or linear density) and with a given number of turns. Subsequently, this standard yarn is examined (for strength, elongation, uniformity, appearance, etc.), and conclusions are drawn from the results with regard to a yarn with a different fineness and torsion that is to be manufactured from this cotton under normal mill operations.

The spinning test may be performed in a specially developed mini-spinning plant (Fig. 1) or on normal spinning machinery that has been modified for this purpose and to which only small quantities of the cotton may be fed. Such spinning tests are being performed on a continuous basis, especially in official testing houses in some cotton-producing countries. This has been done, for example, for many years in Egypt (in the Alexandria Testing House) and in the U.S.A., by the United States Department of Agriculture (U.S.D.A.), and also in some international institutes, but seldom in spinning mills.

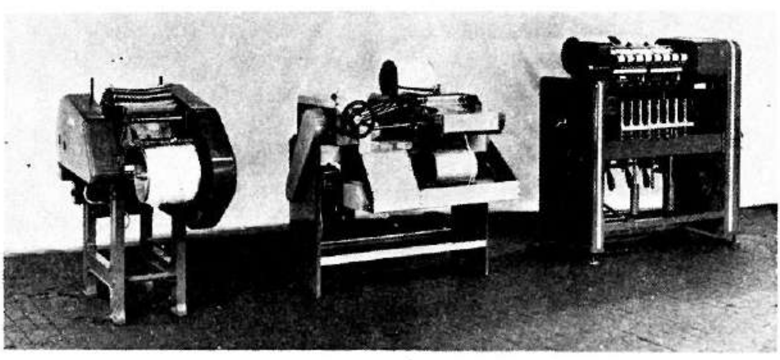

Fig. 1
The Platt Shirley Miniature Spinning Plant

Spinning tests have some disadvantages: thus, for example,, it is often difficult to draw conclusions from the properties of a standard yarn produced in the laboratory (having a specific fineness and with a particular twist) that can be applied to deduce the properties of a yarn (having a different fineness and with a different twist) spun in the mill from the same cotton.

3. THE COTTON TEST

In contrast to the spinning test, the cotton test (i.e., the cotton-fibre test) has been introduced on a world-wide basis. In this cotton test, the various properties of cotton fibres are each determined separately.

Many test methods and testing instruments have been developed during the last 30 years, but only a few of these are suitable for use in actual practice. In the international cotton trade, this has certainly been the case with regard to only two test values, i.e., the Micronaire value and the Pressley value. However, the processor would like to know some additional properties of the cotton and lay them down in purchase contracts as far as possible.

There are four kinds of cotton test:

(*a*) *scientific tests*: slow, tedious, and costly, values very accurate;
(*b*) *internal rapid tests*: used only in a single laboratory for internal purposes, values accurate enough to show trends;
(*c*) *rapid tests*: used in some or in many laboratories, more or less accurate, accuracy partly unknown, not ready for cotton contracts;
(*d*) *recognized rapid tests*: used on world-wide basis, accuracy known, values laid down in cotton contracts.

Rapid tests that are used only in an industrial laboratory for internal purposes can, of course, also be useful and helpful for the mill. The processor wants to have universally used test methods that given internationally recognized values. He thus has the opportunity to buy the cotton for which such data are available and to obtain the 'optimal' cotton from the different growth from all over the world.

Before a testing method can achieve such world-wide application and the values thus determined be reflected in international purchase contracts (i.e., cotton contracts), certain prerequisites must be fulfilled:

—the testing instrument must not be too complicated or too expensive; any laboratory assistant should be in a position to make tests after a short period of familiarization; chemical methods have to be safe and simple;
—the test values must be accurate, that is to say, reproducible within narrow and known limits;
—for any test method, international test standards (i.e., international calibration cottons) with known test values should be available;
—for each method, so-called internationally 'recognized laboratories', which decide on disputes, ought to be established, and these should be supervised continually (there are so far recognized laboratories only for the Micronaire test).
—for each parameter, reasonable tolerances should be settled.

4. FIBRE PROPERTIES, TEST METHODS AND INSTRUMENTS

4.1 Introduction

In this paper, only such tests and instruments that are useful in practice and of interest to growers, merchants, and processors will be mentioned.

4.2 The Micronaire Value

The Micronaire Test is the most widely applied test for cotton, since it is used throughout the world. Micronaire values are agreed on in cotton contracts, and in numerous cotton mills the spinning lots are put together on the basis of these values. The Micronaire value—a combined parameter for fibre fineness and maturity—gives, together with other properties, valuable indications of the spinnability, the nepping tendency, the yarn appearance, and the yarn's dyeing behaviour. However an unmistakable indication can be obtained only when the growth is considered. Thus, for example, cotton with the same Micronaire value but of different growths may show different numbers of neps and may differ in dyeing behaviour.

Many types of instrument are available for the determination of the

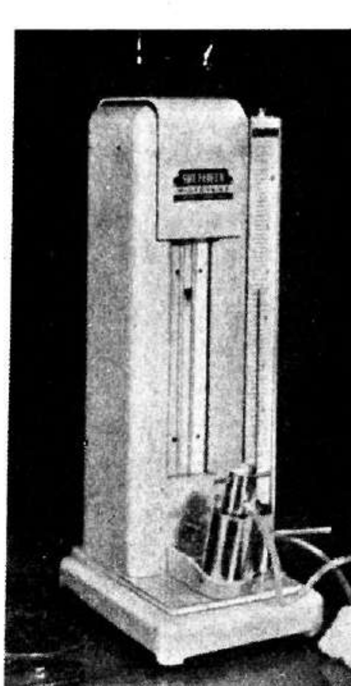

Fig. 2
The Sheffield 60600 model of the Micronaire instrument

Fig. 3
The Fibronaire

Micronaire value. All work by means of air-flow. All air-flow testers on the market give the same and sufficiently accurate values, provided that the Micronaire scale has been calibrated with international calibration cottons and that the instrument used is regularly checked with these. Fig. 2 and Fig. 3 show the two types of instrument mostly used nowadays.

There are no problems in Micronaire-testing on a world-wide basis if instruments of differing types are used.

4.3 Fibre Tenacity

In practice, the tenacity of cotton fibres (often called the fibre strength or Pressley strength) is chiefly determined on fibre bundles by the Pressley Tester (Fig. 4) with zero gauge length. The Pressley index (P.I.) in 1bf/mg is first

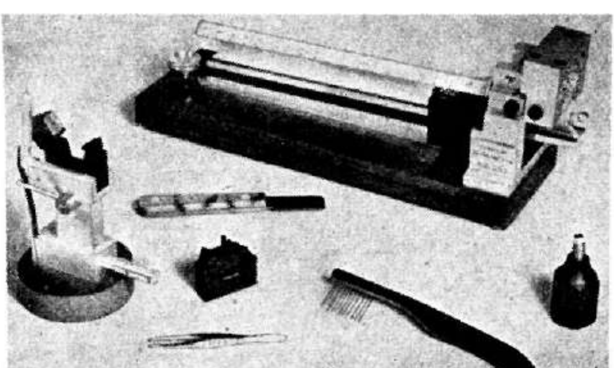

Fig. 4
The Pressley Bundle-strength Tester, with accessories

determined, and after correction with the help of an international calibration cotton, it is generally indicated in cotton contracts in lbf/in^2 (p.s.i.) and this always as a minimum value (e.g., nothing below 80,000 p.s.i.) but in cotton certificates also in 1000 p.s.i. (= M.p.s.i.). It should be noted here that 1 lb/8 in.) and specified in gf/tex.

In the U.S.A. particularly and also in many other laboratories, in addition to these Pressley tests, the bundle tenacity of cotton is determined by the Stelometer (Fig. 5) with a gauge length of 3.2 mm (= 1/8 in.) and specified in gf/tex.

This bundle tenacity at 3.2 mm has not so far found acceptance in international cotton contracts, even though these values give a closer correlation with the yarn strength.

In principle, for international purposes, most yarn-strength testers can also be used for the determination of the fibre-bundle tenacity, provided that so-called Pressley clamps are used as well as international calibration cotton for the determination of correction factors. For international arbitration, only the Pressley Tester should be used in order to avoid additional differences in the results obtained.

4.4 Fibre Length and Fibre-length Distribution

In practice, it is not the length of the single fibre that will be measured but certain parameters of a cotton sample, i.e., the mean length, the coefficient of variation of length, the short-fibre content, etc. These parameters are of

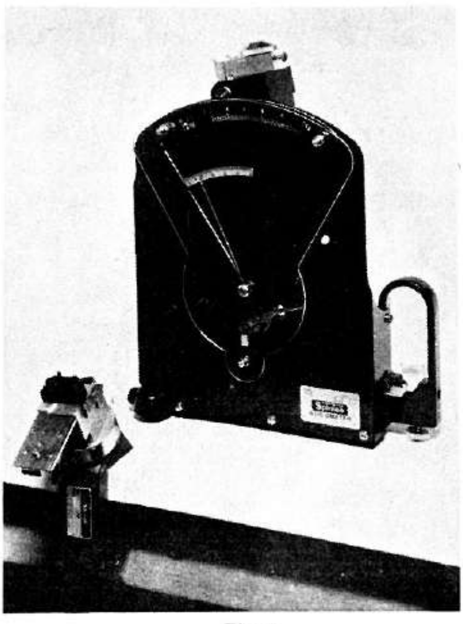

Fig. 5
The Stelometer

considerable value to the spinner. In the last 50 years, many mechanical and semi-automatic instruments for testing the various length parameters have been developed. More than 4000 staple sorters of various types are in world-wide use for internal measurements. The method is admittedly time-consuming, and the results often show greater differences from laboratory to laboratory. They are reproducible within narrow limits and comparable only if the measurements are always made by the same operator on the same instruments. This method is therefore not practicable on an international basis, and staple-sorter values are not useful in cotton contracts. Fig. 6 shows the Johannsen–Zweigle type of staple sorter which is the most widely used model.

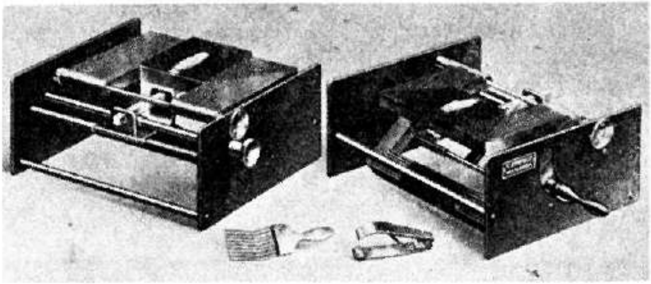

Fig. 6
The Johannsen–Zweigle type of staple sorter, with two separate needle fields

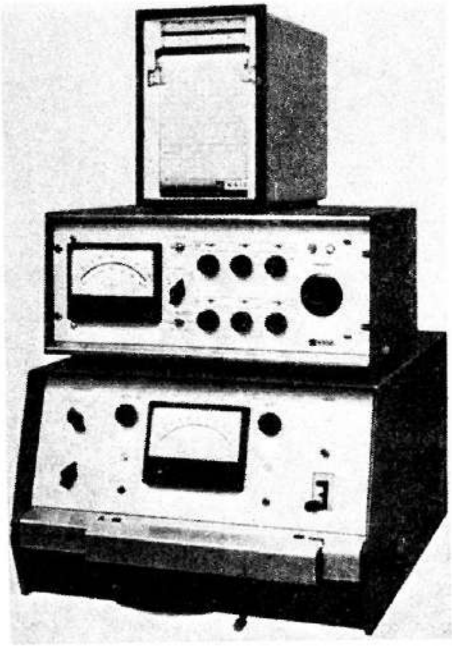

Fig. 7
The Almeter

During the last few years, some interesting electronic length-measuring instruments have been developed. These may be distinguished as those which—like the staple sorter—measure a fibre beard with arrayed ends, for example, the Almeter (Fig. 7) and those in which a fibre beard without arrayed ends is sensed electronically, for example, the Fibrograph (Fig. 8), the Autosampler, and the Motion Control Instrument. the last-mentioned instrument is also inserted in the so-called 'test-line'. In this case, it is not the true lengths of the fibres but the so-called 'span lengths' that are measured.

Fig. 8
The Digital Fibrograph, Model 430

Although electronic instruments carry out measurements particularly rapidly, the values obtained by these have not so far been introduced into cotton contracts. The lengths of cotton fibres are still given in the form of the classer's staple lengths.

This is hardly understandable, since some of the length parameters, e.g., the short-fibre content, the uniformity ratio, and the coefficient of variation from length dispersion, do represent—in addition to the classer's staple length—valuable parameters for the processor. But all the various types of instrument give different length parameters, which in most cases are not highly correlated.

4.5 The Maturity of Cotton

The maturity of a cotton fibre is also a very important parameter. Various methods—microscopical, chemical, and pneumatic—have been developed for the determination of maturity, but so far none of these methods has found world-wide application, and no maturity index has been included in cotton contracts. All these methods give different maturity indices for the same cotton and different relations with the Micronaire value, partly depending on the growth

Table I

Maturity Indices Found by Different Methods on Seven Cottons of Various Growths, All-Having the Same Micronaire Value

	Test Method	Mexico Alta-mira	U.S.A. Mem-phis	U.S.A. El-Paso	Mexico Mexi-cali	U.S.A. Cali-fornia	Guate-mala	Iran
	Micronaire value	4.3	4.3	4.3	4.3	4.3	4.3	4.3
	Causticaire index (18% NaOH)	77	76	77	78	76	77	77
Miscroscopical Methods	18% NaOH Percentage of mature fibres	60	55	60	70	59	60	54
	British Standard method	0.82	0.79	0.80	0.91	0.80	0.81	0.74
	Polarization Percentage of mature fibres	66	53	52	64	66	67	65
	Roehrich method	7.6	7.5	7.2	7.6	7.4	7.8	7.8

(Table I). This means that the maturity indices give additional information to the Micronaire values, but so far nobody knows which of these different maturity indices gives the best information regarding the spinnability, the dyeing behaviour, etc.

In mill laboratories, the maturity test is occasionally carried out according to the Causticaire method (with 18%NaOH) as well as the so-called 'red–green test' (the Goldway, Smith, and Barnett method). These tests, however, supply good comparable values only if they are always performed by the same operator. Between laboratories, there are great differences, which also occur with the microscopical maturity method.

Of interest in this connexion are the air-flow instruments, such as the Maturimetre and the IIC–Shirley fineness–maturity Tester (Fig. 9), in which the resistance to air-flow of the same tuft of cotton, exactly weighed, is measured twice, at two difference compressions. With the help of a mini-computer, the Micronaire value of the cotton, the maturity according to the British and American methods, and the mean fineness expressed as the linear density in mtex are indicated immediately. This method seems to have a great future.

4.6 The Colour of Cotton

The colour of cotton is to-day being evaluated in practice almost exclusively by the classer. There have, of course, been efforts to find a method to determine data expressing the colour of cotton by an electronic device. In the 'test line' in the U.S.A., such a device has been used for many years.

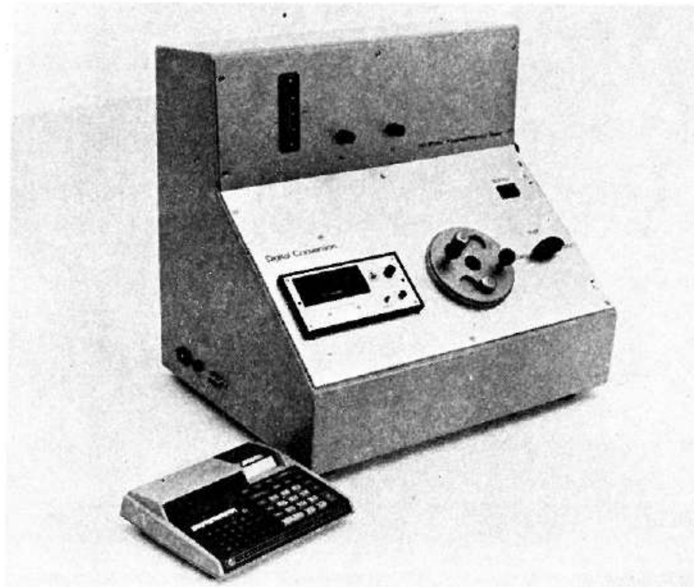

Fig. 9
The IIC–Shirley Fineness Maturity Tester Model 1A, equipped with the Hewlett Packard HP975 calculator

In the U.S.A., the Nickerson–Hunter cotton Colorimeter, which, besides the colour, also indicates the content of extraneous material, has been widely employed for a long time. Even so, it has not been able to replace evaluation by classers. The instrument is, however, giving valuable help in making up the American cotton standards (Universal Standards). Its use has made it possible to establish more uniform standards, especially with regard to colour hues, than could be done previously without this instrument. The Hunter Colorimeter should be of interest to all cotton-producing countries, even if later classing by the dealer or the spinner should be done by the classer without this instrument.

4.7 The Non-lint Content

For the determination of the non-lint content of a cotton, there are available at present several testing instruments of varying types, i.e., the well-known Shirley Analyser, the Non-lint Tester, and the newly developed Trash Selector. None of these has found widespread acceptance in practical operations so far, evaluation continuing to be made by the classer as in the past.

4.8 Neppiness

The tendency to neppiness of a cotton is closely correlated with the fineness, the length, and the maturity of the fibres, but more particularly with the content of immature, i.e., thin-walled, fibres, which are especially susceptible to the formation of neps.

For determining the tendency to neppiness, neps are produced intentionally in a suitable test instrument (Nepotometer, nep-testing machines, or nepcard) or in a normal card, always under extreme strain. The number of the neps produced in this way depends, however, not only on the tendency of the cotton to neppiness but also on other factors. For this reason, the nep test has not found application in practice. It is customary instead to rely upon the Micronaire value of the cotton, which—if due consideration is given to the growth and the spinning machinery—supplies indications of the number of neps to be expected.

An instrument in which one can count the number of neps within a silver or within a top visually is the Nep Tester. This instrument, equipped with another drawing system, is in widespread use for determining the number of neps and the percentage of vegetable matter and coloured fibres in wool tops. It is not possible to count neps within the raw cotton with this instrument. The cotton must first be in the form of a silver.

4.9 Moisture Content

For the determination of the moisture content of raw cotton, the market offers a large number of instruments of different types. At the International Textile Machinery and Accessories Exhibition 1975 in Miland, thirteen firms exhibited over twenty different types of instrument. Basic distinctions between these are instruments in which the cotton specimen is dried by the application of a hot-air stream and instruments working on an electrical basis. The moisutre content is always calculated as a percentage of the dry mass.

The determination of moisture content by drying in a conditioning oven is time-consuming, but this is still considered to be the most reliable method. However, electronic instruments—developed in some cases as portable pocket instruments—indicate the percentage of moisture content instantly. For large and uniformly packaged lots, e.g., cotton bales of approximately equal mass, dimensions, and types of packaging, the forte instrument, which instantly indicates the mass as well as the mean percentage moisture content of the whole bale is used.

Contrary to the situation with cotton yarn, there is as yet no internationally accepted percentage moisture content for raw cotton. In some places, too high a moisture content in a bale is expressed in kg and not as a percentage. This appraisal is made by experts very rapidly.

4.10 Other Properties of Cotton

Other properties of cotton are: the wax content (including the chemical composition of the wax surrounding the fibres), which is of decisive importance for the spinnability of the cotton, and stickiness, which may be caused, for example, by the so-called honeydew infestation or other causes. Whereas all these properties can be expressed in figures, such determinations have not so far been introduced in practice because they are either too complicated or time-consuming (or both), because they do not provide sufficiently reproducible values in the absence of international standard specifications, or because experience in this field is not yet wide enough.

5. THE ACCURACY OF THE TEST VALUES

In connexion with the modern cotton test, the question arises: how accurate is a test value of a parameter measured in *one* laboratory on *one* sample by *one* operator on *one* instrument? Is it reproducible within known and narrow limits and reproducible, moreover, not only in the same laboratory but also in any other well-managed laboratory throughout the world?

This means that, if in the laboratory of a cotton farmer a Micronaire value of 4.0 is measured on a homogeneous cotton sample, a control test on the *same* sample in a mill laboratory or in any other laboratory should also show a Micronaire value of 4.0, or a value that will not deviate too much from it in either direction.

If different values are found in these two laboratories, then it often cannot be decided which of the two laboratories has measured better or more correctly. This can, however, be determined if the same cotton sample were also tested by many other laboratories using the same standard test specifications. It may be stated that the average value of all laboratories will correspond to the true test value of the cotton sample, or come very near to it, if a sufficiently large number of laboratories have participated in this 'round test'.

The accuracy of a test method, and consequently the accuracy of the values measured by this method, cannot be determined by one operator alone. The operator cannot say either whether the average value measured by him on one cotton sample (e.g., the mean Pressley value derived from several tests) is equal to the 'true' average value of this specimen or how large the deviation is. The operator would not be able to indicate this, even if he could carry out innumerable tests on the same sample, because each operator has his own 'level' at the time of testing.

An operator normally does not know his 'level', i.e., he does not know the confidence limits of his values with regard to the true values of the tested sample. But he can recognize it and estimate the accuracy of his test values if he regularly participates in what are known as 'round tests' together with many other laboratories.

The accuracy of test values differs with the various methods, from parameter to parameter, and also depends on the growth.

6. INTERNATIONAL ROUND TESTS

The aim of all round tests is:

to give the participating laboratories the opportunity to compare their own test values with the test values of other laboratories and the average

for all laboratories (i.e., control and harmonization);
to know the differences (i.e., dispersion) of the test values between laboratories under everyday testing conditions;
to determine the causes of such differences;
to calculate the accuracy of the test values and express it as confidence limits (also including the dispersion of the test values between laboratories); and
to give help in the calculation of reasonable control limits.

At the present time, there are two round tests of international significance, which are described below.

Since 1957, the International Calibration Cotton Standards Check Test has been carried out twice a year with two samples of various cottons. This round test is organized by the U.S.D.A. on behalf of the I.C.C.St.C. Under this programme, the Micronaire values and the bundle tenacity at zero gauge length of these two samples are determined. At present, 360 laboratories participate in the Micronaire test and about 250 laboratories in the Pressley test.

The Bremer Rundtest has been carried out every month since its inception in 1956. In each round test, the Micronaire value, the bundle tenacity at zero gauge length and the fibre length (measured with various types of instrument, i.e., Fibrographs, staple sorters, and Almeters) are determined with one well-homogenized cotton of previously unknown properties. Since July, 1978, the maturity (determined by various methods) as well as the bundle tenacity at 3.2 mm (1/8 in.), determined by the Stelometer, and the fibre fineness, determined by double-pressure air-flow instruments, have been added. Altogether, sixteen test methods are now included.

In this way, the participants (more than 110 laboratories from 25 countries) are in a position to compare their own test values twelve times a year with those of other laboratories and to recognize and eliminate mistakes in testing very quickly.

7. INTERNATIONAL STANDARD SPECIFICATIONS

It is very important that, for test methods that are used on a world-wide scale or become of international importance, there should be available international (i.e., ISO) specifications. Official tests should only be carried out to these specifications.

So far, there exist only two such ISO specifications for testing cotton:

Determination of Micronaire Values (ISO 2403);
Flat Bundle Strength Test (Pressley Test) (ISO 3060).

The following ISO specifications are under preparation:

Determination of Fibre Length and Uniformity Index (Span Lengths) (DP 4913)

Maturity of Cotton—Microscopical Classification of Fibres Swollen in Sodium Hydroxide Solution (DP 4912)
Length and Length Distribution of Cotton Fibres (Array Method) (Doc. 38/6/1–N 93)

Besides these ISO specifications, there also exist some national standard specifications for various cotton-testing methods. Of primary importance are the American ASTM Standards, which are published in the 'Annual Book of ASTM Standards', Part 33, some of which are likely to become ISO specifications' later, either in their present form or in a modified form.

8. INTERNATIONAL CALIBRATION COTTONS

In the modern cotton test, it has become particularly clear that even a uniform adjustment of the test instrument, a uniform method of making measurements according to standard specifications, and a uniform evaluation of test results do not necessarily supply a guarantee for reproducible values. Rather has it been proved that an end control after the adjustment of the instrument with cotton of known test values is meaningful and necessary. Since cotton is a product traded on a world-wide basis, uniform calibration cottons should also be used throughout the world in such end controls.

International calibration cottons (ICCs) of this type—ten different cottons ranging in Micronaire values from 2.6 to 7.5—are produced and distributed by the U.S. Department of Agriculture, Washington, by order of the so-called International Calibration Cotton Standards Committee (= I.C.C.St.C). They are at present available only for Micronaire readings, and fibre tenacity (Pressley flat-bundle test with zero gauge length). In the near future, such ICCs will also be available for 2.5% and 50% span-length measurements.

In addition to these international standards, the U.S.D.A. issues national U.S. Cotton Standards for the following methods:

bundle strength (in gf/tex) with breaking elongation at $\frac{1}{8}$ – in. (3.2-mm) gauge length;
length and length distribution of cotton fibres (array method);
length measurement with the Fibrograph; and
Causticaire maturity and Causticaire fineness.

As long as there are no International Calibration Cottons available for use with these test methods, it is advisable to make use of the U.S. Cotton Standards.

9. CONTROL LIMITS

In international cotton trade, the following question (among others) is of great importance: what differences may occur in the Micronaire and Pressley values between two laboratories when in each laboratory a different sample from the same bale is measured? This is always the case if, for example, the first test is made in the country of origin and the second (the control test) in the country of purchase on another, newly drawn sample. This question can be answered only if the following details are known:

> the dispersion of the test results, e.g., the Micronaire values, from sample to sample within a bale;
> the number of samples drawn from different sides of a bale;
> other influences at the time of testing (instrument, operator, i.e., sources of errors of measurement); and
> the weight of the samples.

All these factors must be considered if control limits are settled for each parameter. These are the allowable deviation of the retest values (e.g., those obtained in a laboratory of the country of purchase) from test values agreed upon in a cotton contract.

For the control test in the country of purchase, there normally will be drawn only one sample from one part of the high-density pressed bale. Extensive research by the laboratory of the Bremen Cotton Exchange has shown that the dispersion of Micronaire values within a bale is not the same for all growths but is of varying size from one growth to another.

Other research carried out in the same laboratory has shown that the Pressley values within a bale very considerably less than Micronaire values but that the error of measurement is much larger with this method than with the Micronaire test. For this reason, Pressley measurements should always be carried out in each laboratory by two or three operators—each of them using a different Pressley tester and different clamps—and the mean value should be calculated and given in the certificate.

The example in Tables II and III show the influence of the number of operators in determining the bundle tenacity on the Pressley tester at zero gauge length. The data show how much the 'true' mean Pressley value of a cotton sample may deviate from the mean Pressley value of six measurements carried out on the same sample by one, two, or three well-trained operators (confidence limits at 95% probability).

The maximum differences (A) that may occur between two laboratories are:

> A_1 if in both laboratories the same single sample of a bale is tested;
> A_2 if in both laboratories another single sample of the same bale is tested.

In most cases, the deviations and the maximum differences will, of course, be smaller than those indicated in the above example (sometimes they may be zero) but in five out of 100 cases they will be even larger.

In fact, in practice nobody knows the true mean value—e.g., the mean Pressley value—of cotton within a bale. At least, one should know what the limits within this mean value will be if one or two samples out of the bale are tested by one or two operators in one laboratory. These limits are different from parameter to parameter and depend on several factors.

Table II

Operator	Number of Measurements by Each Operator	Confidence Limits (%)
1	6	±4.1
2	3	±3.0
3	2	±2.4

Table III

Operator	Number of Measurements by Each Operator	Maximum Differences (%)	
		A_1	A_2
1	6	5.8	7.7
2	3	4.3	5.3
3	2	3.4	4.4

10. SUMMARY

It is not the aim of the spinning test and of the modern cotton test (i.e., the rapid test) to replace the classing system, but rather the objective is to supplement it in a meaningful way by ascertaining additional properties of the cotton. The tests are meant to give the seller and the processor of cotton valuable indications for smooth processing and an optimal input of the cotton in the light of the desired end-product to be manufactured from it. The tests must not become a goal in themselves, and they should not serve as a basis for claims because of market fluctuations. Testing should be done not more than is necessary but only as much as is necessary.

The measurements should be performed conscientiously and by a well-trained operator according to international standard specifications. One should always bear in mind that it is better not to indicate any test values than to give inaccurate or even faulty ones, which may cause the processor to draw erroneous conclusions and lead to an inadequate input of the cotton.

It is also important that producers, dealers, and processors should have the same knowledge about the spinning test and the cotton test so as to be able to interpret the test values correctly and the deviations in a control test from the values of earlier measurements or from the guaranteed test value.

We are still in the early stages of the development of the modern cotton test, and it is essential that this development be carried on with drive, but also with caution, in the right direction.

At the last International Cotton Test Meeting, in Bremen, West Germany, in January, 1978, Mr. Batorffy from Brazil mentioned in his paper 'The Meaning of the Cotton Test for Cotton-producing Countries' that troubles are arising, especially for the cotton producing countries, from the fact that various test methods are used for the same cotton-fibre properties and that correlations are not available between the test values obtained by these methods. He proposed to establish an International Technical Committee in which all problems relating to the testing and processing of cotton would be discussed on an international basis, as has been done for more than 20 years for wool side by the Technical Committee of the International Wool Textile Organization (IWTO).

The present author supports this proposal because there certainly seem to be difference tendencies in developing and using cotton test methods (in U.S.A., in Europe, in other countries of the wester world, and in the socialist countries). In this committee, which could meet once a year or at two-yearly intervals, all problems could be discussed and the most useful methods and instruments for world-wide practical application could be determined. This would be in the interests of cotton growers and of dealers in and processors of cotton—and last but not least in the interest of King Cotton.

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11—THE TRANSVERSE DIMENSIONS AND MECHANICAL PROPERTIES OF COTTON FIBRES

By K. E. DUCKETT and B. C. GOSWAMI

For samples of nineteen cotton cultivars examined, fibre tenacity is shown to be correlated negatively with the degree of convolution induced into the fibre on initial drying. Furthermore, the degree of convolution and consequently fibre tenacity can be explained largely in terms of two cross-sectional parameters, perimeter and wall thickness. Specific ratios of perimeter to wall thickness establish minimum tenacity levels for fibres of constant perimeter. It is observed that any deviations from the normally accepted relation between fibre tenacity and the degree of convolution can be explained in terms of changes in the ratio of fibre perimeter to wall thickness. The results of these findings support the general view whereby fine fibres constitute higher-tenacity fibres as well as the apparently anomalous behaviour in which very coarse fibres are occasionally observed to be unusually strong.

1. INTRODUCTION

The intrinsic strength of an idealized natural cotton fibre has been reported by DeLuca[1] as 151.7 gf/tex, i.e., 148.7 cN/tex. A more recent examination of intrinsic fibre strength by Neelakantan[2] supports this. In reality, cotton-fibre tenacities do not approach these idealized levels but fall to considerably lower values. These lower strength levels vary widely, depending upon the cultivar tested and the gauge length of the specimen.

Reduced tensile strengths and differences between cultivars are attributed to a variety of factors. These include cellulose content and crystallinity, crystallite orientation, and the spiral nature of the fibrillar stucture. Differences in these parameters appear to be relatively small for commercial cottons[2–4], and attention is increasingly being directed to other physical properties and mechanisms for interpreting tensile behaviour. These physical properties include structural changes in the vicinity of points of fibrillar reversal[5,6] and morphological features, such as the convolution angle[7,8].

In addition to emphasizing the importance of the collapsed state of the natural fibre on fibre strength, the results presented here suggest the existence of a relation between the degree of convolution and the cross-sectional dimensions of the fibre. A mechanism for interpreting the unexpectedly high strengths found in some very coarse cottons[9] is proposed.

2. EXPERIMENTAL

Samples of nineteen cotton cultivars representing both *Gossypium hirsutum* L. and *G. barbadense* L. species were chosen for this study because a great deal of information about their physical properties had been compiled through the joint efforts of several laboratories[10]. The tensile properties examined included fibre tenacity and elongation as measured by the Stelometer[11]. The perimeter, linear density, and cell-wall thickness were calculated from specific-surface-area and immaturity-ratio measurements obtained from the Arealometer[12].

The degree of fibre convolution was determined from azimuthal-intensity scans of reflected light from the surfaces of parallel arrays of fibres[13]. Experimentally, a monochromatic beam of light (0.6328 μm) from a helium–neon laser is directed perpendicular to the plane of the fibre array. A 1-mm^2 silicon semi-conducting photodetector monitors the back-scattered light in a direction 30° from the incident beam. The detector revolves at a constant rate about the optical axis, and the intensity of the reflected light is chart-recorded.

The parameter designated the optical angle, ϕ_{50}, arises from measuring the angular half-width of each azimuthal arc at half-maximum intensity, zero reflected light being used as the base reference. Five specimens were tested on each of the nineteen cultivars. The optical angles were then averaged within each group of five to give a single value representing the degree of fibre convolution.

3. RESULTS AND DISCUSSION

Data on this series of cottons are presented in Table I. Two tenacities are listed. These, T_0 and T_1, correspond to tenacities obtained from specimens tested at zero and 1/8-in. (3.2-mm) nominal gauge lengths, respectively. Both are in units of centinewtons per tex. The elongation, E_1, is that which corresponds to the 1/8-in. (3.2-mm-gauge) strength test.

The range of T_0 across cultivars is between 30.38 and 51.16 cN/tex. On the other hand, T_1 ranges between 14.80 and 29.30 cN/tex. The decrease in tenacity level with an increase in gauge length is substantial, as is the tenacity variation between cultivars for each test gauge length. The over-all reduction in tenacity level with increasing test gauge length is generally attributed to an axial 'weak-link' distribution[14]. The reduction between cultivars at a specific test length is attributed to fundamental differences in the samples. These differences can be discussed in terms of the macroscopic fibre geometry, as will be shown.

A linear-regression analysis of T_1 on T_0 produces a correlation coefficient of $r = 0.88$. For the 17 degrees of freedom, a coefficient $r = \pm 0.575$ establishes the 99% probability level for interaction between two parameters. The relation between T_0 and T_1 is therefore very real, which suggests that the mechanism contributing to the zero gauge level of strength substantially influences the drop in strength with increased gauge length.

A regression analysis between T_1 and E_1 is less enlightening. A correlation coefficient of $r = -0.440$ is obtained. This is slightly less than that required for a 95% probability lever where $r = \pm 0.456$. Nevertheless, the negative sign indicates that the strongest cottons tend towards lower breaking extensions. This general trend can also be partly explained in terms of the degree of convolution in the fibre.

Table I

Tensile and Geometrical Properties of Nineteen Cottons

Cultivar	Species	T_0 (cN/tex)	T_1 (cN/tex)	E_1 %	Perimeter (μm)	Wall Thickness (μm)	Linear Density (tex)	Optical Angle (deg)
DeRidder Red	*G. hirsutum* L.	32.14	14.80	7.6	59	3.7	0.26	36.5
CR–4–C	*G. hirsutum* L.	43.71	18.91	6.0	49	2.9	0.18	28.1
Lengupa	*G. barbadense* L.	35.18	20.38	10.2	57	3.4	0.24	33.5
NR–AHA–C	*G. hirsutum* L.	45.28	26.07	7.5	51	3.7	0.22	27.0
Paymaster	*G. hirsutum* L.	32.73	17.64	9.8	53	2.4	0.17	38.4
SL (SLS)	*G. hirsutum* L.	30.38	15.78	10.3	53	2.7	0.18	35.4
Lankart	*G. hirsutum* L.	30.78	16.56	9.6	52	2.7	0.18	35.4
A4–42–176	*G. hirsutum* L.	47.53	26.46	6.9	50	2.5	0.16	29.6
Bobshaw	*G. hirsutum* L.	39.40	19.99	7.1	55	3.0	0.21	35.7
Thef 96	*G. hirsutum* L.	48.80	23.91	6.0	44	2.3	0.13	27.8
A–4–42–176	*G. hirsutum* L.	39.59	21.66	7.4	52	2.4	0.16	31.4
HA–46–124	*G. hirsutum* L.	51.16	29.30	6.8	47	2.8	0.17	25.1
DPL–15	*G. hirsutum* L.	33.91	18.82	8.6	52	2.6	0.17	30.1
Peruvian Tanguis	*G. barbadense* L.	34.97	19.40	8.7	51	2.9	0.19	33.3
Acala 1517C	*G. hirsutum* L.	38.22	20.68	8.0	50	2.5	0.16	31.2
Coastland RNXET	*G. barbadense* L.	40.96	24.21	8.4	51	2.9	0.19	28.9
Pima S–1	*G. barbadense* L.	44.79	28.22	8.2	43	2.6	0.14	24.6
Amsak	*G. barbadense* L.	45.28	28.03	7.9	47	2.6	0.15	24.4
Old Pima	*G. barbadense* L.	37.83	23.32	8.4	48	2.3	0.14	26.5

Fibre geometry is described here by three parameters, all of which are listed in Table I. Two of these—the perimeter, p, and wall thickness, t—describe the cross-sectional dimensions of the fibre. The perimeter and wall thickness are correlated, with a coefficient $r = 0.584$ establishing certainty in the interaction at the 99% probability level. The correlation is positive, which implies that the cell-wall thickness of a fibre will generally increase with increasing perimeter. As always, there are important exceptions to such a generalization.

The third physical and geometrical property listed is the average linear density, ρ, of the fibre. The geometrical interpretation is one representing the cross-sectional area, when it is assumed that the volume density of the secondary wall in the natural raw-cotton fibre is a constant.

Linear density is sometimes used as a descriptive term for fineness, and, as is often observed, tenacity and fibre fineness in this context are related. A linear-regression analysis for T_1 versus ρ gives a correlation coefficient $r = -0.450$. This is not particularly high, although the 95% probability level is almost reached. The negative coefficient corroborates the general consensus that fine cottons, with their low linear density, are strong cottons and that coarse cottons, with their high linear density, are weaker cottons. But, as already noted, there are important exceptions, which can be explained in terms of cross-sectional geometry.

The last column in Table I lists the optical angles, ϕ_{50}. These constitute an experimental measure of the average convolution angle of the particular cultivars. For example, the data demonstrate that DeRidder Red and Paymaster are highly convoluted cultivars. On the other hand, Pima S–1 and Amsak are relatively free of convolutions. It should be mentioned that the latter two are fine cottons and low in linear density. For reference, the measured optical angle of a cylindrical polyester fibre free of convolutions is 7.5°.

With these preliminary remarks made on the data in Table I, comments and discussion on the interrelationships between fibre geometry and tensile properties can proceed.

The 1/8-in.-gauge (3.2-mm-gauge) tenacity is plotted against the degree of convolution in Fig. 1. Linear-regression analysis shows the correlation coefficient to be -0.86. This is highly significant. The correlation is negative, which denotes weakness in fibres having a high natural twist or convolution, provided that all other influencing factors remain constant.

A geometrical contribution to the induced twist is observed between the fibre perimeter and the optical angle, ϕ_{50} (Fig. 2). Although the correlation between the two parameters is slightly less than that obtained for the tenacity and optical angle, the relationship is very real. The correlation is positive, which implies that the degree of convolution in the fibre is directly proportional to the fibre perimeter. In view of the negative correlation between the fibre strength and optical angle, low-perimeter fibres will normally be the stronger fibres.

A number, signifying the wall thickness, is given next to each point in Fig. 2. The values range from 2.3 to 3.7 μm. A casual observation of the distribution of wall-thickness values shows the lower values to be roughly distributed below the

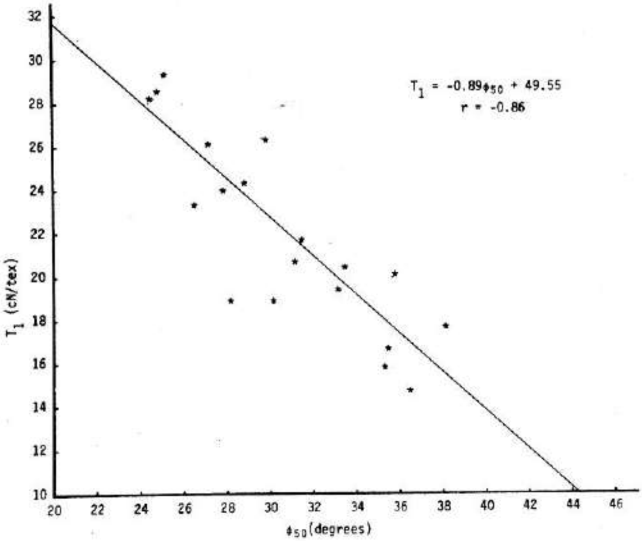

Fig. 1

Plotted data showing the relation between 1/8-in. gauge (3.2-mm-gauge) flat-bundle tenacity, T_1, and the degree of fibre convolution described through the use of the optical angle, ϕ_{50}

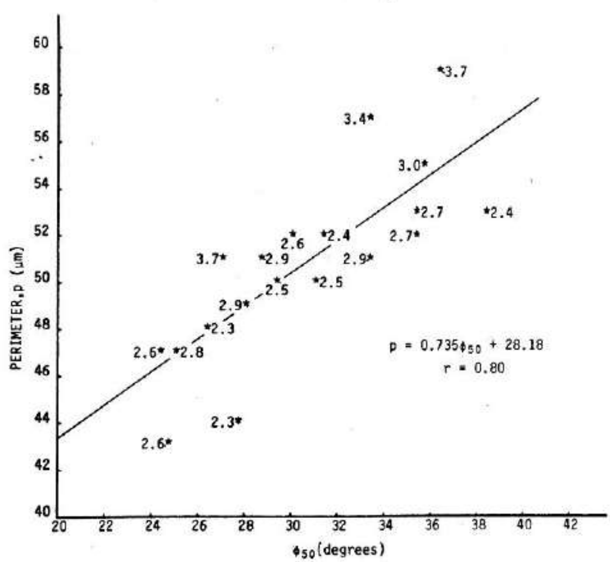

Fig. 2

Plotted data showing the relation between the fibre perimeter and the optical angle, ϕ_{50}; numbers next to each data point denote wall thicknesses perimeter—optical—angle regression line, whereas the thicker fibres generally lie above it. This distribution suggests that both the perimeter and the wall thickness may influence the level of convolution induced into the fibre. Indeed, a stepwise regression analysis that includes both the perimeter and the wall thickness as independent variables does raise the correlation from $r\phi_{50,p} = 0.80$ to $R\phi_{50(p,t)} = 0.87$. At this level, the fibre tenacity may be interpreted largely through these two cross-section parameters.

To understand this, as well as the anomalous strength levels of some coarse cottons, one may consider Fig. 3, in which the fibre-wall thickness is plotted against the optical angle. The correlation between the two parameters is extremely low, i.e., $r = 0.20$. However, if one observes the fibre perimeters, which are given next to the corresponding data pairs, it will be noted that a pattern emerges as a result of the high level of correlation between the perimeter and convolution demonstrated in Fig. 2.

Contours of constant perimeter can be drawn through the data, restricted to the following boundary limits. It will be recalled that optical angles of $\phi_{50} = 75°$ are obtained on round, cyclindrical fibres. This angle, for cotton fibres, should occur both for fibres with zero wall thickness and for fibres in which there is no lumen, i.e., in which the wall thickness equals the uncollapsed radius of the fibre. Now, only one other point, lying in the vicinity of the distribution of data in Fig. 3, is required to sketch in a non-linear contour of constant perimeter.

The broad assumption is made that convolutions are largely maximized for this group of cottons. Consequently, contours of constant perimeter can be drawn through the data in the figure. This is accomplished as follows. The lower five perimeters average very nearly 45 μm. The geometrical centre of these five data points is marked with a cross. This point designates the maximum optical angle for fibres having a perimeter of 45 μm. A smooth curve is drawn through this point and the two extremes where $\phi_{50} = 7.5°$. The result is shown in Fig. 3.

The same procedure is applied to five data points in the centre of the distribution, which have an average perimeter near 50 μm, and again to five data points whose perimeters average approximately 55 μm. Smooth contour curves for these two perimeters are also illustrated in the figure. It should be noted that all three contours converge to $\phi_{50} = 7.5°$ for wall thicknesses approaching zero. At the other extreme, each contour approaches an optical angle, ϕ_{50}, equal to 7.5° for wall thicknesses corresponding to their respective uncollapsed radii. Thus the lines in the upper portion of the figure are substantially separated.

It should now be observed that the maximum optical angles are subject not only to the perimeter of the fibre but also to the wall thickness as previously indicated. For example, the extent of convolutions in fibres having a perimeter of 45 μm will be a maximum when the wall thickness is approximately 2.5 μm. Fibres of perimeter 50 and 55 μm will similarily maximize the extent of their convoluted geometry when the wall thicknesses are near 2.6 and 2.7 μm, respectively.

Any one of these three curves can represent a series of cottons having identical perimeters. Cottons can vary from one to another in wall thickness and

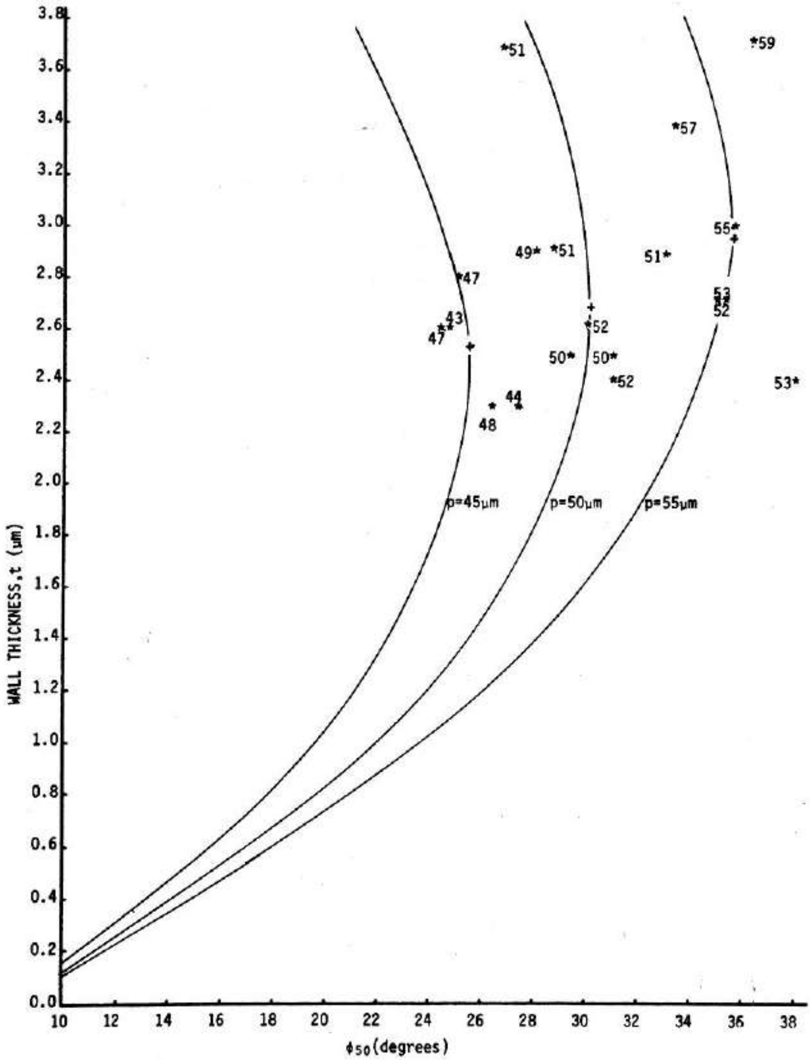

Fig. 3

Cotton-fibre wall thickness plotted against the optical angle, ϕ_{50}. Each of the three curves represents the expected relation between wall thickness and the optical angle for fibres having constant perimeters as designated. The points of maximum optical angle for each curve of constant perimeter are denoted by a cross

therefore lie at separate locations on the same curve of constant perimeter. All the data shown here lie near the broad peaks. The effect on tenacity due to differences in wall thickness is therefore very limited. However, the contours do provide a generalized interpretation of the contribution of perimeter and wall thickness to the level of convolution.

Initially, the cell wall of a cotton fibre contains considerable water within and between the layered structure. The loss of the molecules of water on first drying initiates a radial and azimuthal contraction. Because of the fibrillar helical geometry, dehydration forms a collapsed, ribbon-like, structure. The extent of the convolution is determined by a balance between the resistance of the cell wall to deform and the sum total of the inter-molecular forces tending to draw the fibrils together.

It appears that, of all the wall-thickness possibilities, there will be only one that, for a fixed perimeter, will produce a maximum degree of convolution. Wall thicknesses greater than this value contribute more to the resistance of the wall to be deformed than to the increase in molecular forces producing readjustment of fibrils. As a consequence, the convolution angle decreases as the wall thickness increases. Because tenacity is highly influenced by convolution, very coarse cottons having low convolution could be expected to show high tenacity levels, as are, in fact, observed in some cottons[9].

On other comment relative to the contribution of perimeter and wall thickness to the convoluted geometry is now made. The ratios of perimeter to wall thickness for each of the three previously specified conditions are, respectively, 18.0, 19.2, and 20.4. These values are only approximate, but they jointly suggest that the maximum level of convolution in a fibre will occur when the perimeter of the cotton fibre is greater than its wall thickness by a factor of roughly 19.

A few remarks concerning the decrease in tenacity with increasing gauge length are now appropriate. Neelakantan[4] has suggested that fibre fineness alone may account for this decrease. The difference $T_0 - T_1$ were examined from the standpoint of the level of convolution, and the results are shown in Fig. 4, where

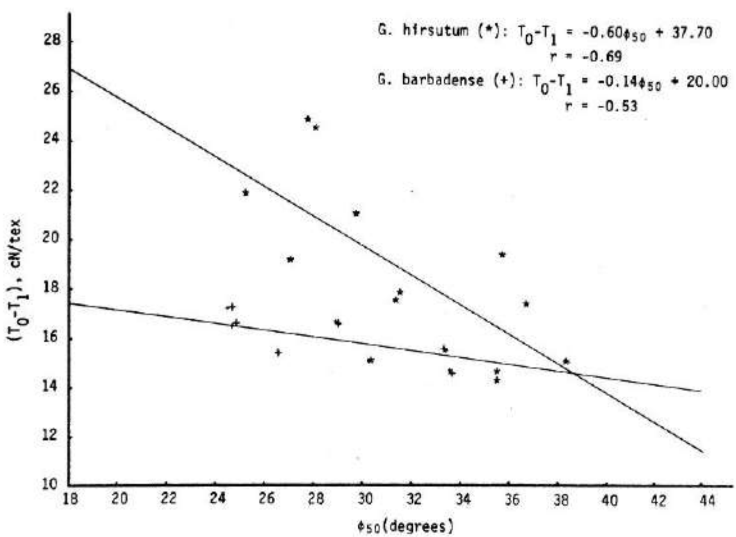

Fig. 4

The loss in strength with increased gauge length plotted against the optical angle

*Cultivars from species *G. hirsutum* L.

+Cultivars from species *G. barbadense* L.

separate symbols distinguish the two species. When all nineteen cultivars are grouped together, no clear relationship is observed. The correlation coefficient, $r = -0.402$, is below that required for a 95% probability level.

When the specimens are analysed separately however, the negative correlation between $(T_0 - T_1)$ and ϕ_{50} is enhanced. The two species converge at large optical angles but differ greatly at low angles. The *G. barbadense* cultivars show a much smaller loss in strength with optical angle than do the cultivars of *G. hirsutum*. This probably results from the fact that the T_0 values of the *G. barbadense* samples in this group of nineteen cottons lie at slightly lower levels than those making up the *G. hirsutum* samples. A similar species separation is not observed in the T_1 data.

The fact that $(T_0 - T_1)$ is negatively correlated with the optical angle is rather puzzling. This implies that T_0 decreases as ϕ_{50} increases at a greater rate than does T_1. It is well known that zero nominal gauge length is not a true gauge length[15]. This finite spacing at zero nominal gauge length, although small, is apparently sufficient to initiate the major effect of convolution on the breaking-load level. Otherwise, one could expect the rate of decrease in T_0 with increasing optical angle to be less than that of T_1.

Finally, the effect of convolution on the longation of tensile-loaded samples is demonstrated. Fig. 5 illustrates this. Although the effect is significant only at the 95% level, fibres with large convolution angles do tend towards greater elongations at break. A fibre with a high level of convolution can be interpreted as fibre with an effective length greater, in direct proportion to its convolution, than the nominal gauge length. Tensile loading reflects this additional effective length as a strain, producing the increased elongation. This same mechanism may, in part, explain why weak cottons are generally prone to have greater elongations than stronger cottons. This interpretation deserves a closer examination.

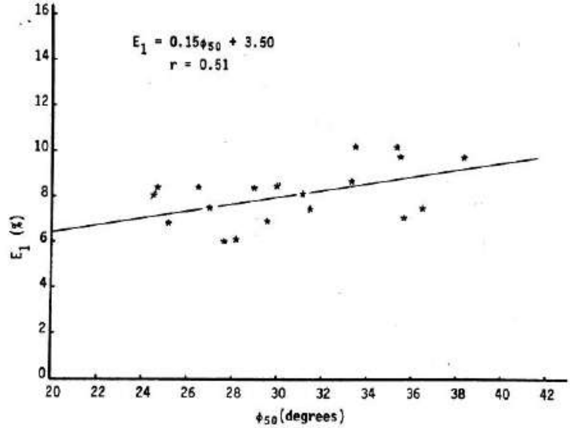

Fig. 5
The elongations at break (E_1) of Flat-bundle specimens of 1/8-in. (3.2-mm) nominal gauge length plotted against the optical angle

4. CONCLUSIONS

The degree of convolution of cottons is negatively correlated with their tenacity and positively correlated with their elongation at break. The contribution of the twisted nature of the fibre to the loss in strength between zero and 1/8-in. (3.2-mm) nominal gauge lengths, however, is not clear. The experimentally observed elastic modulus of the fibre under tensile stress does appear, however, to be closely related to the level of convolution.

The level of convolution is determined largely by the perimeter and cell-wall thickness of the fibre. Maximum convolution probably occurs when the ratio of the perimeter to the wall thickness is near 19. Deviation from this ratio explains the unexpectedly high strengths in some very coarse cottons, as well as the expected high strengths in fine cottons.

ACKNOWLEDGEMENTS

The authors appreciate the valuable comments and suggestions offered by R. S. Krowicki, Reba Lawson, and H. H.Ramey.

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12—THE IMPACT OF MAN-MADE FIBRES ON COTTON TEXTILES

By J. G. Parikh

The dominance of cotton in the world of textiles started to decline with the advent of man-made fibres. In 1940, cotton production was seven times that of man-made fibres, and within two decades cotton production was only three times that of man-made fibres. In the following decade, the production of man-made fibres had increased to three-quarters of the total production of cotton. Thus the inter-fibre competition between cotton and man-made fibres has become intense.

The demand for textiles in India has continued to increase with the growing population and the economic development of the country. The production of cotton in India has remained more or less stagnant for many years. The requirements of increasing textile production, even with the low per-capita consumption, have had to be met by man-made fibres.

Of late, the significance and utility of man-made fibres in textiles have been realized, and this has led to the production of different types and blends of textiles, in which man-made fibres have been used in increasing proportions. Blended textiles have been gaining popularity and consumer acceptance in India. The cotton textile industry is emerging as a multi-fibre industry. Increasing use is being made of man-made fibres in combination with cotton for the production of textiles. The impact of man-made fibres on cotton textiles is such that the production of 100% cotton textiles is being progressively reduced.

The impact of man-made fibres is being felt in India and the developing countries, though not to the extent that it is in developed countries. In India, it has been due to the low consumption of textiles and the division of the textile industry into various sectors. Furthermore India is a cotton-growing country.

The man-made fibres have emerged as the fibres of the future. The varying degree of impact that is being felt in the developed and developing countries is the outcome of the unplanned exploitation of these fibres in the developing countries. The importance that man-made fibres have achieved to-day calls for expert selection, advice, and planning for their over-all growth in developing countries in the interests of mankind.

1. INTRODUCTION

The discovery of man-made fibres is one of the most outstanding achievements of man brought about by his ingenuity in the field of science and technology. The introduction of man-made fibres in the early twentieth century has enriched the resources of textiles, not only by providing substitutes to natural fibres but also by opening new avenues for textiles.

The birth of man-made fibres has been a turning point in the history of textiles. Its induction in the textile world ushered in a new era, revolutionizing the textile scene in terms of utility, versatility, and output.

The developed countries, where these fibres emerged, realized their importance, and massive efforts were made to enlarge their scope and use. In these countries, research and development are being continued to evolve new fibres, as well as to modify the existing ones.

Consciousness is dawning in the developing countries with regard to the importance and utility of man-made fibres. It has now been realized that man-made fibres have a much greater rôle to play in the developing countries looking to the increasing population and prevailing socio-economic situation.

2. THE WORLD POSITION OF MAN-MADE FIBRES

The advent of man-made fibres dislodged cotton from its prestigeous position as the King of Fibres. The shortage of natural fibres and the inherent qualities and aesthetic appeal of man-made fibres have brought them to an unassailable position in a short period.

Before the commencement of production of rayon, the first man-made fibre, cotton production in 1890 was 2715 million kg out of a total fibre production of 3454 million kg. By 1900, cotton production had risen by 16.7%, and man-made-fibre production was only 1.0 million kg in a total fibre production of 3920 million kg. An appreciable fivefold increase in the production of man-made fibres occurred between 1930 and 1940 when there was a 29% increase in total fibre production and a 17.6% increase in cotton production (Table I). This was the period when the increase in man-made-fibre production was highest, mainly because inroads had been made by rayon continuous-filament yarns in hosiery and by staple-fibre yarns in spun and blended fabrics. By 1940, rayon staple-fibre production was on a par with that of rayon continuous-filament yarns. The acceptance of staple fibres compared with filaments was reflected in their steady rate of growth during the next three decades. By 1972, staple-fibre production almost doubled that of filaments. In the 1970s, however, the growth rate of staple fibres remained low.

The production of synthetic fibres in filament form commenced in the 1940s, and by the 1950s the growth of synthetic-fibre production occurred in both continuous-filament and staple-fibre forms. From 1970 onwards, the production of continuous filaments was almost equal to that of staple fibres, and in the next six years the total synthetic-fibre production had not only doubled but was also way ahead of that of the cellulosic man-made fibres, which demonstrated the increased acceptance of synthetic fibres for textile use. In 1976, man-made-fibre production amounted to 46% and cotton production to 49% of total fibre production, with intense competition dating from 1970.

3. DEVELOPMENTS IN INDIA

Cotton fibre has been used for textile production in India from time immemorial. Cotton fabrics such as muslins and calicos made India famous as far back as the sixteenth century. The production of cotton fabrics in India at present is 7945 million metres, compared with 850 million metres of man-made-fibre fabrics and 299 million metres of blended-fibre textiles. Cotton still remains

Table I

World Production of Textile Fibres*

Year	Cotton	Wool	Silk	Cellulosic			Non-cellulosic			Total Man-made Fibres	Grand Total
				Filament	Staple Fibre	Total	Filament	Staple Fibre	Total		
1890	2715	727	12								3454
1900	3170	732	17	1		1				1	3920
1910	4318	805	23	8		8				8	5154
1920	4477	809	21	19		19				19	5326
1925	6174	914	47	85		85				85	7220
1930	5939	1005	59	205	3	208				208	7211
1935	6068	982	55	425	65	490				490	7595
1940	6985	1136	59	543	586	1129			5	1134	9314
1945	4677	1036	11	402	200	602			16	618	6342
1950	6661	1059	19	876	739	1615	55	15	70	1685	9424
1955	9512	1268	29	1045	1239	2284	184	83	267	2551	13360
1960	10129	1469	31	1133	1472	2605	418	286	704	3309	14938
1965	11629	1495	33	1377	1969	3346	1128	927	2055	5401	18558
1970	11782	1602	41	1393	2043	3436	2363	2337	4700	8136	21561
1971	13007	1566	41	1400	2047	3447	2861	2744	5605	9052	23666
1972	13665	1455	42	1342	2217	3559	3210	3165	6375	9934	25096
1973	13710	1425	44	1362	2299	3661	3829	3809	7638	11299	26478
1974	14020	1502	45	1302	2233	3535	3781	3704	7485	11020	26587
1975	11798	1487	48	1136	1824	2960	3765	3590	7355	10315	23648
1976	12502	1209	49	1190	2022	3212	4130	4468	8598	11810	25570

*All figures are in millions of kilograms.

the fibre consumed to the greatest extent for the production of textile in India. However, cotton in India, as elsewhere, is facing competition from man-made fibres. Man-made-fibre fabrics were introduced into India in the 1930s, when the growing popularity of rayon fabrics in Japan, the U.S.A., and Europe led to their subsequent importation into India. In addition to the existing silk mills in India at that time, a progressively increasing number of comparatively small rayon-weaving mills began to be set up by the erstwhile importers of rayon fabrics. The production of fabrics from man-made fibres in India was originally exclusively for that particular sector and took many years to infiltrate into the cotton and woollen sectors. With the increased imports of rayon continuous-filament yarn, the use of rayon increased in woven as well as knitted fabrics.

An impetus to the use of rayon was given by the commencement of the production of viscose rayon continuous-filament yarn in 1950. Starting at 1.32 million kg, the production capacity of viscose rayon continuous-filament yarn has increased to 39.085 million kg. Viscose rayon staple-fibre production started in India in 1954 with a capacity of 5 million kg. Acetate production in India commenced in 1954 with a small capacity of 1.6 million kg. Acetate-fibre production remains limited at 4.1 million kg, including both continuous-filament and staple-fibre forms.

Blended and mixed textiles came to be produced as rayon staple fibres became available. Thus these fibres were introduced on a small scale into some of the smaller units using power looms in the cotton and woollen sectors.

Rayon found use in industrial textiles, and the production of high-tenacity viscose rayon tyre-cord yarn commenced in India in 1961 with a capacity of 7.0 million kg. At present, this capacity has increased to 19 million kg.

The next stage of development of man-made fibres in India was the production of nylon continuous-filament yarn. This production started in 1962 with a capacity of 1.6 million kg. The total production capacity of nylon continuous-filament yarn to-day is 18.5 million kg. Nylon tyre-cord production started in 1971, and its capacity is now 11.99 million kg. Three years after the commencement of the production of nylon, the first unit producing polyester staple fibre was established with a capacity of 2.0 million kg.

In the last three years, with the setting up of new units, the production of polyester staple fibre in India has reached 25.3 million kg. A small beginning in the production of polyester-fibre continuous-filament yarn was made in 1969, and to-day there are seven nylon units producing polyester-fibre continuous-filament yarn under a diversification policy and one unit producing it exclusively, the total capacity being 3.5 million kg. The capacity of polyester-fibre continuous-filament yarn is at present 6.5 million kg. The production of polypropylene fibre for textile purposes commenced in 1977, and acrylic-fibre production has just started.

4. THE POSITION IN INDIA

On analysing the pattern of textile production in India, it is found that, up to the middle of the 1930s, natural fibres were used exclusively for textile production. During the subsequent decade, 100% rayon fabrics made from continuous-filament yarns were being used on a very limited scale. From 1950 onwards, the use of rayon continuous-filament yarns in textiles increased, and in 1954, with the introduction of rayon staple fibres, the variety of fabrics produced increased because of the use of spun rayon yarns and blends with cotton and wool. Rayon fabrics had come to be accepted because of their lower cost and their lustrous appearance and silky feel. Rayons had found wide use in sarees and dress materials and in suitings to some extent. During the same period, synthetic fibres were introduced into India as imports and found great acceptability by the man-made-fibre sector of the textile industry. The demand for synthetic fibres grew, and, with indigenous production being started, synthetic-fibre fabrics became more and more popular, especially in saree material.

In 1950, rayon constituted only 0.3% of the total production of all fibres. By 1960, the production of cellulosic man-made fibres amounted to 43 million kg, compared with 788 million kg of cotton, so that it still constituted only 5.1% of total fibre production (Table II). With the introduction of synthetic fibres in the 1960s, man-made-fibre production started to grow, and by 1970 it was 118 million kg, compared with 965 million kg of cotton. The synthetic-fibre component was only 16 million kg. The percentage growth rate of cotton fibres had decreased from 33% between 1950 and 1960 to 22.5% between 1960 and 1970. Furthermore, by 1970, man-made fibres contributed 10.7% of total fibre production, and by 1976 the figure was 13.7%. Compared with this, the world production of man-made fibres in 1976 was 46% of the total fibre production, which amounted to 3.5 times that of the production in India.

Table II

Production of Textile Fibres in India*

				Cellulosic			Non-cellulosic			Total Man-	
Year	Cotton	Wool	Silk	Fila-ment	Staple Fibre	Total	Fila-ment	Staple Fibre	Total	made Fibres	Grand Total
1951	591	8		2	—	2	—	—	—	2	601
1955	739	9		7	6	13	—	—	—	13	761
1957	807	13	1	11	8	19	—	—	—	19	939
1960	788	13	2	21	22	43	—	—	—	43	846
1965	939	18	2	37	37	74	2	1	3	77	1036
1970	965	20	2	38	64	102	10	6	16	118	1105
1971	881	20	3	39	61	100	11	6	17	117	1021
1972	973	22	3	41	71	112	12	7	19	131	1129
1973	998	33	3	38	63	101	13	10	23	124	1158
1974	1006	39	3	38	77	115	10	8	18	133	1181
1975	989	39	3	35	67	102	16	14	30	132	1163
1976	1006	35	3	43	84	127	18	21	39	166	1210

*All figures are in millions of kilograms.

There are various reasons for the low percentage of man-made fibres used in textile production in India. Primarily India is a cotton-growing country. A deficiency in textile fibres was felt only recently, when cotton production started showing signs of stagnation. For some time, the deficiency was met by imports of cotton. With the shortage of cotton and the rapid growth in the production of man-made fibres throughout the world, India also has realized the importance of man-made fibres to make up for the cotton short-fall. The division of the textile industry in India into various sectors, such as cotton, woollen, and man-made-fibre, is perhaps one of the main reasons for the lateness of this realization. The sector-wise division created barriers against the free utilization and promotion of man-made fibres for textile production. Each sector believed in its own survival and neglected the promotion of man-made fibres without realizing their importance as the fibres needed for the future survival of the entire textile industry.

5. THE PATTERN OF CONSUMPTION

The development and use of various fibres have influenced the consumption pattern of textiles all over the world. A shift has been noticed in the consumption of fibres from natural to man-made types (Tables III and IV).

During the last one-and-a-half decades, the consumption of all fibres increased steadily with the rising population, with the exception of a fall in 1974. This was the result of economic recession in both developed and developing countries during that year. In 1974, the utilization of synthetic fibres declined by 2% because of a shortage of energy and petrochemical feedstocks. The utilization of natural fibres also declined, but the percentage consumption of natural fibres rose marginally to 58% from 57% in the previous year, whereas that of man-made fibres decreased from 43% in 1973 to 42% in 1974. By 1976, man-made-fibre consumption had once again increased to 46%, and that of natural fibres had decreased to 54%.

Over the seven-year period between 1970 and 1976, total fibre consumption increased by 21%. Synthetic-fibre consumption expanded by 83%, and the consumption of cellulosic man-made fibres declined by 6%. Natural-fibre consumption showed a marginal increase of 5.8%.

The per-capita consumption of all fibres by the world population rose by about 200–300 g per annum until 1973, when it reached 7.1 kg. However, in 1974, it receded to 6.7 kg. The per-capita consumption of natural and cellulosic man-made fibres showed an insignificant change during this period, while that of synthetic fibres rose by more than 50% from 1.2 kg in 1969 to 1.9 kg in 1974.

The per-capita consumption of textile fibres in India is rather insignificant when compared with that in the world as a whole. During the decade between 1964 and 1973, the per-capita consumption of cotton slowly decreased from 2.2 to 1.9 kg. It may be observed that in 1973 the per-capita consumption of cotton in India was equivalent to that of synthetic fibres throughout the world. Cellulosic-fibre per-capita consumption in India has remained stagnant at 0.2 kg from 1964

Table III

Consumption of Textile Fibres (World and India)*

Consumption / Year	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
World													
Cotton	10918				11440		11862	12289	12727	13038	14020	11798	12502
Wool	1569				1637		1666	1640	1713	1608	1502	1487	1209
Flax	694				727		753	752	718	707	703		
Silk	34				36		38	37	43	44	45		
Cellulosic fibres	3397				3458		3454	3484	3594	3699	3535	48	49
Synthetic fibres	2195				3628		4842	5790	6576	7811	7485	2960	3212
												7355	8598
Total	18807				20926		22615	23992	25371	26907	27290	23648	25570
India													
Cotton	1060	1031	997	994	1052	1034	1070	1011	1102	1109	1007	989	1006
Wool	15	16	17	17	20	20	20	20	22	33	39	39	35
Cellulosic fibres	69	77	82	98	111	108	119	118	128	111	116	102	127
Synthetic fibres	10	9	8	11	14	17	22	27	29	32	23	18	29
Total	1154	1133	1104	1120	1197	1179	1231	1163	1262	1285	1185	1148	1197

*All figures are in millions of kilograms.

Table IV

Per-Capita Consumption of Textile Fibres (World and India)*

Consumption \ Year	1965	1968	1970	1971	1972	1973	1974
World							
Cotton	3.2	3.3	3.3	3.3	3.4	3.4	3.3
Wool	0.5	0.5	0.5	0.4	0.4	0.4	0.4
Flax	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Silk	—	—	—	—	—	—	—
Cellulosic fibres	1.0	1.0	1.0	1.0	1.0	1.0	0.9
Synthetic fibres	0.7	1.0	1.3	1.6	1.7	2.1	1.9
Total	5.6	6.0	6.3	6.5	6.7	7.1	6.7
India							
Cotton	2.1	2.0	2.0	1.8	2.0	1.9	—
Wool	—	0.1	—	—	—	—	—
Flax	—	—	—	—	—	—	—
Cellulosic fibres	0.2	0.2	0.2	0.2	0.2	0.2	—
Synthetic fibres	—	—	—	0.1	0.1	0.1	—
total	2.3	2.3	2.2	2.1	2.3	2.2	—

*All figures are in kilograms.

onwards, whereas that of synthetic fibres has only been significant from 1971 and has remained at 0.1 kg.

The production of cotton in India is expected to remain constant and is insufficient to meet the requirements of the Indian textile industry. All additional requirements of fibres for textiles have to be met by man-made fibres.

The existing plants producing synthetic staple fibres and filaments have been allowed to expand by 40–60%, which will only partly meet the present demand. A further increase in the production of man-made fibres will be necessary if they have to meet the basic textile demands.

6. FUTURE REQUIREMENTS

The future requirements for textiles depend on the growth of population and standard of living. The population in India exceeded 600 million in 1976. The population projections prepared by the Expert Committee set up by the Government of India foresees that by 1981 the total population will be 668 million, rising to 801 million in 1991 and to 945 million in the year 2001. The future requirements for textiles have been projected in Table V on the basis of this expected population increase. Two different assumptions have been considered. The first projection is based on the assumption that the per-capita fibre consumption would remain constant at the present level of 2.2 kg, in which case the man-made-fibre requirement in 1981 would work out at 420 million kg,

Table V

Projected Consumption of Man-made Fibres in India

Year	Population* (millions)	Per-capita Consumption of of 2.2 kg/year		Per-capita Growth Rate of 0.1 kg/year	
		Total Fibre Consumption (million kg)	Man-made-fibre Consumption (million kg)	Total Fibre Consumption (million kg)	Man-made-fibre Consumption (million kg)
1971	547	1163	145 (12%)	1163	145 (12%)
1981	668	1470	420 (29%)	1670	620 (37%)
1991	801	1762	712 (40%)	2803	1753 (63%)
2001	945	2079	1029 (50%)	4252	3202 (75%)

*Expert Committee projections set-up by Government of India.

compared with 1470 million kg of all fibres. In 1991, on the same basis, man-made fibres would account for 43% of all fibres, amounting to 712 million kg. Man-made fibres expressed as a proportion of all fibres would be 50% by the year 2001, with a total fibre requirement of 1029 million kg. During this period, the natural-fibre consumption has been assumed to remain steady at 1050 million kg as it is to-day.

The second projection has been based on the assumption that, with the passage of time, the per-capita consumption of textiles in India will rise. By taking a fairly low growth, it has been assumed that, by the year 2001, the per-capita consumption in India should reach a minimum of 4.5 kg at a rate of increase of 0.1 kg every year. If the natural-fibre consumption were to remain steady at, say, 1050 million kg, then, in the year, 1981, the man-made-fibre requirement would be 6020 million kg, amounting to 37% of all fibres. In the year 2001, the proportion of man-made fibres to all fibres would reach 75% with a consumtpion of 3202 million kg, i.e., almost three times that projected with a per-capita consumption of 2.2 kg. The situation demands serious thought and planning for the future expansion of man-made-fibre production in India.

7. CONCLUSIONS

The production of man-made fibres in India started early with cellulosic fibres, whereas the other developing countries, which initiated production later, started with synthetic fibres, when they had established themselves. Another phenomenon of the production pattern of man-made fibres in India and other developing countries is that India produces three times as much cellulosic fibre as synthetic fibre, whereas the reverse is the position in most of the developing countries (Table VI). This inbalance is one of the major factors obstructing the progress of the textile industry as a whole in India. It is therefore imperative that the relative amounts of the different fibres produced should be formulated after thoughtful deliberations and study.

Table VI

Production of Man-made Fibres in Selected Developing Countries*

Country \ Year and Fibre Type	1970		1971		1972		1973		1974		1975		1976	
	Cellulosic	Synthetic	Cellulosic	Synthetic	Cellulosic	Synthetic	Cellulosic	Synthetic	Cellulosic	Synthetic	Cellulosic	Synthetic	Cellulosic	Synthetic
Turkey	1.4	11.9	2.3	15.9	2.5	33.7	6.4	39.4	5.9	44.2	4.0	47.2	4.2	44.7
Argentina	9.8	23.4	13.8	31.3	16.1	37.8	17.8	46.3	18.0	46.5	14.5	46.1	10.3	40.0
Brazil	47.9	44.1	53.2	52.4	54.6	73.3	59.1	103.1	53.7	115.7	49.2	125.6	53.9	156.7
Chile	3.7	6.0	4.3	9.0	5.8	9.7	5.4	9.6	3.6	9.0	2.9	5.3	4.0	7.0
Colombia	8.8	13.2	11.4	15.2	9.7	19.5	7.4	23.6	7.0	23.4	5.6	23.5	3.6	31.3
Mexico	33.0	46.7	34.4	63.1	32.8	83.6	35.4	104.6	31.1	126.5	30.2	155.0	30.9	162.6
Peru	1.7	4.1	2.2	6.1	2.3	11.0	2.4	13.3	1.7	17.0	1.8	19.2	2.0	26.0
Venezuela	2.8	7.8	4.0	9.9	5.1	14.2	3.6	14.7	3.8	13.6	3.3	15.4	2.9	16.8
India	118.7	15.6	116.2	16.7	132.0	20.9	120.0	24.3	134.5	23.1	121.3	33.4	143.8	43.7
Indonesia	—	0	—	0	—	0	—	0.6	—	4.1	—	7.8	—	38.4
Malaysia	—	0	—	0	—	0	—	0	—	3.2	—	2.5	—	10.0
Nigeria	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Pakistan	5.7	1.7	2.9	1.5	3.3	1.9	3.2	2.3	3.8	1.9	2.9	1.8	2.6	2.4
Philippines	—	1.5	—	3.2	—	6.7	—	12.1	—	14.6	—	18.6	—	21.8
Singapore	—	0	—	0	—	0.6	—	1.4	—	1.5	—	0	—	0
Thailand	—	4.6	—	9.8	—	18.0	—	28.1	—	28.7	—	39.1	2.6	56.6
Total	233.5	180.6	244.7	234.1	380.4	300.5	260.7	423.4	263.1	473.0	235.7	540.5	260.8	658.0

*All figures are in millions of kilograms.

During the past decade, the growth of man-made fibres in the developed countries has been phenomenal. These countries have the expertise for evaluating the usefulness and future prospects of the different fibres in production. It is in the interests of the developing countries, where the industry is emerging, to draw from the wealth of knowledge gained by the developed countries to establish an industry ideally suited to their own requirements and not just to introduce something because it is new. Some fibres have become obsolete, and their introduction and expansion in developing countries would prove futile at this stage.

Self-sufficiency and independence in the production of fibres are difficult to achieve for individual countries because of non-availability of the necessary resources for all fibres. These countries should therefore explore the existing potentialities for the production and utilization of the requisite man-made fibres instead of venturing into multi-fibre projects, for some of which they may have to be wholly dependent on other countries.

They should bear in mind the constraints that would hamper the growth and development of particular fibres in their country. Man-made fibres offer a wide choice in respect of the raw-material basis and utility. What is required now is a planned growth of the industry to give it the desired impact in meeting the growing needs of world textiles.

It is being observed that in the developed countries the use of certain fibres has declined with the emergence of a better fibre. Consequently, the production of such fibres is suspended and the discarded plant eventually finds its way to a developing country, mainly on economic grounds, the result being a short-term gain. Proposals of this nature need to be thought over carefully to prevent failures. With the importance that the man-made fibres have achieved to-day, the selection and planning of suitable fibres in developing countries and advice on their production and utilization should be the task of an international agency like UNIDO (the United Nations Industrial Development Organization), which is keenly interested in the development of the industry and the betterment of mankind.

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13—THE FATIGUE OF COTTON FIBRES AND YARNS

By J. W. S. HEARLE and Mrs. N. HASNAIN

Investigations are described in which the method of fatigue-testing involving rotation over a pin, which has given fatigue failures of synthetic fibres similar to typical failure in use, was applied to cotton fibres. Instrument modifications were required to deal with cotton. Despite the shape of the cotton fibre and the problems of irregularity (and the difficulty of normalization), reasonable statistical results on fatigue life are shown to have been found. Scanning electron microscopy demonstrates that the failures are by multiple splitting similar to those found in cotton fibres in use. Tests made in air and in water and on untreated, mercerized, and Prograde-treated cotton fibres are reported.

Other studies made on cotton yarns, which are easier to handle in testing and give useful comparative figures of fatigue life, are also reported. The changes in yarn structure and fibre damage as fatigue proceeds are followed.

1. INTRODUCTION

Fig. 1 shows three examples of failed cotton fibres: a typical tensile fracture, a typical result of wear in use, and a typical result of a laboratory abrasion test. The tensile test gives a form of failure which is different from that of other fibres and strongly reflects the peculiar structural features of cotton, namely, the reversing helical assembly of fibrillar units. In contrast to this, the worn fibre shows features that are common to most fibres in most uses in clothing and household goods and are also revealed in the laboratory abrasion test.

In general, in the authors' work on fibre fracture, it has been found that the usual laboratory method of evaluating the 'strength' of a fibre by measuring its breaking load in simple tension gives forms of rupture that are characteristic of particular fracture mechanisms, resulting from particular structures. These breaks are scientifically interesting but are apparently irrelevant to the consumer's utilitarian requirement of 'strength' in a material, since what is then required is really long-term durability in use*.

The wear of fibres in use is predominantly a consequence of repeated bending and twisting, either in complex buckling or in the rolling backwards and forwards of fibres that pass over edges as in cuffs and collars. The characteristic form of breakdown is then multiple splitting, followed by rupture of the separate portions to give a brush-like fibre end, and often a subsequent wearing of the fibre ends to round them off. Generally similar breaks have been found in nylon, polyester, acrylic, wool, cotton, and other fibres. The differences between different fibre typre are comparatively slight. Cotton, particularly when subject to a breakdown in wet conditions, as in the mechanical disturbance of washing,

**N.B.* There are specialist industrial uses where textiles are subject to high loads and where the concept of simple tensile strength is more relevant.

(*a*)

(*b*)

(*c*)

Fig. 1
(*a*) Typical tensile fracture of a cotton fibre (— = 10μm)

(*b*) Typical example of cotton fibre after wear in use (from worn cotton shirt collars) (— = 10 μm)

(*c*) Typical example of cotton after laboratory abrasion test (from boss-abrasion test of cotton sheet after laundering) (— = 10 μm)

shows a somewhat greater tendency to separate into sheets of fibrils rather than into separate strands.

Multiple splitting as a form of failure is not normally found in the most common laboratory tests, which give simple tensile or torsional fracture, tensile fatigue, or flexural fatigue by oscillating backwards and forwards across a pin. The first laboratory method to show the effect was the biaxial-rotation test introduced by Lyons[1]. In this method, a coarse monofil was bent through 90°, and both ends were then rotated together. Because it was not possible to make such an instrument on a small enough scale to examine fine fibres, Hearle and Wong[2] developed an instrument in which a fibre was hung through 90° over a pin, with one end driven in rotation and the other carrying a suspended weight. Calil[3] later devised a means of rotating both ends of a fibre passing over a pin, while still maintaining a tension by means of a suspended weight attached to one fibre clamp, with axial slip over meshed rotating gears. The work of Hearle and Wong[4–6] and of Calil and Hearle[7] demonstrated the development of multiple splitting as a failure mechanism in these biaxial-rotation tests of nylon and polyester fibres, and there was a close similarity between the forms of fracture in the laboratory test and typical fibre wear in use in shirts, trousers, and socks. The statistical spread of the lifetimes was not unduly large for fatigue-testing, and the method is easily adapted to study fibres subjected to various treatments or environments. However, the results do, of course, depend on the fibre fineness, the pin radius, and the tension, and, although some approximate relations have been found, the problem of normalizing the conditions to compare fibres of different diameters has not been properly solved, though major differences can be demonstrated even if fibres of identical dimensions are not available.

The present paper is concerned with the extension of this method of testing to cotton. This gives rise to a number of potential difficulties: the fineness and lower strength of cotton fibres make more delicate handling necessary, the non-circular shape leads to a non-uniform rotation over the pin, the variability in fineness intensifies the problem of the normalization of test conditions, and larger coefficients of variation can be expected. As a possible way of avoiding some of these problems, although introducing others, consideration was given to testing yarns as well as single fibres.

Accounts of the tensile fracture and fatigue of cotton are given in papers by Hearle and Sparrow[8,9], of the wear of cotton in use in papers by Hearle and Lomas[10,11], and of fibre fracture and fatigue generally in a paper by Hearle[12].

2. EXPERIMENTAL METHOD

2.1 The Fatigue Apparatus

Preliminary trials were made with the instruments used by Hearle and Wong[2] and by Calil[3], but these proved unsatisfactory for cotton fibres, mainly owing to the effects of vibration. For delicate fibres, it is essential to have a fairly heavy, firmly constructed mechanism, which will rotate smoothly; a motor mounted on a separate base to isolate the fibre from vibrations; a tension mechanism that gives a constant tension without disturbance; and suitable fibre clamps, maintaining the fibre position on the pin. The clue that led to a suitable instrument design was the recognition that the tension in the fibre could be controlled by monitoring the force exerted on the pin, instead of by a suspended weight acting on the fibre.

The new instrument is shown in Fig. 2. It was convenient to modify the biaxial-rotation tester used for coarse monofils by Hearle and Vaughn[13] since this was robustly constructed on a heavy metal frame with substantial drive shafts and bearings. The drive comes through flexible links from a separately mounted motor. There is provision for changing the angle between the axes of rotation, but this was kept fixed at 90°. The test pin, over which the fibre passes, is fixed in a frame, which is mounted on a phosphor-bronze beam fitted with a strain gauge bridge network. The beam is, in turn, mounted on a frame, which can be moved up or down by a micrometer screw. The strain gauges are connected through appropriate electronics to a meter, which therefore indicates the force exerted by the pin on the beam.

As shown in Fig. 2(*c*), a fibre or yarn under test is first fixed in a central position in one clamp, passed over the test pin, and then passed around the positioning pin in the other clamp to a suspended weight. The weight is selected to give the required test tension. The second clamp is then fixed, the suspended weight cut off, and the rotation started. Any change in tension is prevented by adjusting the micrometer screw in order to maintain the meter reading constant. The meter was calibrated to indicate yarn tension by mounting a nylon filament in the instrument, as in Fig. 2(*c*), and then suspending weights of mass ranging from 0.5 to 50 g.

A drop in tension to zero signifies fibre breakage and is used as a signal to read the cycle counter, which thus gives the fatigue liftime. In yarns, where individual fibres break separately, there is a reduction in tension as failure approaches: this eventually becomes too rapid for adjustment of the micrometer, and the end-point was taken when the tension fell to 5% of the initial value.

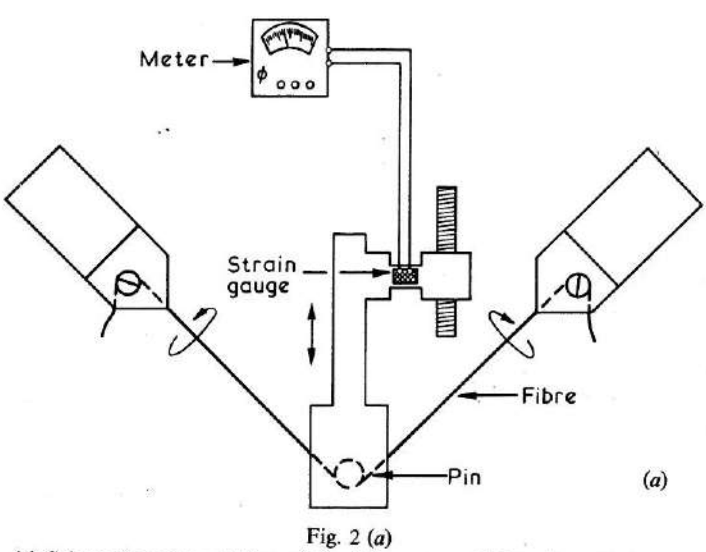
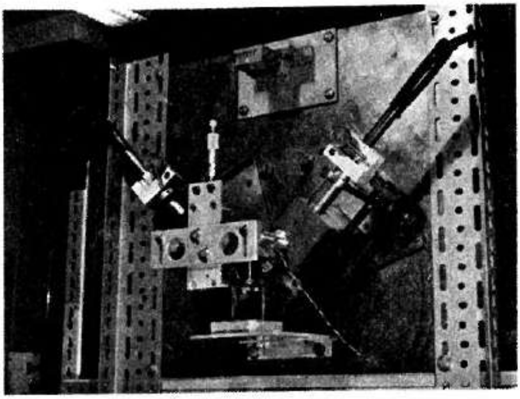
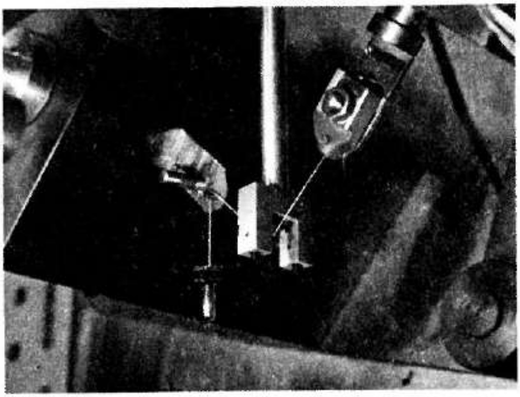


Fig. 2 (*a*)

(*a*) Schematic representation of the fatigue tester. Note that this is not correct in three dimensions: the beam, carrying the strain gauges and leading to the screw adjustment, would be perpendicular to the plane of the diagram



(*b*)



(*c*)

(*b*) General view of the tester: F is a heavy metal frame; C is the fatigue-cycle counter; f_1 and f_2 are flexible drives to the clamps; W is a beaker containing water

(*c*) Detail of clamping arrangements: C_1 and C_2 are clamps; P_1 and P_2 are fibre-positioning pins; S_1 is the adjustable jaw and s_1 the tightening screw; P is the test pin, held in frame f, connecting by rod R to the strain-gauge beam

In order to be able to handle short cotton fibres, it was necessary to stick each end of the cotton fibre to fine nylon monofilament, which was in turn mounted on card and fixed in the tester.

Preliminary tests of the instrument were made with nylon and polyester fibres, and it was found to give good and reproducible results. Various improvements in design would be possible in order to simplify the testing procedure and make it more automatic, but the operation was satisfactory for the series of tests that are the subject of the present paper.

2.2 Test Conditions

The pin used in the tests was of stainless steel and 0.18 mm in diameter; the tension for fibre tests was 1 gf (10 mN) and that for yarn tests 20 gf (200 mN); the rate of rotation was 6 rev/sec.

Tests were carried out at 20°C, either in air at 65%r.h. or in water. One odd set of yarn tests was made at a different humidity when the air-conditioning was switched off.

2.3 Materials Studied

In a more extensive study, it might be possible to measure individual cotton-fibre dimensions and correlate these with the fatigue-test results. However, for the main series of tests at present under consideration, a single reasonably uniform sample of cotton of the variety Sudan 6GL was chosen. One set of tests was carried out on this cotton as received. A second set of tests was made on cotton mercerized by the following procedure. A bundle of fibres was clamped in a frame, immersed in 0.4% wetting-agent solution for 15 min, slack-mercerized in 18% sodium hydroxide solution for 15 min, rinsed several times in water at 30°C, neutralized in 1% acetic acid for 5 min, rinsed several times in water, restretched to the original fibre length, and dried in an oven at 80°C for 30 min.

For the yarn tests, both ring-spun (RS) and open-end-spun (OES) yarns were produced from the Sudan 6GL cotton. The yarns were of 20 tex and spun to a machine twist factor of 4 on the cotton system (40 $tex^{1/2}$ cm^{-1}) 45 000 rev/min. for open-end spinning and 9000 rev/min for ring-spinning. The yarns were mercerized by a procedure similar to that used for fibres.

It was not possible to treat these fibres or yarns with liquid ammonia, but Coker cotton yarn was obtained in the untreated and commercially Prograde-treated form. These yarns were tested, and, in addition, single fibres extracted from the Prograde-treated yarn were tested.

3. RESULTS

3.1 Fatigue Lifetimes

Table I summarizes the results for the fatigue lives of the cotton fibres, and histograms are given in Fig. 3. In view of the variability of cotton, coefficients of variation between 36 and 58% are reasonable. The mercerized fibres show less variability than the untreated fibres. The distributions are skew with a tail of high-durability fibres. In fatigue-testing, with some fibres showing abnormally high or low lives, it is often better to use the median rather than the mean, but in these results both follow similar trends, with the skewness causing the mean to be between 4 and 15% higher.

Noting the values of the confidence limits (CL) for the means at the 95% level, one sees that the untreated fibres have significantly longer lives in water than in air and that the mercerized fibres have about twice the fatigue life of

Table 1

Fatigue Lifetimes of Cotton Fibres

Fibre State	Environ-ment	Number of Tests	Fatigue Life (cycles) Mean	Median	SD*	95%CL†	Coefficient of Variation (%)
Untreated	Air	50	2685	2361	1280	± 364	48
Untreated	Water	50	3312	3125	1917	± 545	58
Mercerized	Air	50	5775	4898	2084	± 592	36
Mercerized	Water	12	5662	5451	2193	± 1394	39
Prograde-treated	Air	12	4899	4406	2114	± 1344	43

*Standard deviation.
†Confidence limits.

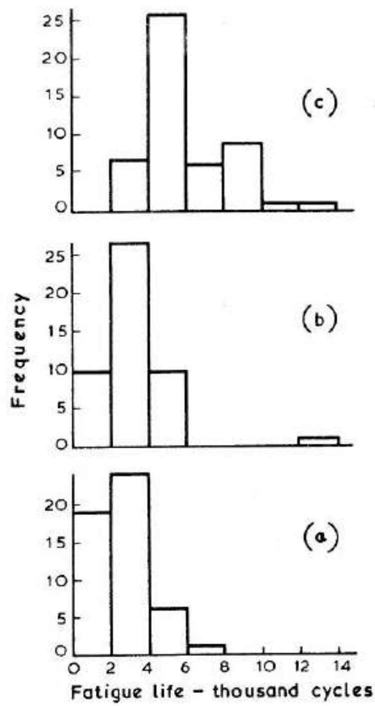


Fig. 3
Histograms of cotton-fibre fatigue lifetimes

(*a*) Untreated fibres in air
(*b*) Untreated fibres in water
(*c*) Mercerized fibres in air

untreated fibres, although there is no significant difference between mercerized fibres in air and in water. The Prograde-treated fibres appear to lie between untreated and mercerized fibres, but, because of their different variety and origin, this result cannot be relied on with confidence.

Table II gives the yarn breaking loads as obtained on an Instron Tensile Tester, with the expected differences between untreated and mercerized and between ring-spun and open-end-spun yarns.

Table II

Breaking Loads of Yarns*

Yarn	Breaking Load (N)		Coefficient of Variation (%)
	Mean	SD†	
Untreated RS	272	21	8
Untreated OES	204	28	14
Mercerized RS	412	55	13
Mercerized OES	272	45	16
Untreated Coker	158	31	20
Prograde-treated Coker	310	58	19

*Tests made at gauge length of 15 cm and rate of extension of 5 cm/min.

†Standard deviation.

Table III

Fatigue Lifetimes of Cotton Yarn

Yarn	Environment	Number of Tests	Fatigue Life (cycles)				
			Mean	Median	SD*	95% CL†	Coefficient of Variation (%)
Untreated RS	Air	50	4379	3480	2430	± 691	56
Untreated OES	Air	50	5149	4754	1782	± 507	35
Untreated OES	Water	50	949	783	528	± 150	56
Untreated OES	Air	15	5142	4888	1592	± 1931	31
Untreated OES	Air (50% r.h.)	15	2526	2457	751	± 911	30
Mercerized RS	Air	10	6962	7083	2792	± 1997	40
Mercerized OES	Air	50	5728	4450	3443	± 979	60
Untreated Coker	Air	50	2461	2292	857	± 244	35
Prograde-treated Coker	Air	30	2502	2198	867	± 323	35

*Standard deviation.

†Confidence limits.

Table III summarizes the fatigue results for yarns, and Fig. 4 shows histograms. The variability is similar to that for fibres, and so is the skewness of the distributions. The reproducibility of the results is illustrated by comparing the 50 tests of the untreated OES yarn in air with a separate set of fifteen tests.

The untreated OES yarn has a significantly longer life than the corresponding RS yarn, but the situation is apparently reversed in the mercerized yarn, though the difference may not then be significant. The mercerized yarns have longer lives than the corresponding untreated yarns, but there is no significant difference as a result of the Prograde treatment. The low lives of the Coker yarns are probably due to the different yarn specification.

The most striking differences are between the results for yarn tests in water, those in air (at 65% r.h.), and the odd test carried out in air at 50% r.h., though

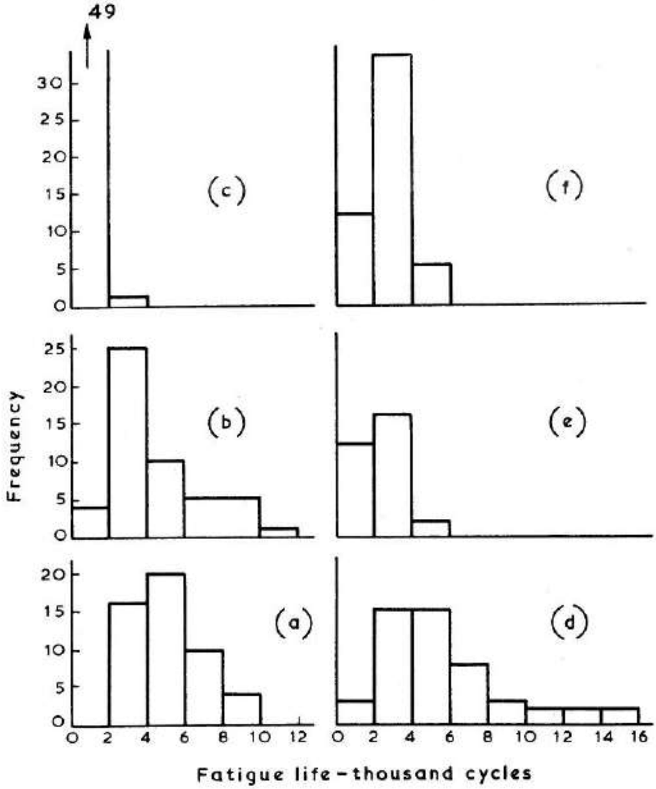


Fig. 4
Histograms of cotton-yarn fatigue lifetimes

(*a*) Untreated OES yarn in air
(*b*) Untreated RS yarn in air
(*c*) Untreated OES yarn in water
(*d*) Mercerized OES yarn in air
(*e*) Prograde-treated Coker yarn in air
(*f*) Untreated Coker yarn in air

values are only available for the untreated OES yarn. In water, the life is very short, presumably because fibres easily slide past one another, and at 50% r.h. the life is also low, presumably because the fibres are most brittle and split up more easily. The longest values were those at 65% r.h.

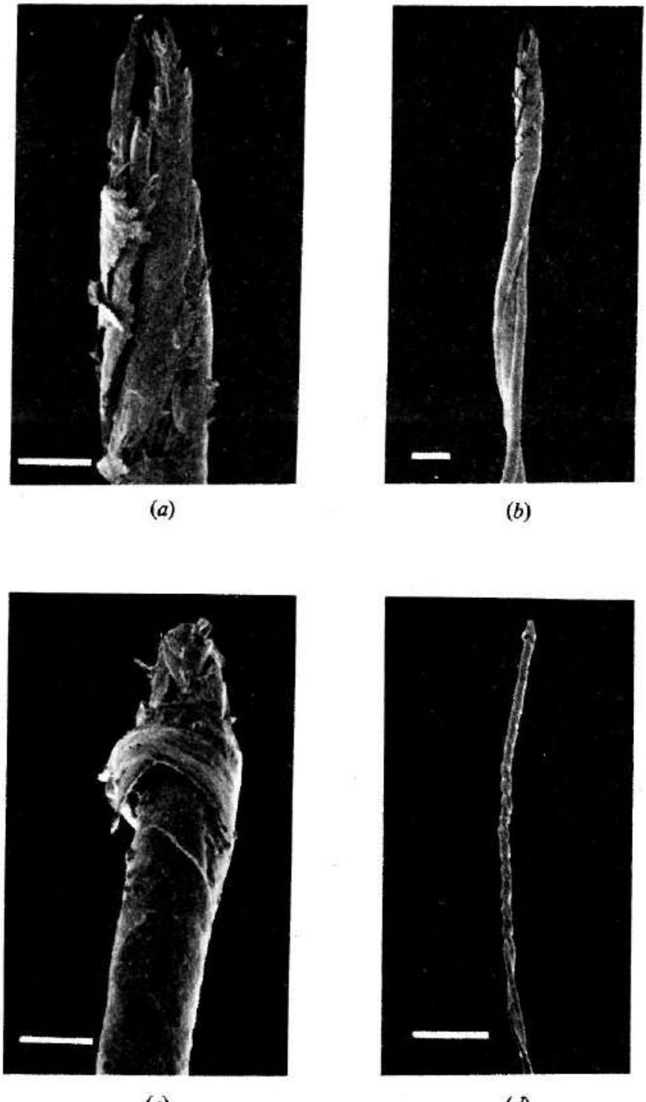
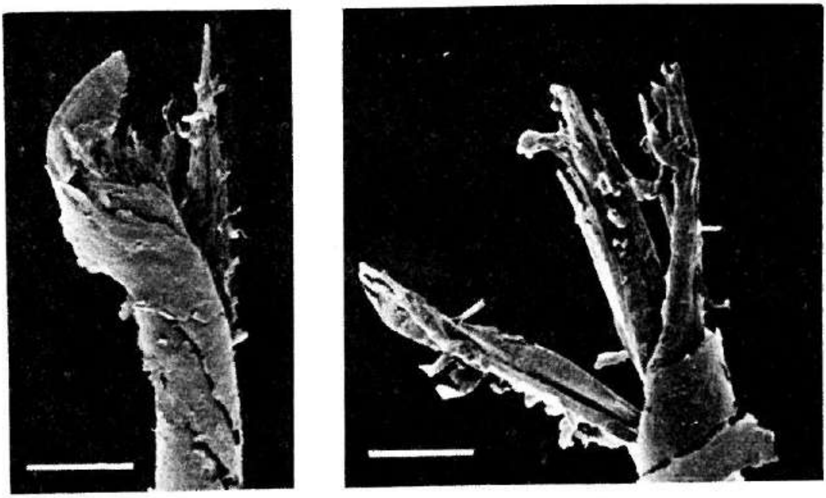


Fig. 5
Untreated cotton fibres in air

(*a*), (*b*) One end of fibre, failed at 1898 cycles (—(*a*) 10 μm, (*b*) 20 μm)
(*c*), (*d*) Other end of fibre, failed at 1898 cycles (—(*c*) 10 μm, (*d*) 100 μm)

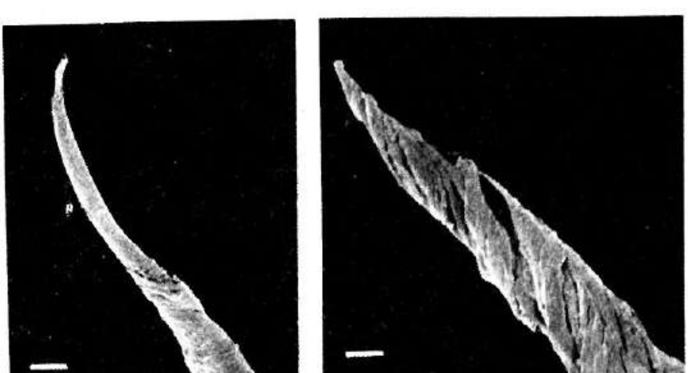


(*e*) (*f*)

Fig. 5
(*e*), (*f*) Opposite ends of another fibre, failed at 1912 cycles (—(*e*) 10 μm, (*d*) 10 μm)

3.2 Scanning-electron-microscope Studies

Fig. 5 shows SEM pictures of untreated cotton fibres taken to failure. It has been previously observed that, for reasons that will be discussed later, there is always a false-twist effect in biaxial-rotation testing, with the portion over the pin lagging in rotation behind the driven clamps and so causing twist in opposite directions on either side of the pin. In cotton, because of the reversing helical structure and the convolutions, this effect must show up as an alternating intensification and reduction of the natural fibre twist, as is clearly seen in the



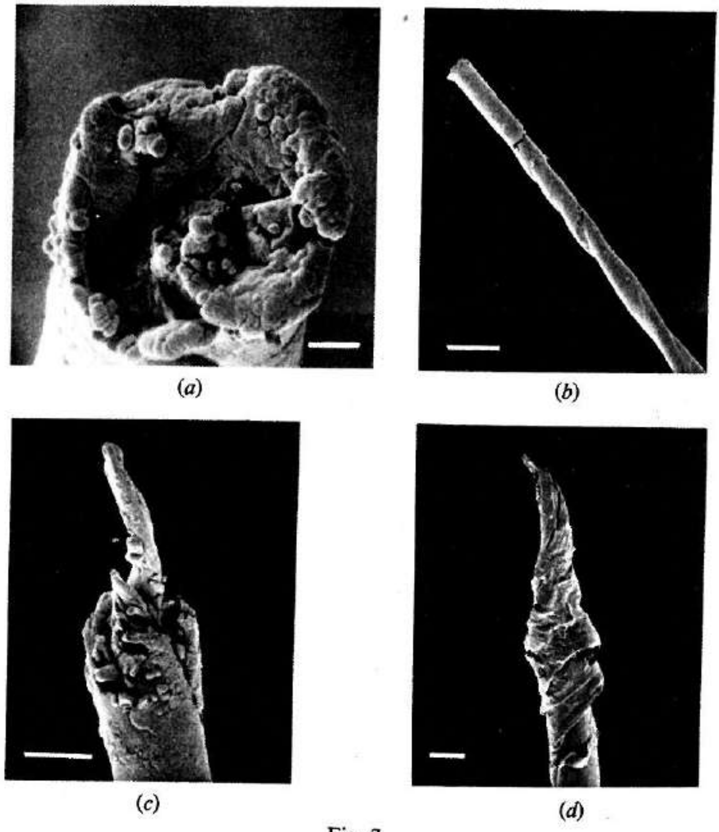
(*a*) (*b*)

Fig. 6
Untreated cotton fibres in water

(*a*) Fibre failed at 3499 cycles (— = 10 μm)
(*b*) Another fibre, failed at 12750 cycles (— = 10 μm)

low-magnification view in Fig. 5(*d*). The failure is clearly due to multiple splitting of the fibre, with the fibre in Fig. 5(*e*) and (*f*) being rather more split in the other fibre. The outer layer of the fibre usually peels off separately.

Fig. 6 shows two fibres that had been tested in water and had failed after an average life and a very long life. Again there is multiple splitting, but, because of the separation of fibres due to the absorbed water, they have tended to break independently, which leads to a gradual thinning of the fibre end. The split regions also tend to cling together during drying.



(*a*) (*b*) (*c*) (*d*)

Fig. 7
Mercerized cotton fibres

(*a*), (*b*) Opposite ends of a fibre failed at 12 303 cycles in air (— = 30 μm)
(*c*) Another fibre, failed at 5053 cycles in air (— = 10 μm)
(*d*) A fibre failed at 2198 cycles in water (— = 10 μm)

Mercerized fibres, tested in air and water, are shown in Fig. 7: there is multiple splitting, but it is not as sharp as in the untreated fibres, and the edges are left somewhat rounded. The Prograde-treated fibres, illustrated in Fig. 8, show very pronounced and sharp multiple splitting.

Fig. 9 shows a ring-spun yarn fatigued in air. There is a gradual thinning

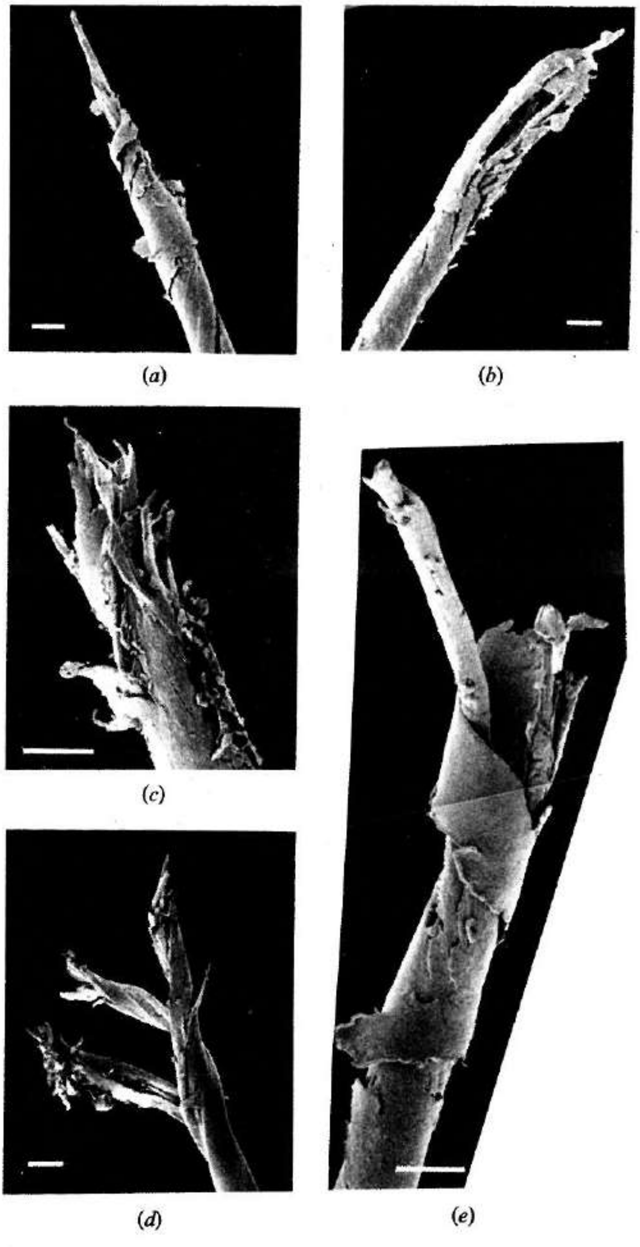
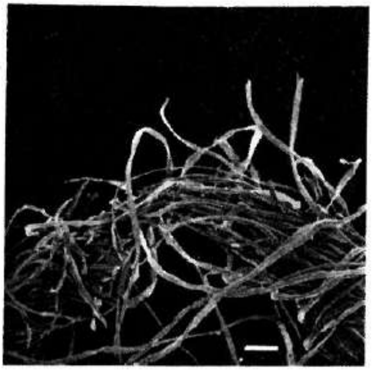
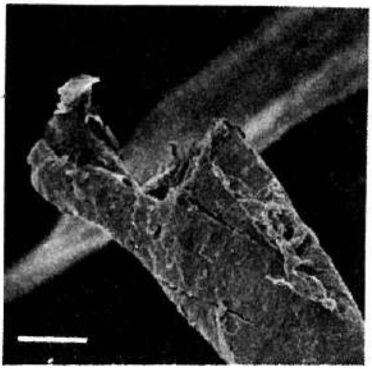


Fig. 8
Prograde-treated cotton fibres in air

(*a*), (*b*) Opposite ends of a fibre failed at 7762 cycles (— 10 μm)
(*c*), (*d*) Opposite ends of another fibre, failed at 2052 cycles (— = 10 μm)
(*e*) Another fibre failed at 6919 cycles (— = 10 μm)



(*a*)



(*b*)

(*c*)

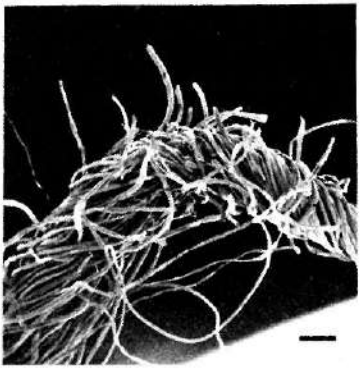
Fig. 9
Untreated RS yarn in air

(*a*) Failing portion of yarn after 4628 cycles (— = 100 μm)
(*b*), (*c*) Individual fibres from same yarn (— = (*b*) 10 μm), (*c*) 10 μm)

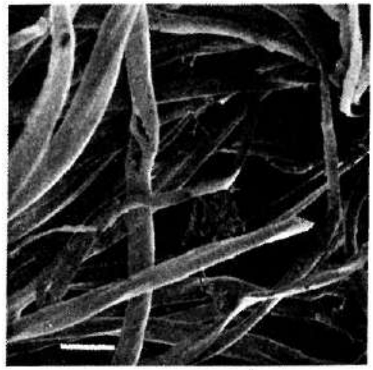
down as fibres break and are no longer present in the yarn cross-section. The increased stress may also draw the yarn out locally by fibre slippage to cause a further reduction. The progressive thinning of yarn ends is similar to the effect in single fibres in water, where individual elements (fibres) break separately. The individual fibre breaks show the characteristic multiple-splitting failure. Similar effects are found in mercerized yarn (Fig. 10). In Fig. 10(*b*), various stages of multiple splitting can be seen. The final fibre break, shown in Fig. 10(*c*), is very sharp and brush-like, in contrast to the appearance of the mercerized single fibres.

In open-end-spun yarn tested in air, as shown in Figures 11 and 12, the influence of the 'belt' or wrapping fibres is clear and may be intensified by the rotation over the pin. There is a very marked thinning down of the yarn. The individual fibre breaks are sharp and brush-like. After being tested in water (Fig. 13), the fibres show marked damage due to the separation of fibrillar sheets: the appearance is similar to that in sheets that have been subjected to multiple laundering.

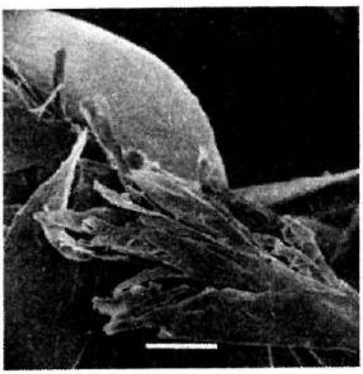
The Prograde-treated yarns shown in Fig. 14 have the characteristic sharp multiple splitting of individual fibres.



(*a*)



(*b*)



(*c*)

Fig. 10
Mercerized RS yarns in air

(*a*) Failing portion of yarn after 4188 cycles (— = 100 μm)
(*b*) Region showing initial craks in fibres (— = 30 μm)
(*c*) Individual fibre from same yarn (— = 10 μm)

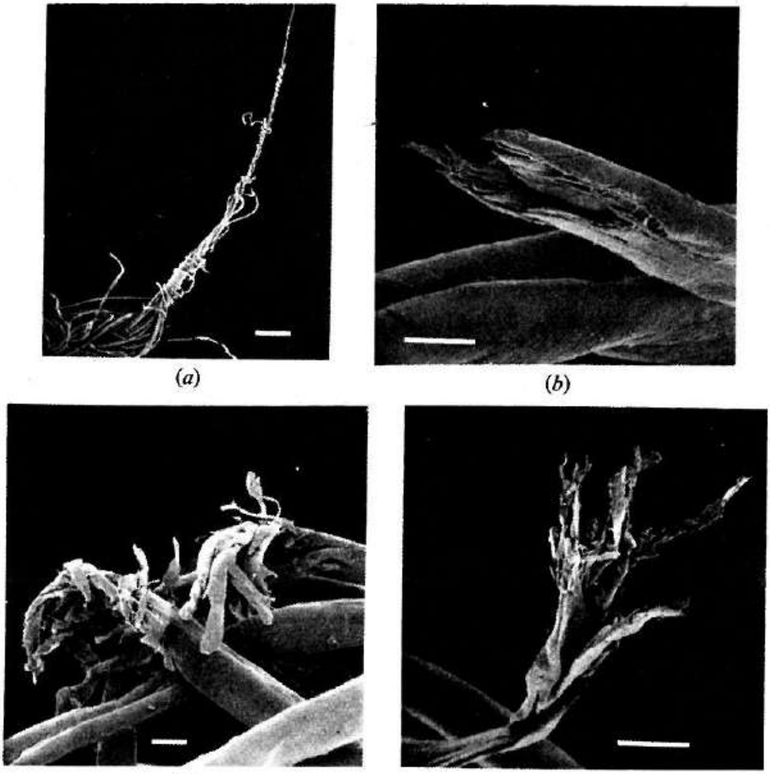
3.3 Correlation between Fatigue Life and Failure Type

The SEM micrographs of the failed untreated cotton fibres were arranged in increasing order of fatigue life. Those fibres which had the longest life (4000–6000 cycles) were found to be breaks at reversals, while those with lives shorter than 4000 cycles were broken either near a reversal or between reversals.

3.4 Tension Change during Tests

When untreated fibres were tested in air, the tension tended to increase at the start of a test, doubtless owing to the fibre twisting, but, once adjustment had been made during the first few cycles, little further change was needed. However, in tests in water, it was necessary to adjust the tension repeatedly throughout the test. Mercerized fibres tested in air showed less need for adjustment in the initial stages, presumably because the more circular fibres contracted less than ribbon-like fibres in twisting; in the wet tests, the behaviour was similar to that of untreated fibres.

All the yarns need adjustment to prevent an increase in tension in the initial stages and then further adjustment to compensate for fibre breakage.



(*a*) (*b*) (*c*) (*d*)

Fig. 11
Untreated OES yarn in air

(*a*) Failing portion of yarn after 5311 cycles (— = 200 μm)
(*b*), (*c*), (*d*) Individual fibre breaks from same yarn (— = (*b*) 10 μm, (*c*) 10 μm, (*d*) 10 μm)

4. DISCUSSION AND CONCLUSION

4.1 The Test Method and its Relevance

The results presented in this paper show that the method of fatigue-testing by biaxial rotation over a pin can be adapted to be suitable for cotton and that the problems arising from the delicacy, shape, and variability of the fibres can be overcome or at least do not lead to impossibly high irregularity of the results. Furthermore, the test method can be applied to yarns.

The mode of break found in this form of fatigue-testing is multiple splitting and is similar to that found in the majority of failure situations in use. The test method is well suited to a comparative examination of different fibre treatments and test environments. In the yarn tests, there may be an acceleration of failure due to fibre slippage, which may make yarn tests unreliable as a measure of fibre failure, although the yarn effects are real and relate to yarn behaviour in use: this effect of low fatigue life, presumably due to fibre slippage, was very noticeable in the tests on wet OES yarn. If fibre slippage is not dominant, then yarn tests will indicate the fibre response. The protective effect of the wrapping fibres in OES yarns is also apparent in this test as it is in use.

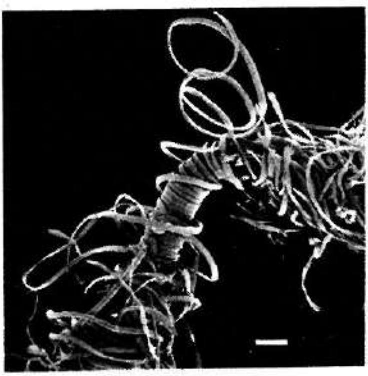
A considerable number of statistically significant differences in fatigue lives were found, and the most important of these are:

(*a*) the longer fatigue life of mercerized fibres and, though stated with less certainty because of the difference in fibre type, of Prograde-treated fibres, in comparison with untreated fibres;

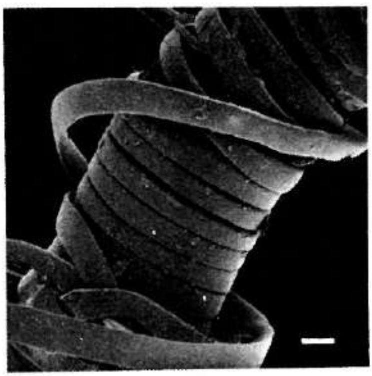
(*b*) the longer life of wet untreated fibres compared with that of dry (65% r.h.) fibres;

(*c*) the longer life of OES yarns, compared with RS yarns, when untreated, though this is not shown in the mercerized yarns;

(*d*) the shorter life of OES yarns wet and at 50% r.h. in comparison with the value at 65% r.h.



(*a*)



(*b*)

(*c*)

Fig. 12
Mercerized OES yarn in air

(*a*) Failing portion of yarn after 4382 cycles (— = 100 μm)

(*b*) Enlarged view of wrapped fibres (— = 20 μm)

(*c*) Individual fibre break from another yarn, failing at 3432 cycles (— = 10 μm)

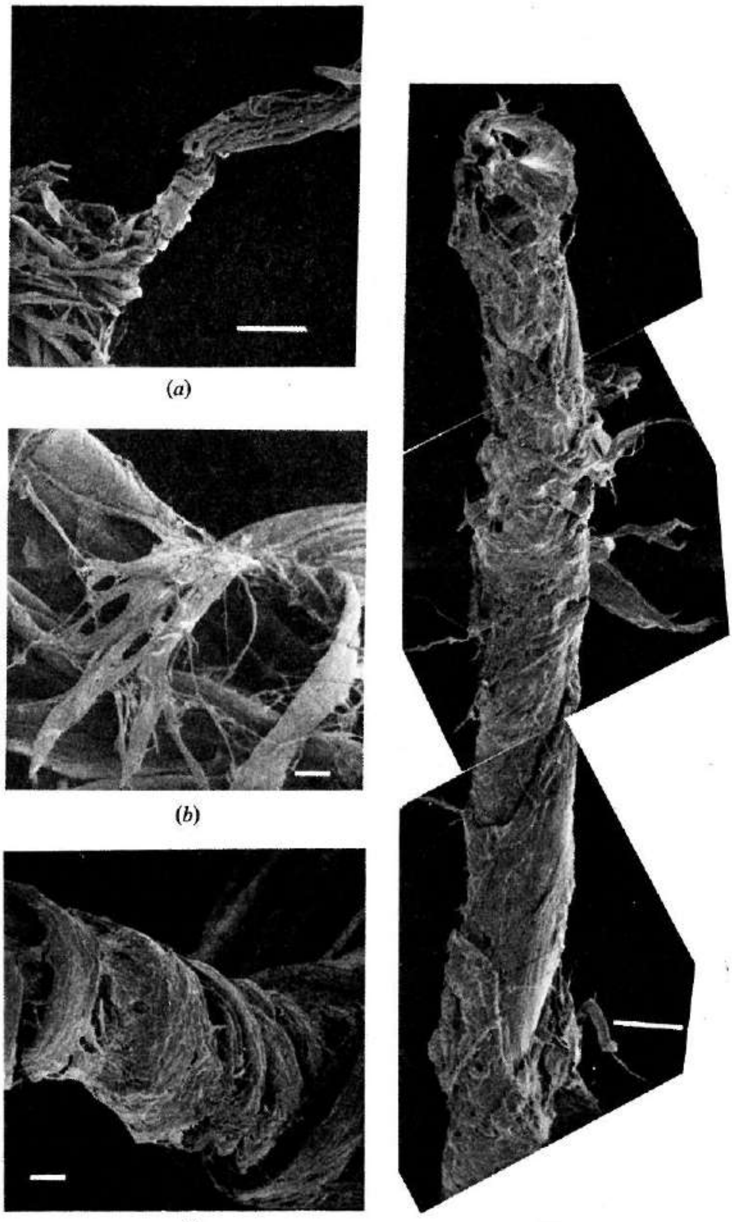
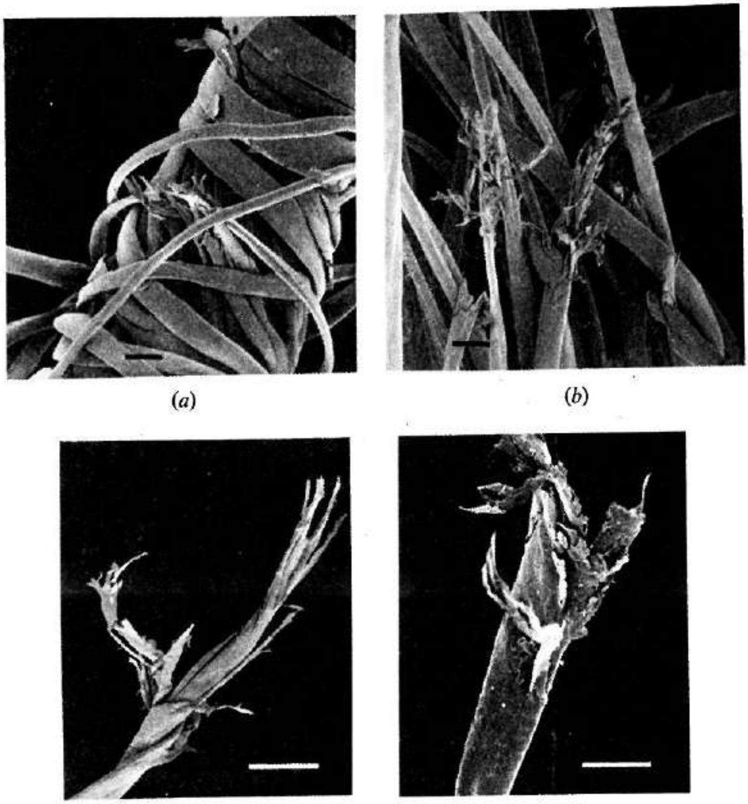


Fig. 13
Untreated OES yarn in water

(*a*) Failing portion of yarn after 1845 cycles (— = 100 μm)
(*b*), (*c*) Fibre damage (— = (*b*) 10 μm, (*c*) 10μm)
(*d*) Individual fibre break from yarn that failed at 885 cycles (— = 10 μm)



(*a*) (*b*) (*c*) (*d*)

Fig. 14
Prograde-treated yarn in air

(*a*) Failing portion of yarn after 146 cycles (— = 20 μm)
(*b*) Region showing fibre-splitting (— = 20 μm)
(*c*), (*d*) Individual fibre breaks (— = 10 μm)

4.2 The Failure Mechanism

When fibres are bent over a pin, they are subject to compressive strain on the inside of the bend and tensile strain on the outside. For cotton fibres, with diameters of 10–20 μm, passing over a pin with a diameter of about 0.2 mm, this would give maximum strains of 5–10% on each surface if the neutral plane remains central. In many fibres, there is easy yielding on the compression side, which leads to a lower tensile strain and a higher compressive strain as the neutral plane moves out to a more favourable position. However, it is not known whether this occurs in cotton, and, in view of the structure of cotton it may well not do so.

When the fibre is rotated, the material is subject to alternating tensile and compressive strain, most strongly on the surface layers and reducing towards the centre. There will be an associated alternating stress, and this will certainly be one of the causes of fatigue failure.

However, a twisting effect, in opposite directions on either side of the pin, is also observed. This is partly due to surface frictional drag as the fibre rotates over the pin. But it is markedly increased by 'internal friction'. If there is mechanical hysteresis in the cycle of tensile and compressive strain, then there must be an energy loss in each cycle. This energy can only be supplied by the work resulting from a product of torque and rotation, since there is no other combination of external force and displacement in the direction of the force. Thus there must be a torque arising from the hysteresis. In terms of the equilibrium of moments, this is associated with the fact that the hysteresis will cause the peak stress to lead the peak strain, so that the bending moment will be out of phase with the curvature and can act in an unexpected direction to balance the torque in the portion of fibre between the clamps and the pin.

The effect described in the preceding paragraph is common to all fibres, but there is a special effect that occurs in cotton. Locally, the cotton structure will have a natural twist that alternates between S and Z directions, separated at the reversal points. The twist resulting from the biaxial rotation may then either add to or substract from the local twist.

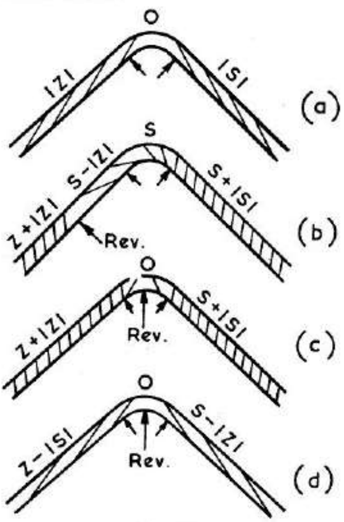


Fig. 15
Twist distribution

(*a*) In a fibre with no natural twist
(*b*) In cotton with reversal remote from pin, with twist on one side intensified and that on other side reduced
(*c*) In cotton with reversal on pin, with twist intensified on both sides
(*d*) In cotton with reversal on pin, with twist reduced on both sides

Fig. 15 summarizes the situation that can occur. With a 'normal' fibre with no natural twist, as in Fig. 15(*a*), there is a symmetrical situation at the edge of the region of contact with the pin, where the alternating bending strain is combined with the maximum torque (equal but opposite on either side), and failure will occur equally on both sides as is found in practice. With cotton, if there is no reversal in the pin region, as in Fig. 15(*b*), we have an asymmetrical situation with intensified twist on one side and reduced twist on the other. One of these situations will be weaker, and failure will occur on that side. However, if there is a reversal in the pin region, as in Fig. 15(*c*) and (*d*), then there is either intensification or reduction equally on each side: in one of these, both sides will be weak and the expected fatigue life will be unaltered, but in the other both sides will be strong and the fatigue life must be longer. This explains the observation that all the breaks occurring at long lifetimes (more than 4000 cycles in untreated cotton) were failures at reversals.

ACKNOWLEDGEMENTS

The authors express thanks to Mr. Allan Heap and the International Institute for Cotton for supplying material and for helpful advice, and to Miss Brenda Lomas for assistance in scanning electron microscopy.

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14—THE PROCESSING BEHAVIOUR AND PROPERTIES OF BLENDED-FIBRE YARNS OF TEXTURED POLYESTER STAPLE FIBRE AND COTTON

By A. Naik and F. Lopez-Amo

Synthetic fibres are mechanically crimped to facilitate their processing during the different stages of spinning. The crimp introduced is not very durable and is gradually lost in the ensuing stages of processing. Textured polyester staple fibres are blended with cotton, and their processing behaviour with respect to the surface-geometry components throughout the whole process is studied. It is observed that the presence of cotton fibres (67% textured polyester fibres and 33% cotton) reduces inter-fibre contacts and fibre-slippage resistance. The micro-crimp in the fibres is not only preserved during these processes, but in some cases it even increases because of the fibre's potential to contract on relaxing.

The physical properties and the influence of fibre characteristics on the properties of conventional ring-spun cotton-system yarns and open-end rotor-spun yarns are studied. It is observed that these textured fibres have a high propensity to twist and that some of the open-end-spun yarns have a twist factor that is smaller than or equal to that of similar ring-spun yarns. As a consequence, the breaking extension of these open-end-spun yarns is lower than that of similar ring-spun yarns. A method for determining the residual strength and residual twist of open-end-spun yarns is explained.

1. INTRODUCTION

The basic constructional element of any textile product is the fibre. The fineness of a textile fibre and its geometrical properties basically determine the performance characteristics of a textile product. Crimp is a very important staple-fibre property, since it enhances processability and spinnability and contributes to yarn characteristics. Wool is characterized by inherent crimping and cotton by convolutions and also by short rather than continuous fibre elements. However, most synthetic-polymer fibres, because of the way they are manufactured, have a smooth surface, and, when these continuous-filament yarns are converted into fabrics, they feel slippery to the touch and clammy when worn next to the skin. Some of the required aesthetic and comfort characteristics could be developed in fabrics by using synthetic fibres in crimped and staple form. As is evident, achieving this characteristic involves an additional process of crimping, which can be accomplished either chemically or mechanically. Chemical crimp is achieved by the extrusion of two different types of polymer, resulting in a bicomponent fibre. This chemical crimp is durable as opposed to mechanical crimping, achieved through deformation in stuffer-box or gear crimping. Crimp is convenient for the efficient manipulation of the fibre in the early stages of mechanical processing, especially on opening and carding equipment, and facilitates contact, friction, and slippage-resistance of in-process fibre assemblies and uniformity of fibre-processing. The planar saw-tooth crimp geometry is easily detected in synthetic staple fibre by visual inspection, especially in unopened stock. However, it should be remembered that this mechanical-crimping process introduces defects in the fibres, such as prominent zones and related surface deformations. These defects can be easily observed by straightening a crimped fibre under low tension, when the deformations tend to project out of the line of the fibre axis. It may also be demonstrated that the crimp geometry and crimp properties of synthetic staple fibres decrease considerably or disappear during the ensuing stages of processing[1].

One of the methods of obtaining durable crimp in synthetic fibres through mechanical crimping is to impart false twist during the texturing process of a continuous-filament yarn. The texturing process modifies the surface geometry and structural characteristics of the fibre.

2. OBJECTIVES

The general objectives of the study reported in the present paper were to investigate the spinnability of textured polyester staple fibres blended with cotton. A different crimp geometry in the fibre was introduced by varying the texturing conditions. Specific objectives included the following:

(i) to study the processing behaviour of the fibres at different stages of processing;
(ii) to investigate the effects of processing on the fibre-crimp durability;
(iii) to evaluate the influence of fibre characteristics on the yarn properties;
(iv) to determine the properties of conventional ring-spun cotton-system yarns and open-end (OE) rotor-spun yarns; and
(v) to evaluate the differences between conventional ring-spun and OE rotor-spun yarns.

3. PROCESSING AND PROPERTIES OF TEXTURED POLYESTER STAPLE FIBRES

3.1 Fibre Production

A 76-dtex 34-fil polyester-fibre yarn was textured on a Sotexa SW 16 texturing machine by the false-twist-texturing process under fourteen different texturing conditions. These yarns, in the form of cables, were fed to a converter, where they were cut to a staple length of 40 mm.

3.2 Fibre Characteristics

In order to evaluate the influence of fibre characteristics on yarn properties, the various characteristics indicated in Table I were determined.

Table I

Characteristics of Textured Polyester Staple Fibre

Sample	Mean Fibre Length (mm)	CV%	Fibre Fineness (dtex)	CV%	Breaking Strength (cN)	CV%	Tenacity θ (cN/tex)	Breaking Extension (%)	CV%	Crimp Contraction: Before Processing (%)	Crimp Contraction: After Processing (%)	Rigidity Index
A	38.4	6.62	2.70	4.29	12.88	5.59	47.70	45.35	13.27	12.48	12.16	0.2840
B	37.8	7.30	2.70	4.86	13.24	5.79	49.04	44.71	12.39	10.16	15.95	0.2961
C	36.8	8.04	2.65	3.39	13.08	4.70	49.36	50.4	10.52	10.82	14.00	0.2595
D	36.65	5.36	2.70	3.44	13.25	7.56	49.07	44.87	11.68	10.18	10.19	0.2953
E	37.2	4.56	2.66	3.20	13.25	3.79	49.81	45.36	12.64	10.65	13.31	0.2921
F	39.75	5.48	2.70	3.41	13.04	5.57	48.30	42.46	11.23	11.87	10.54	0.3071
G	39.30	7.03	2.76	4.19	13.27	3.29	48.08	48.76	9.49	13.43	12.29	0.2721
H	40.7	7.13	2.80	6.17	13.09	3.57	46.75	47.96	7.67	9.15	13.30	0.2729
I	38.1	5.04	2.68	3.83	13.41	4.71	50.04	48.26	10.84	12.84	12.76	0.2778
J	39.0	4.37	2.70	4.06	13.28	3.33	49.19	47.02	8.89	12.29	12.73	0.2824
K	38.6	7.67	2.70	3.94	13.17	4.47	48.78	47.24	10.34	12.98	13.50	0.2788
L	40.7	6.31	2.68	3.27	13.58	5.17	50.67	45.54	8.62	12.56	14.35	0.2982
M	39.9	5.32	2.70	3.97	13.23	3.82	49.00	46.24	10.99	11.64	12.12	0.2661
N	40.4	7.01	2.65	3.83	13.26	3.52	50.04	49.94	8.06	12.31	13.48	0.2655
Giza Cotton	40	22.68	1.50	18.38	6.59	25.08	37.23	10.10	29.31	—	—	0.6525

3.3 Blending with Cotton

The main purpose of blending is to mix together fibres with different characteristics to produce yarn qualities that cannot be achieved by using one type of fibre alone. Homogeneous blending is obtained by intimately mixing the fibres. When cotton is blended with short-staple synthetic fibre, the latter does not need cleaning. It needs carding to open the fibres and form a sliver. Having been carded, it does not have to be combed. The blending operation was done after carding. A three-process drawing system was used before the regular drawing. A blend of 67% textured polyester fibre and 33% cotton fibre was thus achieved.

3.4 Processing Behaviour

3.4.1 Fibre Properties Influencing Processing Behaviour

The fibre-surface-geometry components that influence the processing behaviour can be considered to be the following five:

(i) the fibre surface, its surface area, its roughness, and the fibre finish;
(ii) the cross-sectional shape;
(iii) the fibre length;
(iv) the fibre fineness; and
(v) the fibre-crimp durability.

3.4.2 Fibre Surface

Textile yarns pass over guide surfaces in spinning and winding operations, and the fibres rub against each other during drafting, weaving, and knitting. The surface area of the fibre depends on its surface geometry, and this is very important during its processing, since the number of contact points between the fibres determine their slippage motion. It has long been a practice to use textile lubricants and fibre finishes to reduce friction, wear, and static electricity. Textured yarns destined for the knitting industry usually contain 4–5% of the fibre weight of fibre finish. This amount of finish presents initial difficulties in the opening and carding processes. The textured fibres tend to accumulate on the carding surfaces and block the whole system. The first step was therefore to determine the ideal amount of fibre finish that would give the optimum carding conditions. It was found that 2–2.5% of fibre finish gave satisfactory processing conditions. An excess of fibre finish was eliminated by washing the fibre in cold water containing a non-ionic detergent. This process was employed because textured fibres are quite sensitive to heat treatments and in order not to introduce any changes in the surface geometry of the fibre.

Fibre roughness can be considered as a useful guide to the compatibility of various fibre blends. However, the present authors consider that the fibre crimp is the most important geometrical component and that the influence of fibre roughness is overruled in the presence of fibre crimp and fibre finish.

3.4.3 *Cross-sectional Shape*

Synthetic fibres can be extruded either with a circular cross-sectional shape or with a variety of shapes. The influence of a non-circular cross-sectional shape is not very remarkable, but it does bring about some differences in the processing behaviour and in the performance characteristics of textile products. The whole surface of round fibres is accessible to contact[2], whereas, with a fibre of polygonal shape or a non-circular one, the re-entrant surface would be inaccessible to inter-fibre contact. In the yarn, the cross-sectional shape affects the lateral contact area and the fibre-packing density. It is a known fact that, on texturing, the circular cross-sectional shape of the fibre is deformed to a polygonal shape, whereas there is no substantial deformation in the fibre cross-sectional shape when it is mechanically crimped. On mixing this fibre with cotton, which is also non-circular, the processability of the blend increases.

3.4.4 *Fibre Length*

Fibre length is important in drafting operations and influences sliver regularity. In OE rotor-spinning, the best processing behaviour for finer yarns is obtained[3] by spinning fibres of staple length not exceeding 40 mm. Very long fibre lengths are used for spinning coarse yarns. The rotor circumference depends on the fibre length spun and is slightly greater than the length of the longest fibre processed. It is evident that, from the point of view of power consumption and mechanical strength, the rotor diameter should be as small as possible. Fibre length also influences the twisting stress; the longer the fibre, the greater will be the twisting stress on the sheath fibres. Hence logically the shorter fibres must be twisted more than long fibres to obtain a practical yarn strength.

3.4.5 *Fibre Fineness*

In cotton fibres, the fibre finesness is related to the fibre length, the relation between the two having a very high negative coefficient of correlation, and thus its influence during processing is correspondingly great. In synthetic fibres, on the other hand, the fibre fineness is independent of the fibre length and so has a great influence on the fibre processability and yarn properties. The finer the fibres, the greater will be the number of fibres in the yarn cross-section for the same yarn linear density. Twist will have a greater effect because the number of fibres in the yarn core grows more rapidly than it does on the surface, but it will be shown later that the fibre-surface geometry and the torsional rigidity of the fibre are more important than the fibre fineness, at least for the fibres studied in this investigation.

3.4.6 *Fibre-crimp Durability*

In the opening and carding processes, the crimp in the fibres contributes materially to the improvement in their processing behaviour. This leads to a uniform distribution of the fibres on the working surfaces of the opening and carding machinery. The nature of the crimp in the fibres can be established in three categories, as shown in Fig. 1 (*a*), (*b*), and (*c*).

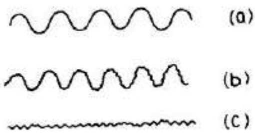

Fig. 1
Fibre crimp classified into three categories: (*a*) macro-crimp (*b*) mixed macro–micro-crimp; (*c*) micro crimp

The crimp introduced into the fibre depends upon the mechanical process employed. Macro-crimp is characterized by a high amplitude, and mixed macro–micro-crimp has, in addition, a high frequency. On the other hand, micro-crimp is characterized by low amplitude and high frequency. This crimp geometry has a very significant influence on the fibre motion. In one of the studies of Plonsker and Backer[4], it is demonstrated that crimped fibres (i.e., those possessing macro-crimp) move in the drafting zone with an erratic, springy,

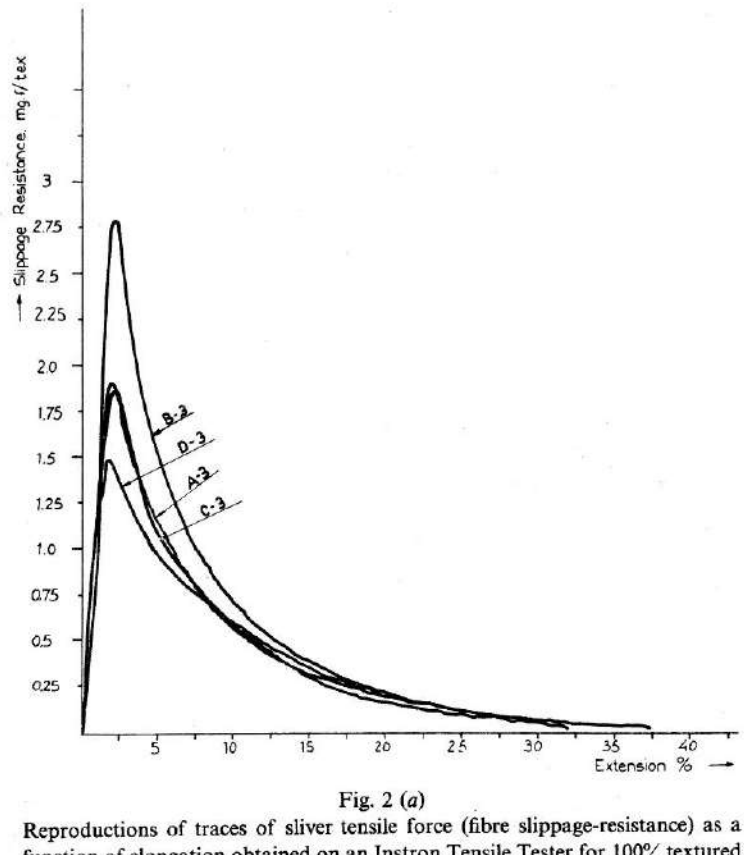

Fig. 2 (*a*)
Reproductions of traces of sliver tensile force (fibre slippage-resistance) as a function of elongation obtained on an Instron Tensile Tester for 100% textured polyester-fibre slivers (A–3, B–3, C–3, D–3)

pulsating motion. This motion is attributed to the nature of the crimp in the fibre and goes on decreasing as the fibre gradually loses crimp during its processing. In the case of the fibres studied, however, the micro nature of the crimp does not give rise to erratic fibre motion. When a fibre loses contact with the adjacent fibre and moves forward to make a new contact, the distance the fibre has to move is very small owing to the presence of low-amplitude rather than high-amplitude crimp. Hence the fibre motion is steady and uniform. In addition, the influence of fibre crimp on sliver bulkiness is not very great. The macro-crimp in the fibre produces a bulky and compressible sliver. On tensioning this sliver axially during drafting, its cross-sectional area is reduced, and, when these forces are released, the sliver again contracts[4]. This gives rise to a considerable difference between the mechanical draft and the actual draft. Since micro-crimp has no great influence on the sliver bulkiness, this difference between the mechanical draft and the actual draft is reduced to a minimum.

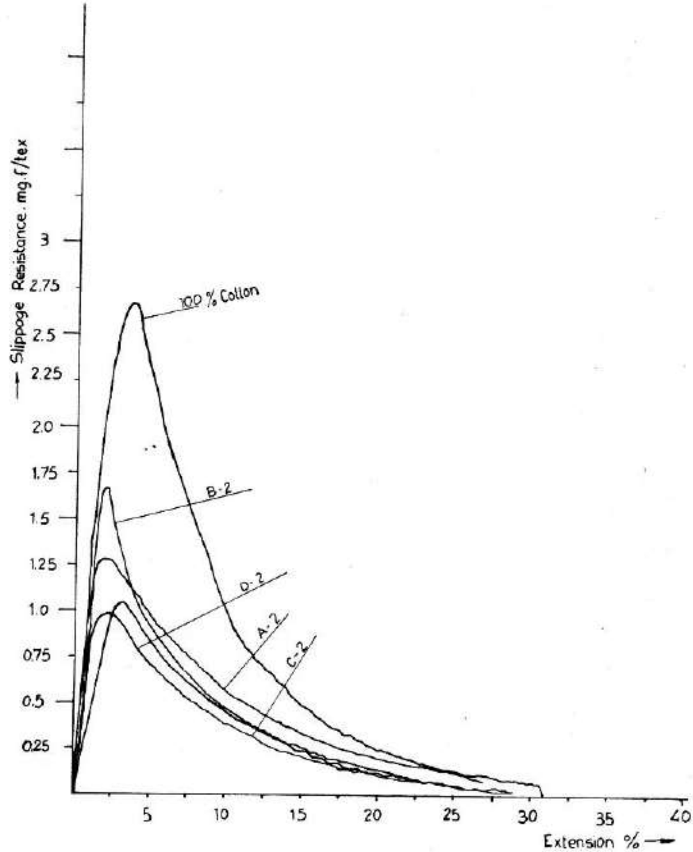

Fig. 2 (*b*)

Reproductions of traces of sliver tensile force (fibre slippage-resistance) as a function of elongation obtained on an Instron Tensile Tester for 67% textured polyester-fibre–33% cotton slivers (A–2, B–2, C–2, D–2)

The crimp permits the fibres geometrically to interlock, mesh, and entangle, which results in a high force being required to cause fibre slippage. Figures 2(*a*) and 3(*a*) represent the sliver tensile force as a function of the elongation obtained on an Instron Tensile Tester. These curves show that the tensile force increases with the strain, reaches a maximum, and then gradually decreases. The maximum force required for stretching and aligning the fibres is attained in a very short time or with very little elongation. In other words, the number of fibres in the sliver cross-section has remained practically unaltered, and fibre slippage has not really begun. The increase of strain results in an increase of stress on each structural element of the sliver and is typical of a continuous material that has not yet yielded. Once this force is overcome, the sliver cross-sectional area starts decreasing, and fibre slippage begins. This is reflected in the latter half of the curves through the fluctuations that may be seen. These slight fluctuations represent the relative fibre motion, which, as mentioned before, confirms the steady movement of the fibres during drafting.

The slippage-resistance, which corresponds to the maximum force, is considerably reduced when these crimped fibres are blended with cotton (Figures 2(*b*) and 3(*b*)). It seems that the presence of cotton fibres reduces the number of contact points between fibres, and these reduce the slippage-resistance.

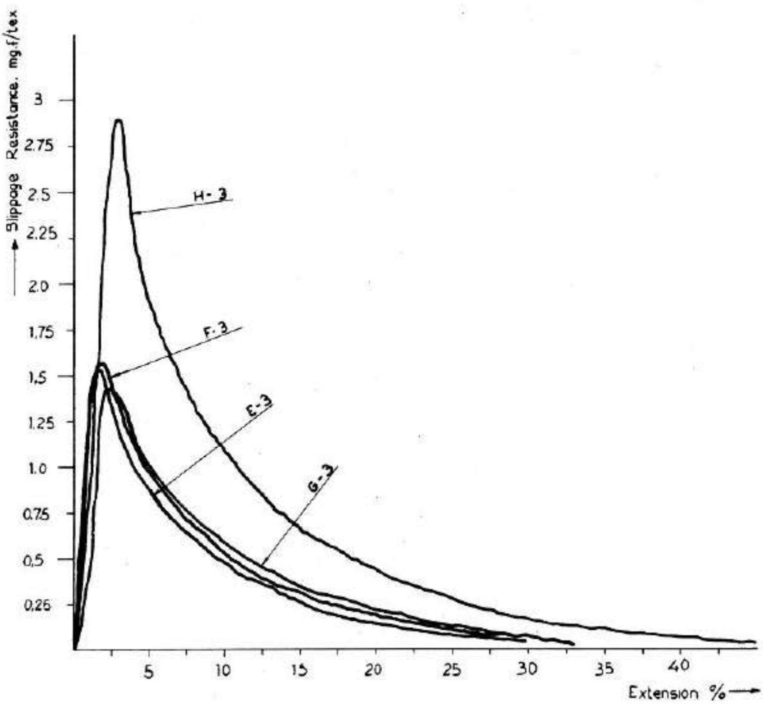

Fig. 3 (*a*)

Reproduction of traces of sliver tensile force (fibre slippage-resistance) as a function of elongation obtained on an Instron Tensile Tester 100% textured polyester-fibre slivers (E–3, F–3, G–3, H–3)

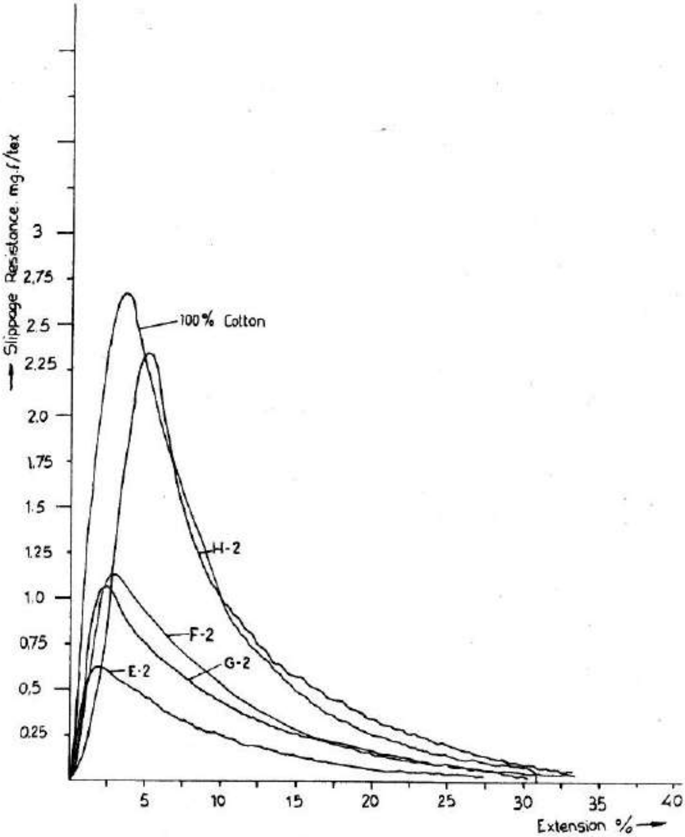

Fig. 3 (*b*)

Reproductions of traces of sliver tensile force (fibre slippage-resistance) as a function of elongation obtained on an Instron Tensile Tester for 67% textured polyester-fibre–33% cotton slivers (E–2, F–2, G–2, H–2)

The slippage phenomena can be explained in the following way. In the determination of the tensile strength of a yarn, all the elements of yarn experience almost the same strain, and the first element to break would be the least elastic. This is especially true for continuous-filament yarns, where the filament breakage can be clearly observed when the yarn is being tested.

A similar reasoning can be applied to the tensile testing of slivers. When the resistance to slippage is overcome, the fibres begin to slip past one another. The slippage will occur between those fibres for which the resistance to slippage is a minimum, that is to say, where the fibre has the minimum number of contact points. The resistance to tensile extension (slippage) of the sliver is further reduced when the relative motion between the fibres increases and the sliver structure is opened. This sliver response to tensile deformation is directly analogous to sliver behaviour during drafting, where the resultant forces in the sliver are determined by the level of strain imposed on it. One of the most important observations after the processing of the fibre through different stages is the durability of the crimp. Table I shows the values of fibre-crimp contraction before and after processing. In many cases, it can be observed that the crimp contraction increases after processing. This is mainly due to the fact that the textured fibres tend to relax after undergoing stress-and-strain forces during processing and mechanical handling. This sort of relaxation suffered by the fibres under zero tension is perhaps the main cause of increasing the crimp-contraction value. In fact, some of the fibres also lose some crimp contraction, depending on the texturing condition, which influences the crimp durability, but this loss is minimal compared with what happens with other types of fibre, where any mechanical crimp introduced almost disappears after processing.

4. EXPERIMENTAL

Yarns were spun on a conventional cotton ring-spinning system and by open-end (OE) rotor-spinning on an 885 Platt machine to a linear density of 26 tex.

In the traditional ring-spinning system, an assembly of more or less parallel fibres is delivered by a pair of nip rollers and is twisted by rotating the emerging end. Owing to the tensioning of the fibres between the nip line and twist nip, fibre slippage is almost impossible. The yarn structure generated may be regarded as a series of interlocking fibre spirals.

In rotor-type OE spinning, fibres are collected inside a rotor, which has a form of centrifugue. The fibres are laid more or less parallel to each other, and the fibre assembly is peeled from the collecting surface and twisted as it passes radially inwards towards the centre of the rotor. The state of order of the fibres in the sliver has a decisive influence on the degree of opening and orientation of the fibres at the exit of the fibre duct and thus on the properties of the OE rotor-spun yarns[5]. Fibres fed to the fibre duct in a badly opened and disoriented state will undergo a small degree of orientation and separation. Even a small amount of drafting of fibres as they pass from the fibre duct to the inner wall of the rotor will have only a limited effect in compensating such shortcomings at the entrance to the fibre duct.

The fibres combed out and conveyed by the opening cylinder are subjected to centrifugal forces and air drag, the strength of which will predominantly determine whether the fibres are conveyed near the base, the tip, or possibly outside the opening cylinder. Here, since the fibre tensions are limited (depending on the coefficient of friction and the normal force acting on the fibre), there is a much greater chance of fibre slippage, especially for those portions of fibres that exist in the outer layer of the yarn. Fibre fineness, fibre length, and frictional conditions that depend on the fibre-surface geometry should be taken into consideration. Yarn emerging from the rotor is usually withdrawn through a stationary funnel and rolls on the internal surface of this funnel. This rolling action introduces into the running yarn a false twist, which is trapped in the

Table II

Properties of Ring-spun Blended-fibre Yarns of Textured Polyester Staple Fibre and Cotton

Sample	Breaking Strength (cN)	CV%	Tenacity θ (cN/tex)	Breaking Extension (%)	CV%	Failure Time (Sec.)	Yarn Linear Density (tex)	CV%	Twist (turns/m)	CV%	Twist Factor, τ	Saturated Twist (turns/m)	Saturated Twist Factor, τ_s
A–2	465.6	11.12	16.93	16.28	9.58	12.18	27.5	6.58	671	5.59	35.19	771	40.43
B–2	487.8	13.70	18.55	16.35	10.04	12.48	26.3	6.39	677	5.43	34.72	771	39.54
C–2	430.0	12.41	15.81	14.35	13.12	10.9	27.2	9.80	642	5.98	33.48	692	36.09
D–2	418.2	11.58	16.08	15.40	13.69	11.8	26.0	5.47	647	5.73	32.99	699	35.64
E–2	395.2	13.05	14.64	14.54	14.72	11.16	27.0	5.53	676	5.94	35.12	826	42.92
F–2	424.0	15.26	15.64	14.98	14.51	11.44	27.1	5.16	665	3.87	34.62	765	39.82
G–2	423.8	13.36	16.30	14.99	16.72	11.60	26.0	8.72	693	4.64	35.34	793	40.43
H–2	465.2	13.39	16.98	13.92	13.14	13.14	27.4	9.08	649	5.36	33.97	749	39.21
I–2	399.6	9.62	14.02	14.86	13.12	11.40	28.5	9.50	639	4.43	32.27	739	39.45
J–2	425.2	9.56	15.53	15.40	10.83	11.86	27.4	5.15	651	5.98	34.08	701	36.69
K–2	420.4	10.78	17.30	15.28	9.02	11.70	24.3	6.04	654	5.32	32.24	754	37.17
L–2	386.0	9.92	15.39	13.67	13.69	10.34	25.08	5.48	680	4.42	34.05	780	39.06
M–2	440.3	14.24	17.47	15.92	8.50	12.26	25.2	6.28	662	4.18	33.40	712	35.74
N–2	507.0	11.40	17.85	16.74	12.67	12.96	28.4	8.37	664	6.32	35.38	814	43.38
100% Cotton	330.2	9.66	12.7	6.12	9.84	5.50	26.0	6.46	630	4.39	32.12	730	37.22

All twist factors are expressed as text$^{\frac{1}{2}}$ (turns/cm).

section of the yarn inside the rotor.[6] This is analogous to the twist distribution in false-twisters used in texturing.

5. RESULTS AND DISCUSSION

5.1 Yarn Properties

5.1.1 Results

The physical properties of conventional ring-spun yarns and OE rotor-spun yarns were determined and are listed in Tables II and III, respectively.

5.1.2 Breaking Strength

In Tables II and III, it can be observed that, for nearly the same twist levels, the ring-spun yarns have a higher strength than similar OE rotor-spun yarns. The percentage reduction in the strength of OE rotor-spun yarns is usually of the order of 10–30%[7]. The lower strength of these yarns has been related by several workers[8] to the yarn structure, which is different from that of ring-spun yarns. Moreover, it also depends upon the type of fibre and yarn linear density. Since the twist factor for some of these OE rotor-spun yarns is less than or equal to that of the conventional yarns (to be discussed in detail later in the paper), it may be expected that this reduction in yarn strength will be fairly high for these yarns. It is known that long fibres are responsible for the formation of 'wrappings' in the yarns, especially in these textured fibres, which have a great tendency to curl easily, act as bridging fibres, and wrap on the yarn surface. This behaviour of long fibres (of 40 mm compared with 28 mm for cotton) also contributes to the reduction in the yarn strength. However, on examining the values of the coefficient of variation of breaking strength of the two yarns, it is quite clear that the OE rotor-spun yarns have a more regular yarn strength than similar ring-spun yarns.

The characteristic value that is generally adopted for the routine testing of OE-span yarns is the residual strength. This can be defined as the tensile strength of an OE rotor-spun yarn in relation to its linear density, determined on a tensile-testing machine after the yarn has been apparently untwisted. It might be expected that this value would be zero, since the fibres in the untwisted state would just slip by without offering any resistance. But this never happens for OE-spun yarns. The values of residual strength in Table III indicate that, along the testing length of the yarn, there is no zone where the twist is completely removed. The break would occur where the twist level permitted the maximum fibre slippage. Hence these values of residual strength give some information about the residual twist in the yarn core. A higher residual strength corresponds to a high residual twist. A 100% cotton OE-spun yarn has a minimum residual strength compared with the other yarns, which indirectly indicates that the residual twist is also very low. All the other yarn samples have a higher residual strength. This depends on the fibre characteristics, which in turn depend on the texturing condition. Similar results and observations are made on 100% textured polyester-fibre OE-spun yarns[9].

Table III

Properties of Rotor-spun Blended-fibre Yarns of Textured Polyester Staple Fibre and Cotton

Sample	Breaking Strength (cN)	CV%	Tenacity θ (cN/tex)	Breaking Extension (%)	CV%	Failure Time (Sec)	Residual Strength (cN)	Tenacity, θ_R (cN/tex)	Yarn Linear Density (tex)
A–2.OE	326.8	11.24	11.63	12.70	10.45	9.40	23.05	0.82	28.1
B–2.OE	381.0	7.78	13.37	14.75	7.97	11.16	43.38	1.52	28.5
C–2.OE	310.3	8.95	11.28	13.44	8.24	10.22	20.90	0.76	27.5
D–2.OE	298.6	9.54	11.46	12.65	8.67	9.52	13.29	0.52	25.8
E–2.OE	309.6	10.56	10.79	11.50	9.54	10.10	18.71	0.65	28.7
F–2.OE	298.5	10.00	11.35	12.75	12.39	9.50	13.49	0.51	26.3
G–2.OE	293.0	7.34	11.02	11.85	9.46	8.90	19.73	0.74	26.6
H–2.OE	304.8	8.65	12.29	12.90	8.65	9.08	26.39	1.06	24.8
I–2.OE	336.8	8.95	12.29	13.40	8.42	10.06	18.65	0.68	27.4
J–2.OE	331.4	10.49	12.32	13.20	12.42	9.86	34.34	1.28	26.9
K–2.OE	372.0	9.50	13.78	14.30	8.86	10.86	25.99	0.96	27.0
L–2.OE	326.4	8.34	11.41	13.17	9.60	10.00	53.40	1.87	28.6
M–2.OE	307.8	8.72	11.62	12.90	8.46	11.40	14.65	0.55	26.5
N–2.OE	345.0	7.65	11.16	13.03	9.28	9.70	23.15	0.75	30.9
100% Cotton	243.6	7.3	9.26	7.00	9.03	6.40	8.87	0.34	26.3

All twist factors are expressed as tex $^{\frac{1}{2}}$ (turns/cm).

* Figures given by Stogdon[3].

5.1.3 Breaking Extension

It is generally accepted that OE-spun yarns have a higher breaking extension than that of corresponding ring-spun yarns and that this high extension in some way balances the low breaking strength. However, for these textured polyester-fibre–cotton blended-fibre yarns, a completely contrary result was encountered. The breaking extension of OE-spun yarns is about 10–12% lower than that of ring-spun yarns. There is a possible explanation for this. The results of machine efficiency and residual twist indicate that the fibres that form the core of the yarn are better twisted, since these textured fibres have a low fibre-rigidity index and can easily be twisted because of the surface-crimp geometry. On twisting these fibres in the same direction, Z, as before (texturing twist Z), a high core-twist value is achieved. On the other hand, when trials were made on twisting them in the opposite direction, S, it was found that the twist efficiency decreased considerably, and a very twist-lively yarn was produced, which was difficult to handle. The decrease in breaking extension is also reflected in the failure time of these yarns when they are tested in a constant-rate-of-extension tensile tester.

5.1.4 Yarn Regularity

Yarn regularity was determined by taking into consideration the variation in the yarn linear density along its length. The values of the coefficient of variation indicate that the OE rotor-spun yarns are more regular than the ring-spun yarns (see Tables II and III).

5.1.5 Yarn Twist

It is well known that with OE-spun yarns there is a difficulty in measuring

CV%	Measured Apparent Twist (*turns*/m)	CV%	Twist Efficiency (%)	Twist Factor, τ	Residual Twist (turns/m)	Actual Twist (turns/m)	Modified Twist Factor τ_M	Saturated Twist (turns/m)	Saturated Twist Factor, τ_S
4.33	618	4.44	82.4	32.76	30.18	648	34.34	718	38.06
5.63	592	4.04	79.0	31.60	67.14	659	35.18	692	36.94
4.75	638	3.15	85.1	33.46	38.16	676	35.45	738	38.70
3.79	653	3.02	87.1	33.17	23.62	676	34.34	703	35.70
6.23	616	1.80	82.1	33.00	37.31	653	34.78	816	43.72
2.97	613	2.94	81.7	31.44	27.29	640	32.82	713	36.56
2.28	648	2.30	86.4	33.42	42.63	690	35.56	798	41.16
6.07	637	3.54	84.9	31.72	56.22	693	34.51	687	34.21
4.50	625	2.10	83.3	32.72	38.24	663	34.70	725	37.95
2.82	627	1.73	83.6	32.52	69.36	696	35.40	727	37.71
4.02	616	4.51	82.1	32.01	61.53	677	35.18	816	42.40
4.08	605	41.3	80.6	32.35	82.24	687	36.70	705	37.70
4.37	652	2.18	86.9	33.56	23.30	675	34.75	702	36.14
3.80	591	3.56	78.8	32.85	32.37	623	34.63	691	38.41
3.20	640	3.89	85.33	33.25	15.40	655	34.03	840	43.08

the actual twist level. Many methods of twist measurement are employed in industry and research, and these rely on the parallelism of the fibres at one predetermined state during the twist measurement, but, owing to the differential-twist structure of OE rotor-spun yarns, it is impossible to achieve the necessary parallelism of the fibres. Of the methods available, the one most commonly used in the industry is the so-called untwist-and-twist method[10]. Hence it was decided to use this method in determining the apparent yarn twist. The yarn length (50 cm) is untwisted and reverse-twisted until the original length is reestablished. It should be remembered that the reverse-twist contraction rate differs from the untwist extension rate, and this is particularly true for OE-spun yarns. One of the reasons for this is that OE-spun yarns have the surface-layer fibres (the fibres forming the sheath) twisted to a different extent from the other fibres (the core fibres) forming the body of the yarn. Hence, on untwisting, a stage is reached at which some fibres are still untwisting whereas others will already be twisting in the oposite direction. The resultant of these simultaneous opposing twisting effects causes different contraction and extension rates, and in addition the measured twist level is less than the real twist of the yarn.

In earlier work by different authors,[11–13] it was demonstrated that the twist factor for maximum strength in OE-spun yarns is higher (by 10–15% or more) than that in ring-spun yarns. This is mainly due to the smaller surface contact that each fibre offers to the others to achieve the necessary friction required in the formation of yarn by the rotor system compared with conventional ring-spun yarns, in which the fibres are much more orientated[14].

A relatively higher twist is needed so that it can run from the yarn that has been formed to the condensed strand to strengthen the joint between them and to prevent end-breakage during rotation. The present authors' results show that the twist factor corresponding to yarn strength (real and maximum) for some of these OE-spun yarns is less than, or in some cases almost equal to, that of ring-spun yarns. This phenomenon can be explained by taking into consideration the twist efficiency.

5.1.6 Twist Efficiency

The reaction to the turning moment of the fibre depends on the torsional rigidity of the untwisted fibre. The mechanical twist is equal to the ratio of the rotor speed to the yarn-delivery speed (37 500 ÷ 50 = 750 turns). Owing to the fibre slippage in the rotor, mentioned previously, the twist efficiency for OE-spun yarns can never be very near to 100%.

Twist efficiency can be defined in the following way:

$$\text{twist efficiency} = \frac{\text{mechanical twist set}}{\text{apparent yarn twist/unit length}} \times 100.$$

When the twist efficiency approaches 100%, it means that the reaction to the turning moment of the fibres is less. The mechanical twist for all the yarns spun was kept constant. It was intended to spin a yarn of fixed linear density, 26 tex, but it can be observed in Table III that there are slight differences. It has been checked that these differences may be attributed to the differences in the sliver linear density. In spite of the fact that these differences are quite small, they allow observation to be made of the differences in the twist efficiency with respect to the linear density of the yarns (Fig. 4).

The losses in twist efficiency range from 21 to 11%, which are considered to

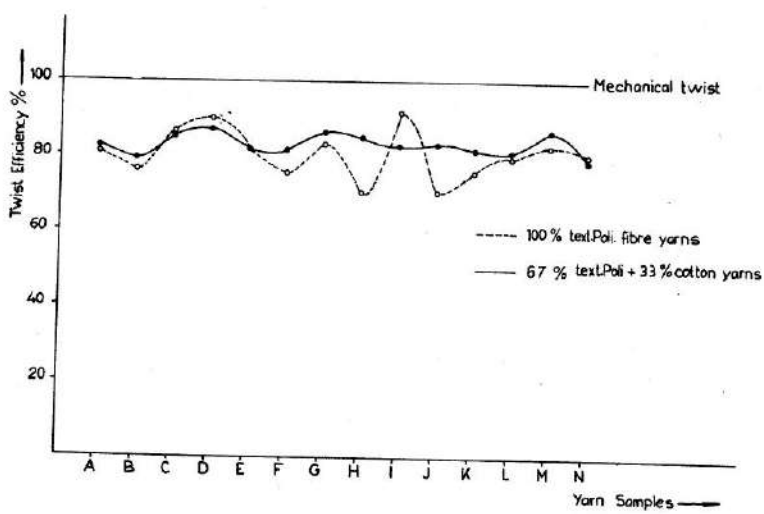

Fig. 4
Comparison of the twist efficiency of 100% textured polyester-fibre yarns and 67% textured polyester-fibre–33% cotton yarns spun on the OE rotor-spinning system

be quite poor for this yarn linear density and fibre fineness. This is mainly due to the surface geometry of the fibre. It should be remembered that these fibres were originally highly twisted (false twist in texturing 3000 turns/m). It is known that the texturing process induces surface changes in the filaments and also that the torsional rigidity of these filaments in the form of fibres is quite low. The fibres possess latent energy, which facilitates their retwisting in the same direction. In Fig. 4, we can observe that the twist efficiency for the blended-fibre yarn is, on the average, higher than that for 100% textured polyester-fibre OE-spun yarn. This is most probably due to the presence of the finer cotton fibres, which reduce the mean fibre fineness of the fibre strand.

5.1.7 *Residual Twist*

It is interesting to determine the residual twist of OE-spun yarns, since it indicates the propensity of the fibres to twist. In order to determine this, it was first necessary to measure the saturated twist and the corresponding maximum breaking strength. A simple experimental technique was employed. It was not possible to vary the yarn twist on the machine (because these yarns were spun on industrial machines in a spinning mill), so twist was added to the yarn by means of a torsiometer. This technique can introduce systematic errors, but these were compensated for by making corrections in the plot of the twist factor against the breaking strength. The initial length of the yarn sample on the tensiometer was 25 cm, and twist was added or removed in a stepwise manner so as to obtain an adequate number of points to enable the curve to be fitted.

The residual twist in the yarn was determined according to the method suggested by López-Amo[15] and described elsewhere. The values obtained are shown in Table III. It may be observed that the residual twist for 100% cotton yarn is the lowest. The values of residual twist in other yarns vary and depend on the texturing conditions to which the fibre has been subjected.

Better twist efficiency for these yarns can still be achieved by adequate machine-setting if one takes into consideration the production and the level of error introduced.

6. THE INFLUENCE OF FIBRE CHARACTERISTICS ON YARN PROPERTIES

As was mentioned earlier, fourteen different types of fibre were employed in this investigation and are referred to as A–N. These were textured under different conditions and are accordingly classified in four groups: Group 1 (A–D), Group 2 (E–H), Group 3 (I–L), and Group 4 (M and N).

During false-twist texturing, the feed-yarn filaments are subjected to bending, twisting, axial tension, and heating. The properties of these filaments are changed and depend on the texturing variables[16].

The texturing process makes the fibre coarser. It is known that the fibre fineness compared with that of the parent fibre becomes coarser on the average by 15%, but the differences are not very significant, and hence their influence on yarn properties is not great.

It seems that there is very good correlation between the fibre tenacity and the yarn tenacity.

One of the fibre characteristics that influence yarn properties is the crimp contraction after processing. For Oe-spun yarns, it can be clearly observed that the yarn breaking extension and residual twist have very good correlation with crimp-contraction values. This supports the previous hypothesis that the latent energy in the fibres, which is manifested in the crimp contraction, is responsible for reducing the fibre torsional rigidity and makes these fibres more sensitive to twisting.

Fibres in Group 1 were textured at different first-heater temperatures. It has been demonstrated in previous work[16] that, on increasing the first-heater temperature, the crimp contraction of the yarn increases. In other words, the degree of crimp frequency is high. It may be observed that the twist factor for yarn A, textured at the maximum first-heater temperature (240°C), is lower than that of the corresponding ring-spun yarn.

The function of the second heater is to set the deformation introduced into the filament. The values of the twist factor for these yarns (Group II) are higher than those of the corresponding ring-spun yarns.

On the whole, one can say that different texturing conditions do influence the twist efficiency and twist factor of OE rotor-spun yarns. In the cases where these values are higher than those of ring-spun yarns, the difference is quite small.

7. CONCLUSIONS

On the basis of the trials and experiments conducted during the course of this research, and from the analysis of the data gathered in relation to textured fibres processed by two different spinning systems, the following conclusions may be reached.

6.1 The surface-geometry component micro-crimp of the textured fibres is not only maintained during the spinning process but in some cases even increases because of the fibre potential to contract on relaxing.

6.2 The presence of cotton fibres in the blend reduces resistance to fibre slippage.

6.3 An adequate amount of fibre finish for these textured yarns is of the order of 2–2.5% on the fibre weight.

6.4 The OE rotor-spun yarns are weaker than similar ring-spun yarns.

6.5 The breaking extenstion of the OE rotor-spun yarns is lower than that of similar ring-spun yarns.

6.6 The twist factors corresponding to the actual and maximum yarn strengths for some of the OE-spun yarns are less than or equal to those for similar ring-spun yarns.

6.7 From the residual strength, the residual twist for OE rotor-spun yarns can be calculated.

6.8 A high twist efficiency can be achieved on spinning textured fibres when the twist direction is the same as that of the texturing twist.

6.9 The fibre-crimp contraction is related to the residual twist and twist efficiency.

6.10 Different texturing conditions influence the twist propensity of the fibre.

ACKNOWLEDGEMENTS

The authors wish to thank Industrias Burés S.A. of Castellvell y Vilar for permiting them to process and spin all the yarns discussed in this paper.

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15—COTTON-FIBRE CHARACTERISTICS INFLUENCING THE QUALITY OF OPEN-END-SPUN YARN

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A study of the influence of cotton-fibre properties on the tenacity and irregularity of open-end-spun yarns is presented in this paper. Statistical analysis of the data shows that the fibre length, fineness, tenacity, and maturity together account for about 80% of the variation in count–strength product (CSP) and that fibre tenacity is the most important fibre property influencing CSP. It is also shown that the quality of cotton and the counts spun have significantly less influence on the irregularity of open-end-spun yarns. Expressions to predict CSP and yarn irregularity are worked out.

1. INTRODUCTION

Open-end (OE) spinning has been attracting the attention of both machine manufacturers and textile technologists of late. A large amount of literature has appeared during the recent past with regard to developments in the manufacture of OE-spinning machines and the properties and end-uses of OE-spun yarns. However, little attempt seems to have been made to understand the relation between the fibre properties and OE-spun-yarn quality and to study the differences between the fibre–yarn structural relations of both OE- and ring-spun yarns. Such a study would provide an information base to assess the quality of cottons required to produce a yarn of specified quality and the extent of utilization of fibre properties in yarn properties. The work reported in the present paper aims to provide this information.

2. EXPERIMENTAL

2.1 Materials

Eighteen cottons varying widely in fibre properties were used for this study. The ranges in the fibre properties of these cottons are given in Table I.

The cottons were processed on conventional machinery. Second-head-drawframe slivers of different hanks were prepared, which ensured that the highest degree of cleanliness was obtained for each cotton during processing. The trash in the sliver did not exceed 0.15%. The cottons were divided into four distinct length groups. From each group, two cottons were selected and spun into four counts at four levels of twist multiplier. From the twist–strength curves, the twist for optimum strength for each group was assessed. These twists were adopted for subsequent spinning tests on cottons in these groups. The spinning was done on an open-end-spin tester by using the most appropriate conditions

Table I

Fibre-property Ranges of Cottons Selected

Fibre Property	Range of Values
50% Span length (mm)	10.2 –15.7
Micronaire value	3.05– 5.10
Tenacity at 3-mm gauge length (gf/tex)	16.4 –35.9
(mN/tex)	161–352
Maturity coefficient	0.72– 0.93

for each cotton. All cottons were spun to four counts within the range of 7s (84 tex)–44s (13 tex), with 14s (42 tex) kept as a common count.

2.2 Fibre Properties

The cottons were tested for length parameters on the Digital Fibrograph, for fineness by the Micronaire, for tenacity by the Stelometer at a 3-mm gauge length, and for maturity by the caustic-soda-swelling method in accordance with the ISI specifications[1]. The fibre properties were combined into a single index called the fibre-quality index (FQI), given by:

$$\mathrm{FQI} = \frac{l \times s \times m}{f},$$

where l is the 50% span length in mm as measured by the Digital Fibrograph, s is the fibre tenacity at 3-mm gauge length (gf/tex) as measured by the Stelometer, f is the Micronaire reading, and m is the maturity coefficient.

2.3 Yarn Properties

The yarns were tested for count, lea strength, single-yarn strength, breaking elongation, coefficient of variation (CV) of strength, evenness, periodic variations, and hairiness by standard laboratory techniques. The properties of the ring-spun yarns were computed from the fibre characteristics by using expressions previously developed at SITRA[2] for this purpose.

3. RESULTS AND DISCUSSION

3.1 Relative Contribution of Fibre Properties to Lea CSP

Since the yarn strength would be expected to be influenced by the major fibre properties, it would be of interest to know the degree of association between the yarn and fibre properties and the order of their importance. For achieving this end, multiple-correlation analyses were carried out between lea strength and the important fibre properties. Since all cottons were spun to 14s (42 tex), data on this count were analysed, and the results are given in Table II.

Table II

Multiple-correlation Analyses between Lea CSP and Fibre Properties

Variables Correlated		Correlation Coefficients			Beta Coeffi-cients
Independent	Dependent	Multiple	Total	Partial	
l (50% span length, mm)	*y* (lea CSP)	0.907**	0.811**	0.332	0.260
s (tenacity at 3-mm gauge length, gf/tex)			0.856**	0.625**	0.534**
f Micronatire value			−0.560**	−0.323	−0.242
m Maturity coefficient			0.225	0.141	0.090

**Significant at 1% level.

It will be noticed from the table that the partial correlation coefficient is highest for the fibre tenacity, which is followed by the length and fineness. The fibre maturity, however, does not appear to show any significant association with the lea CSP. This suggests that the fibre tenacity is the most important single property contributing to the lea CSP, the length and fineness occupying the second place. These observations are also confirmed by the beta coefficients. Nearly 82% of the variation in the lea CSP is explained by the four fibre properties taken together, as shown by the multiple correlation coefficient of 0.91. It is interesting to note in this connexion that the fibre tenacity is the dominant factor influencing the OE-spun lea CSP, whereas the length or fineness occupied a similar place in ring-spun yarns depending on whether the cotton is short- or long-stapled.

The dominant influence of fibre strength on yarn strength may be explained by a consideration of the mechanism of yarn formation and yarn structure in OE spinning. Since the majority of fibres in OE-spun yarns are hooked and not positioned parallel to the yarn axis, the contribution of length to OE yarn strength could be expected to be poor. Moreover, the shortening of the fibre extent increases with an increase in fibre length and thus minimizes the difference between the effective fibre lengths among cottons. Furthermore, owing to the very nature of yarn formation in OE spinning, it has been suggested[2] that even short fibres could contribute to the strength of yarn through more inter-fibre contacts, whereas in ring-spinning this effect is smaller.

3.2 Relation between Fibre Properties and Lea CSP

In establishing a relation between the fibre properties and yarn CSP, it would be desirable to use the fibre quality index (FQI), since this would help in choosing a cotton specifically to spin to a desired count and quality. In this regard, a model of the type

$$\mathrm{FQI} = \frac{l^p s^q m^r}{f^k}$$

was proposed.

The data for 14s count (42 tex) were analysed, and the FQI assumed the form:

$$\mathrm{FQI} = \frac{l^{0.36} s^{0.38} m^{0.13}}{f^{0.25}};$$

the equation connecting the yarn CSP and the fibre properties was worked out to be:

$$\mathrm{CSP} = 340\frac{l^{0.36} s^{0.38} m^{0.13}}{f^{0.25}}.$$

The relative contribution of the fibre properties to the yarn strength when expressed in a relation as above is given in Table III.

Table III

Multiple Correlation Analysis between Yarn CSP and Fibre Properties

Variable Correlated		Correlation Coefficients			Beta Coeffi- cient
Independent	Dependent	Multiple	Total	Partial	
l	y	0.903**	0.808**	0.338	0.269
s			0.854**	0.624**	0.552**
f			−0.548**	−0.282	−0.209
m			0.249	0.080	0.052

**Significant at 1% level.

It may be noted from Table III that the fibre tenacity is the most important property contributing to the OE lea CSP. Furthermore a comparison of Tables II and III reveals that the multiple-correlation, partial-correlation, and beta coefficients are similar. This would suggest that both the models would give the same information, and a choice between them could be made on considerations of convenience. In view of the fact that the contribution to yarn strength by maturity is practically negligible and the powers of l, s, and f are roughly the same, a model of the type

$$\mathrm{CSP} = K\left(\frac{ls}{f}\right)^p$$

was tried. The value of p was found to be 0.35, and K assumed values of 428, 364, 345, and 341 for counts of 14s (42 tex), 26s (23 tex), 36s (16 tex), and 44s (13 tex).

The correlation coefficient between the actual and expected CSP in these count ranges varied between 0.89 and 0.92, with an over-all value of 0.92. A simpler model of the type

$$y = k\,s^{p}$$

was also tried, since the fibre tenacity was found to be the single major factor contributing to the lea CSP. The value of p was found to be 0.56, and k assumed a value of 336, 294, 279, and 276 for the counts studied. The correlation coefficients between the expected and actual lea CSP ranged from 0.860 to 0.873. It is significant to note that the power of s is close to 0.5, which is similar to the parameter $\sqrt{\text{FQI}}$ used for ring-spun yarns[2], with the difference that l, f, and m do not appear in the formula. Thus, when the fibre tenacity alone is available, a reasonably accurate prediction of the yarn CSP can be obtained by using this relation.

The relation between the constant K derived from the expression

$$\text{CSP} = \text{K}\left(\frac{ls}{f}\right)^{0.35}$$

and the count was studied graphically (Fig. 1). It may be seen that there exists a curvilinear relation between the two. An interesting observation is that, as the

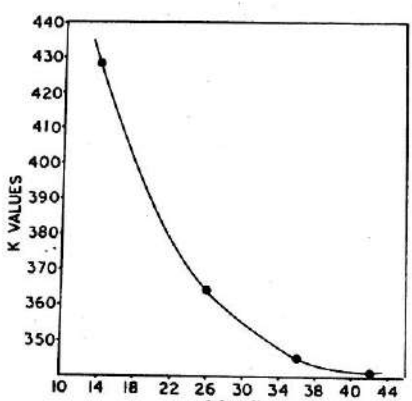

Fig. 1
Relation between constant K and cotton count

count becomes coarser, the value of K increases rapidly, which suggests that the relative contribution of fibre quality to the yarn CSP is greater in this region. Another observation is that the K values decrease slowly beyond 36s (16 tex), which suggests that the CSP would be largely a constant for counts of 36s (16 tex) and finer. In other words, open-end spinning appears to be incapable of bringing out the best in a cotton in fine count ranges, although its performance with coarse yarns is good.

3.3 The Influence of Fibre properties on Single-yarn Tenacity

An analysis of the data revealed a significant multiple correlation of 0.72 between the single-yarn tenacity and the fibre properties; the partial-correlation coefficients, however, were not significant. To establish a relation between the yarn tenacity and the fibre properties, a model of the type

$$\text{Yarn Tenacity (gf/tex)} = \left(\frac{lsm}{f}\right)^p$$

was tried, and p took a value of 0.29 and k values of 3.550, 3.084, 3.014, and 2.941 for the counts studied. The correlation coefficient ranged from 0.69 to 0.81 for different counts, with an over-all correlation coefficient of 0.77. It is worth noting that the correlation coefficient observed for single threads is lower than the figure of 0.91 for lea CSP. The real reasons for this observation are not very clear, but the greater variation of single-yarn tenacity compared with that of lea CSP of OE-spun yarns may influence this behaviour.

3.4 Lea Ratio

A comparison of the lea and single-yarn strengths of OE-spun yarns was made by computing the lea ration:

$$\frac{\text{lea strength (gf)}}{\text{single yarn strength (gf)} \times 160}$$

for 14s (42-tex) yarn spun from different cottons. It was noticed that the lea ratio ranged between 0.71 and 0.92, with a mean of 0.80. An analysis of this ratio revealed that there is a small but singificant positive correlation (correlation coefficient +0.50) between the lea ratio and the fibre quality index, which indicates that, as the cotton quality increases, the difference between the lea and single-yarn tenacities decreases. The physical significance of this observation is that, with increasing FQI, the rate of change of lea strength is greater than that of single-yarn strength.

3.5 Comparison of OE- and Ring-spun Yarns

At optimum twist factors, the CSP of OE-spun yarns was from 11 to 35% lower than that of ring-spun yarns in the count ranges spun in this experiment. The percentage reduction was found to depend on the quality of the cotton used and the count of yarn spun, as can be seen from Fig. 2. For CO 4 cotton, the reduction in CSP ranged from 14 to 27% for different counts; for Menoufi, it ranged from 23 to 35%; finer counts gave higher reductions in CSP. The results further show that the reduction in CSP of OE-spun yarns could be minimized by using a cotton of lower FQI and spinning to a coarser count. For Menoufi cotton, there is a greater probability of the hooking and buckling of fibres and the presence of a greater proportion of wrapped fibres and consequent reduction in

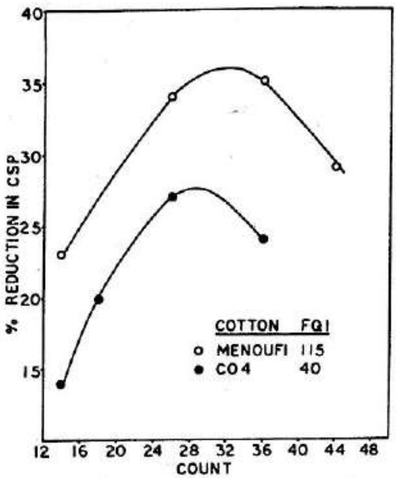

Fig. 2
Relation between percentage reduction in CSP between ring-spun and OE-spun yarns and count for different cottons

yarn CSP. For finer yarns, the ratio of actual nominal twist is lower and the proportion of surface fibres high, both effects contributing to a greater reduction in yarn CSP[4]. Fig. 2 further shows that, for very fine counts (36s (16 tex) in CO 4 and 44s (13 tex) in Menoufi), there is a drop in the percentage reductions in yarn CSP. This phenomenon is most probably due to the differences in the nature of the count–CSP curves for the two systems of yarns. Since OE-spun yarns are weaker than ring-spun yarns from the same cotton, it would be interesting to compute the FQI requirements in OE spinning to obtain the same CSP as in ring-spun yarns. Table V gives the FQI requirements to achieve the same CSP in ring- and OE-spun yarns.

It will be noticed that, in 12s (49-tex) yarn, the FQI requirement for OE spinning is slightly less than that for ring-spun yarns; but, for finer counts, the

Table V

Fibre-quality Requirements in OE- and Ring-spun Yarns

Count	Lea CSP	FQI Required for: Ring-spun Yarn	OE-spun Yarn
12s (49 tex)	1450	24	22
20s (30 tex)	1600	30	49
30s (20 tex)	1750	39	76
40s (15 tex)	1800	44	93

difference rapidly increases and, for 40s (15-tex) yarn, the FQI required for OE spinning is more than double that required for ring-spinning.

3.6 Yarn Uniformity

To examine the possibility of establishing a relation between fibre properties and yarn irregularity, a model similar to one established[5] for ring-spun yarns was assumed:

$$U^2 - U_s^2 = (Qh + a)d,$$

where U and U_s refer to the irregularity of the yarn and the sliver respectively, Q is a parameter depending on the cotton quality, h is the hank of the sliver, d is the draft, and a is a constant. The values of a and Q were estimated from the data by means of the technique reported earlier. The value of a was obtained as 0.2087 and, by using this value, the best estimate for Q for different cottons was computed.

The parameter Q was related with the fibre properties (i) l and f, and (ii) l and $F(=f/m)$ and the following relations were obtained:

$$Q = 9.07\ \frac{f^{1.02}}{l^{1.22}}; \tag{1}$$

$$Q = 2.995\ \frac{F^{1.18}}{l^{0.95}}. \tag{2}$$

Of these two, the first expression may be preferred, since this involves only two variables, and the correlation coefficients between the observed and expected Q values from both the expressions were around 0.65. This expression could be further simplified to the form

$$Q = \frac{kf}{l}.$$

The correlation coefficient between the observed and expected values of U when the simplified equation was used was found to be 0.75 as against a value of 0.74 observed between the actual and expected values when equation (1) was used. This figure is much less than the correlation-coefficient obtained (+0.97) for ring-spun yarns in the authors' earlier study[5]. This means that a detailed investigation of the influence of the opening and combing mechanism of the OE-spinning machine on the uniformity of fibre assemblies fed to the rotor are necessary for a clearer understanding of the irregularity produced in OE-spun yarn. The responses of these mechanisms to cottons having different fibre-friction and cohesion properties are known to be different. Thus the new expression for yarn irregularity could be expressed as:

$$U^2 = \left\{5.62\left(\frac{f}{l}\right)h + 0.2050\right\}d + U_s^2.$$

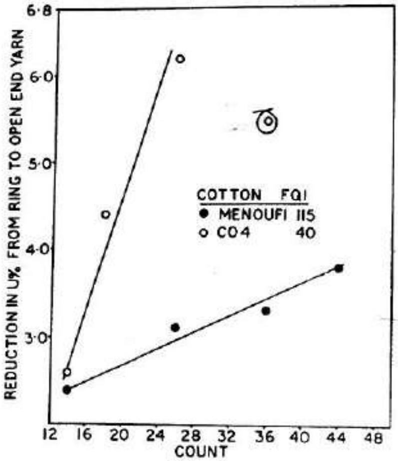

Fig. 3
Relation between $U\%$ differences between ring-spun and OE-spun yarns and count

3.7 The Effect of Fibre and Processing Factors on Yarn Evenness

It is well known that, in ring-spun yarns, the irregularity increases steeply with an increase in the cotton count and draft and a decrease in the fibre quality. The data obtained from OE-spun yarns in this study, however, show that the contributions to irregularity from these parameters are relatively small. Fig. 3 shows the reduction in $U\%$ from ring-spun to OE-spun yarns of cottons CO 4 and Menoufi having FQIs of 42 and 115, respectively. CO 4 cotton shows smaller reductions in uniformity than Menoufi when spun into OE-spun yarns of different counts. This is due to the fact that CO 4 cotton, being shorter, gives yarns of low regularity when spun on the ringframe, whereas Menoufi, being longer, gives yarns of higher regularity when spun on the ringframe.

Table VI gives the minimum irregularity according to Martindale's formula (random irregularity) and the observed irregularity in ring- and OE-spun yarns for two cotton.

It will be noticed that the random unevenness accounts for 50–75% of the total unevenness in OE-spun yarns, whereas it accounts for only 40–55% in ring-spun yarns, the percentage varying with the count. To a greater extent than random irregularity, the contributions from drafting waves and machine conditions seem to be more important in ring-spun yarns, whereas they occupy only a secondary place in OE-spun yarns. Thus the quality of the cotton and the counts spun have significantly less influence on the irregularity of OE-spun yarns.

4. CONCLUSIONS

4.1 The fibre length, tenacity, fineness, and maturity together account for about 82% of the variation in the lea CSP of OE-spun yarns.

Table VI

Minimum and Observed Irregularities of OE- and Ring-spun Yarns

Cotton	Yarn Cotton Count	U%			Randon Unevenness Expressed as Percentage of Total Unevenness	
		Ring-spun	OE-spun	Random	Ring-spun	OE-spun
Menoufi	14s	10.7	8.3	4.3	40	52
	26s	12.4	9.3	5.8	47	62
	36s	13.5	10.2	6.8	50	67
	44s	14.1	10.3	7.6	54	74
CO 4	14s	12.3	9.7	4.9	40	50
	18s	13.3	8.9	5.4	41	61
	26s	15.0	8.8	6.6	44	75
	36s	16.7	11.2	7.8	47	70

4.2 The tenacity at a 3-mm gauge length is the most important fibre property influencing the tenacity of OE-spun yarns.

4.3 The average lea ratio for OE-spun yarns is about 0.80 and is generally higher for cottons having a higher FQI.

4.4 As the counts become coarser and the fibre quality decreases, the strength realized in OE-spun yarn compared with that in ring-spun yarn increases.

4.5 Expressions for predicting the lea CSP and irregularity from fibre properties and spinning parameters have been developed.

4.6 Most of the irregularity in OE-spun yarns is accounted for by the random arrangement of fibres; contributions due to the draft, count, and cotton quality are relatively small, whereas the opposite trend is observed in ring-spun yarns.

ACKNOWLEDGEMENTS

The authors wish to express their sincere thanks to Shri K. Sreenivasan, the Director of SITRA, for his keen interest in this study. Their thanks are also due to Shri R. Ranganathan for the statistical analysis of the data and their colleagues in the Mechanical Processing and Physics Divisions for assistance with the spinning and testing work.

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16—THE PHYSICAL AND DIMENSIONAL PROPERTIES OF COTTON INTERLOCK FABRICS

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The dimensional and physical properties of simple cotton interlock fabrics manufactured by two different methods of machine-setting are analysed and compared. In method 1, stitch-cam settings are kept constant at a position wherein needles just clear the old loops, variations in the length of the structural knitted cell being achieved by dial-height adjustment. In method 2, the dial height is kept constant at the lowest possible setting consistent with a particular yarn linear density, variations in the length of the structural knitted cell being achieved by stitch-cam adjustment.

No significant difference in the dimensional and physical properties or in knittability is found within this range of fabrics manufactured by using different methods of machine-setting.

The dimensional properties of interlock fabric in different states of relaxation can be predicted by using *U*-parameters that approach constants dependent upon the machine tightness factor. Data are available that provide different values of *U*-parameters, which may be used for each tightness factor in a particular state of relaxation.

U-Parameters of low coefficient of variation are obtained when fabrics produced from different yarn linear densities are grouped according to the machine tightness factor. The accuracy of the prediction of fabric width, machine productivity, fabric weight, and fabric shrinkage or growth increases as fabrics approach a state of minimum energy. For fabrics produced by method 1, it is possible to predict the height at which the needle dial is to be set to produce a required length of structural knitted cell.

The variation of *U*-parameters with machine tightness factor and the anisotropic behaviour of certain interlock fabrics are explained in geometrical and mechanical terms by the use of theoretical models of interlock-loop deformation.

The physical properties investigated are fabric air-permeability, fabric thickness, fabric weight, and the biaxial deformation of the interlock structural knitted cell. In the majority of cases considered, the physical and dimensional properties of each 1×1 rib component of the interlock structure are compared with similar 1×1 rib fabrics manufactured on a half-gauge basis.

The intermeshing of the two 1×1 rib components is found to have a considerable effect on the coursewise extension and recovery of each 1×1 rib component of the interlock structure. This effect, known as the structural interference factor, is assessed and analysed. The structural interference factor is found to be that property of interlock fabric which accounts for its unusual widthwise behaviour.

1. INTRODUCTION

Interlock is a double 1×1 rib fabric. It is composed of two 1×1 ribs interlocked together with crossed sinker wales. Each of the two 1×1 rib fabrics in the interlock structure is prevented from contracting fully because of the wales of the other. This contraction gives the fabric a relatively smooth surface on both sides, and there is no tendency to curl when cut. The normal rib characteristics are maintained, the fabric cannot run or unravel from the end knitted first, and, additionally, inter-fabric friction reduces the tendency to run or unravel from the end knitted last.

There are no reliable data on the total global amount and type of fibre used for men's underwear, but lightweight knitted cotton underwear commands a major share of the market. This is not only the case with those countries situated between the Tropics of Cancer and Capricorn, but the wider use of central heating in homes and offices in countries outside the tropics tends to reduce the demand for heavier-quality wool underwear. Cotton garments are particularly suitable for wear next to the skin because of their natural softness, combined with a capacity to absorb water vapour in an amount sufficient to increase the comfort factor. Furthermore, the relatively low price of cotton, combined with its serviceability and ease of washing makes cotton interlock very suitable for summer clothing, leisure wear, and sportswear.

Dial-height adjustment appears to be a machine variable that is not yet well understood. It is suggested that the key to the understanding of its function, particularly in negative-feeding systems, is not to divorce dial-height adjustment from stitch-cam setting and design. From the literature available, it is suggested that statements have been made and advice has been given on this subject without the presentation of suitable analytical or empirical data on which to base that statement and advice. Shepherd[1] argues that, since the disposition of the fabric on a double-jersey machine is such that most of the fabric weight and take-down tension is carried by the dial needles, the loops on those needles are stressed more than the loops on the cylinder needles, this being confirmed by a greater occurrence of yarn breaks on the dial than on the cylinder needles. He suggests that the dial height should not be used as a means of adjusting yarn take-up. Knapton[2] states that the adjustment of the dial height may be the most misused control on a double-jersey knitting machine, for, by altering the dial height, the knitter may adversely affect the knitting performance without really realizing what effect the action of the dial needles has on the machine capacity and performance. Black and Munden[3], when commenting on the possibility of stitch-length adjustment with high-speed non-linear cams, imply that, on dial-and-cylinder machines, a range of stitch lengths could be obtained by an adjustment of the dial height.

2. PRODUCTION AND FINISHING OF EXPERIMENTAL INTERLOCK AND RIB FABRICS

2.1 Machine-settings and Fabric Particulars

Before the production of the experimental interlock and rib fabrics on an 18-in.-diameter (45.7-cm-diameter), 20-gauge, rotating-cambox interlock machine, preliminary trials were made on the machine to ascertain the range of

Table I

Group 1: Interlock Fabrics

Yarn Cotton Count	Yarn Linear Density (tex)	Dial Height (cm) Min.	Dial Height (cm) Max.	S.K.C.L. (cm) Min.	S.K.C.L. (cm) Max.
1/36	16.4	0.040	0.215	1.186	1.775
1/30	19.6	0.075	0.250	1.196	1.797
1/26	22.7	0.110	0.285	1.389	1.970

Table II

Group 2: Interlock Fabrics

Yarn Cotton Count	Yarn Linear Density (tex)	Dial Height (cm) (Constant)	S.K.C.L. (cm) Min.	S.K.C.L. (cm) Max.
1/36	16.4	0.040	1.186	1.736
1/30	19.6	0.075	1.196	1.779
1/26	22.7	0.110	1.389	1.896

Table III

Group 3: 1 × 1 Rib (Half-gauge) Fabrics

Yarn Cotton Count	Yarn Linear Density (tex)	Dial Height (cm) Min.	Dial Height (cm) Max.	S.K.C.L. (cm) Min.	S.K.C.L. (cm) Max.
1/36	16.4	0.040	0.215	0.581	0.879
1/30	19.6	0.075	0.250	0.608	0.906
1/26	22.7	0.110	0.285	0.681	1.000

structural-knitted-cell lengths (S.K.C.L.) available by modifying the dial-height and stitch-cam settings.

The limiting settings were found to be as given in Tables I, II, and III.

In all these preliminary trials, the limiting settings were those reached before the appearance of the first drop stitch or any other deterioration in knitting performance.

Groups of experimental fabrics were then knitted to the specifications given in Tables IV, V, and VI.

These fabrics were produced by using a constant stitch-cam setting, a variable dial height, and a variable structural-knitted-cell length.

Table IV

Group 1: Interlock Fabrics

Fabric Code No.	Yarn Cotton Count	Yarn Linear Density (tex)	Dial Height (cm)	S.K.C.L. (cm)
1	1/36	16.4	0.040	1.186
2	1/36	16.4	0.075	1.308
3	1/36	16.4	0.145	1.557
4	1/36	16.4	0.215	1.775
5	1/30	19.6	0.075	1.196
6	1/30	19.6	0.110	1.335
7	1/30	19.6	0.180	1.579
8	1/30	19.6	0.250	1.797
9	1/26	22.7	0.110	1.389
10	1/26	22.7	0.145	1.509
11	1/26	22.7	0.215	1.740
12	1/26	22.7	0.285	1.970

Table V

Group 2: Interlock Fabrics

Fabric Code No.	Yarn Cotton Count	Yarn Linear Density (tex)	Dial Height (cm)	S.K.C.L. (cm)
13	1/36	16.4	0.040	1.186
14	1/36	16.4	0.040	1.299
15	1/36	16.4	0.040	1.503
16	1/36	16.4	0.040	1.736
17	1/30	19.6	0.075	1.196
18	1/30	19.6	0.075	1.332
19	1/30	19.6	0.075	1.620
20	1/30	19.6	0.075	1.779
21	1/26	22.7	0.110	1.389
22	1/26	22.7	0.110	1.515
23	1/26	22.7	0.110	1.783
24	1/26	22.7	0.110	1.896

These fabrics were produced by using a variable stitch-cam setting, a constant dial height, and a variable structural-knitted-cell length.

These fabrics were produced by using a constant stitch-cam setting, variable dial height, and variable structural-knitted-cell length.

Table VI

Group 3: Rib Fabrics (1 × 1)

Fabric Code No.	Yarn Cotton Count	Yarn Linear Density (tex)	Dial Hieght (cm)	S.K.C.L. (cm)
25	1/36	16.4	0.040	0.581
26	1/36	16.4	0.075	0.650
27	1/36	16.4	0.145	0.779
28	1/36	16.4	0.215	0.879
29	1/30	19.6	0.075	0.608
30	1/30	19.6	0.110	0.671
31	1/30	19.6	0.180	0.795
32	1/30	19.6	0.250	0.906
33	1/26	22.7	0.110	0.681
34	1/26	22.7	0.145	0.744
35	1/26	22.7	0.215	0.868
36	1/26	22.7	0.285	1.000

2.2 Relaxation Treatments

2.2.1 Introduction

After being knitted, areas of fabric were subjected to one of four relaxation treatments as follows.

2.2.2 Dry Relaxation

Fabrics were laid flat on a polished surface for one week in a standard atmosphere before their dimensional properties were measured.

2.2.3 Wet Relaxation (Partial Relaxation)

Fabrics were relaxed in water and wetting agent at 60°C for 30 min, mangled, dried flat, and conditioned.

2.2.4 Full Relaxation (Acceptable Consumer Condition)

Fabrics were relaxed in water and wetting agent at 98°C for 2 hr, hydroextracted for 5 min, tumble-dried for 2 hr at 70°C, and conditioned.

2.2.5 Complete Relaxation (State of Minimum Energy)

Fabrics were treated as for full relaxation, this treatment being performed five times, with the dimensional properties measured after each cycle. The total wet-treatment time was 10 hr at 98°C, the total hydroextraction time being 25 min and the total tumble-drying time 10 hr at 70°C.

3. METHODS OF TEST FOR FABRIC SPECIMENS

3.1 Structural Density

Structural courses and structural wales were measured with a counting glass, the results being the means of twenty readings.

3.2 Structural-knitted-cell Length

Course lengths of 100 structural wales were measured in accordance with B. S. Handbook No. 11. The average of 24 readings was used to calculate the S.K.C.L. for each fabric.

3.3 Fabric Thickness

Thickness was measured in accordance with B.S.2544:1967.

Fabric Mass

Mass per unit area was determined in accordance with B.S.2471:1971 and expressed in g/m^2.

3.5 Fabric Air-permeability

The Shirley Air-permeability Tester was used to determine the air-permeability of the fabrics in accordance with the method described in B.S. Handbook No. 11, 1963, the alternative method given there being used.

3.6 Elastic Recovery

Samples 16 cm in length and 5 cm in width were cut in both coursewise and walewise directions. Tests were made on an Instron Tensile Tester set for a gauge length of 10 cm and at a cross-head speed of 2 in./min (5.08 cm/min). A fresh specimen was used for each of the strain levels considered and subjected to a multiplicity of loading and unloading cycles. The specimen was extended to predetermined strain levels and held at that level for 30 sec, during which time stress-relaxation occurred. The stress on the specimen was then removed and the recovery at zero stress recorded, this retraction being referred to as the initial elastic recovery. The specimen was kept in a state of minimum stress for 1 min for further recovery. The next test cycle was then commenced.

3.7 Symbols and Definitions

S.K.L. = Structural knitted cell = the smaller and repeating unit in any knitted structure

S.K.C.L. = Structural-knitted-cell length = length of yarn in one complete repeating unit (S.K.L.) of the structure

L_u = S.K.C.L.

C_u = Structural courses/cm = the number of visible complete repeats (S.K.C.) measured along a wale in 1 cm of fabric.

W_u = Structural wales/cm = the number of visible complete repeats (S.K.C.) measured along a course in 1 cm of fabric

S_u = Structural density = the number of visible repeats (S.K.C.) in 1 cm^2 of fabric

u_c = $C_u \times L_u$

U_w = $W_u \times L_u$

U_s = $S_u \times L_u^2$

K = MTF = Machine tightness factor = $\sqrt{\text{linear density (tex)}} \times n_t/L_u$ (where n_t = number of needles in the knitting operation in the S.K.C.); K is a measure of the tightness of construction in a knitted fabric.

t_c = Structural or geometrical thickness = fabric thickness at a pressure of 6.888 KN/m^2

H = Dial height = the vertical distance between the top of the needle cylinder and the base of the dial trick

P_a = Fabric air-permeability

IER = Initial elastic recovery = the recovery that takes place instantaneously after a load has been removed

TER = Total elastic recovery = the total recovery that takes place after a load has been removed for a time t

4. RESULTS AND DISCUSSION

4.1 Effect on Fabric Geometry in Producing Fabrics with a Constant Stitch-cam Setting, Variable Dial Length, and Variable Structural-knitted-cell Length

4.1.1 *Interlock Fabrics*

Plots of structural wales/cm (W_u) and structural courses/cm (C_u) against the reciprocal of the structural-knitted-cell length ($1/L_u$) are shown in Figures 1–7. Plots of the Poisson ratio (U_c/U_w) against the machine tightness factor (K) and of the structural density (S_u) against the inverse square of the structural-knitted-cell length ($1/L_u^2$) are shown in Figures 8 and 9 for the completely relaxed state.

In considering the relation between W_u and L_u, it will be noted that, for each set of samples, W_u is linearly correlated with $1/L_u$ at a high level of significance other than for the dry-relaxed state. In the wet-relaxed state, the intercept of the line with the best fit with the ordinate is different from zero for the fabrics in group 5–8, so in this particular case the linear equation

$$W_u = b/L_u + a,$$

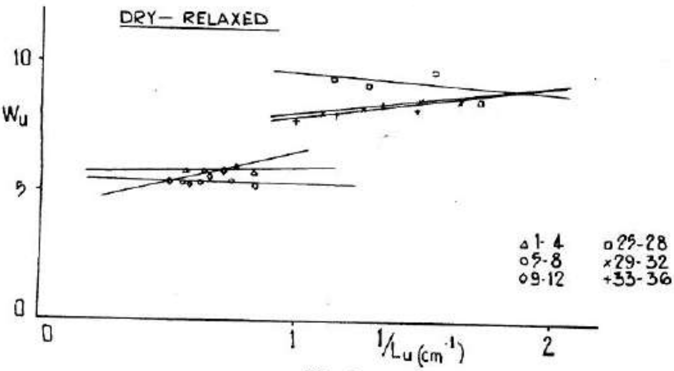

Fig. 1
Relation between structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for dry-relaxed interlock fabrics

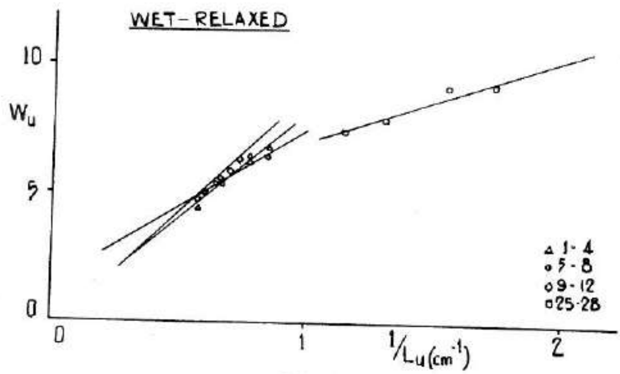

Fig. 2
Relation between structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for wet-relaxed interlock fabrics

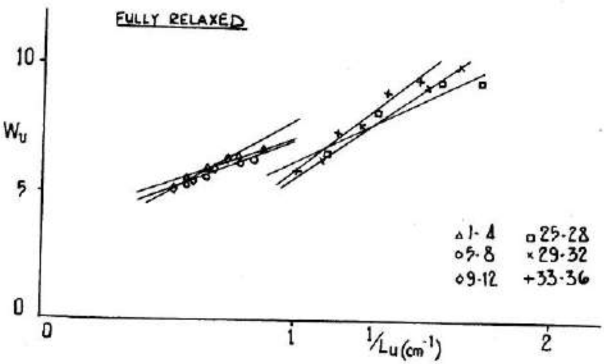

Fig. 3
Relation between structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for fully relaxed interlock fabrics

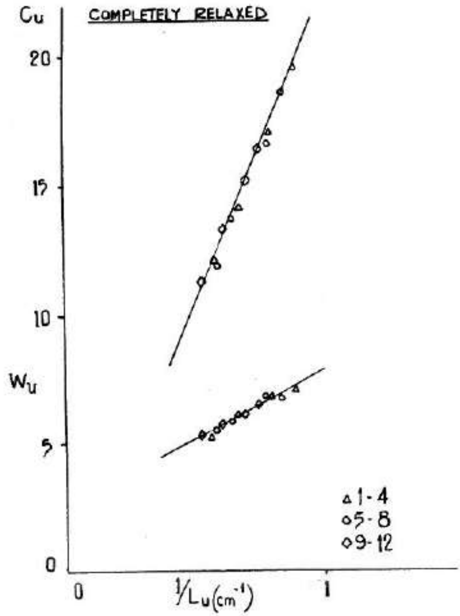

Fig. 4
Relation between structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for completely relaxed interlock fabrics

where a and b are constants dependent on the yarn linear density, would define the relation between W_u and L_u. For fabrics in groups 1–4 and 9–12, the intercepts of the line of best fit on the ordinate approach zero, and it would appear that the equation

$$W_u = b/L_u,$$

where b is a constant dependent on the yarn linear density, would define the relation between W_u and L_u. Since the wet-relaxed state does not correspond to a state of dimensional stability but is merely a transitional state, further dimensional changes may occur during subsequent laundry cycles.

In the completely relaxed state, where fabrics are said to be dimensionally stable, the relation is of the form:

$$W_u = b/L_u + a,$$

the values of a and b approaching constants independent of the yarn linear density. It may be concluded that the prediction of wale-spacing and hence the width of an interlock fabric is not easy but may be done with a reasonable degree of accuracy in the wet-relaxed and completely relaxed states. The value of C_u depends significantly on the value of L_u, the correlation between these two parameters being almost perfect. For each group of fabrics in the states of relaxation considered, the relation between C_u and L_u is linear and of the form:

$$C_u = b/L_u - a,$$

where a and b approach constants dependent upon the state of relaxation and little affected by the yarn linear density. In most cases, the value of the intercepts a on the ordinate are significantly different from zero and, in the dry-relaxed state, rather large. For all states of relaxation other than the dry-relaxed state, the

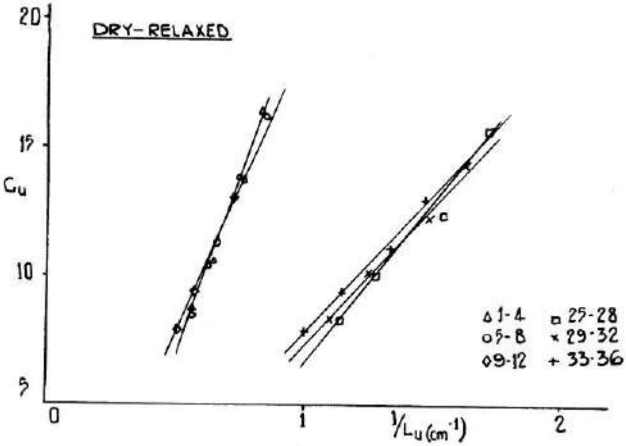

Fig. 5
Relation between structural courses/cm (C_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for dry-relaxed interlock fabrics

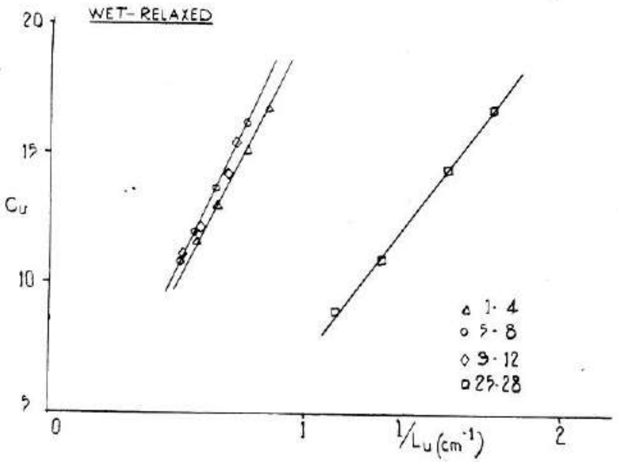

Fig. 6
Relation between structural courses/cm (C_u) and reciprocal of structural-knitted-cell length $1/L_u$) for wet-relaxed interlock fabrics

mean value of U_c is practically independent of the yarn linear density and generally has a low coefficient of variation. The equation

$$C_u = U_c/L_u,$$

where U_c is the mean for each group of fabrics and is dependent upon the state of

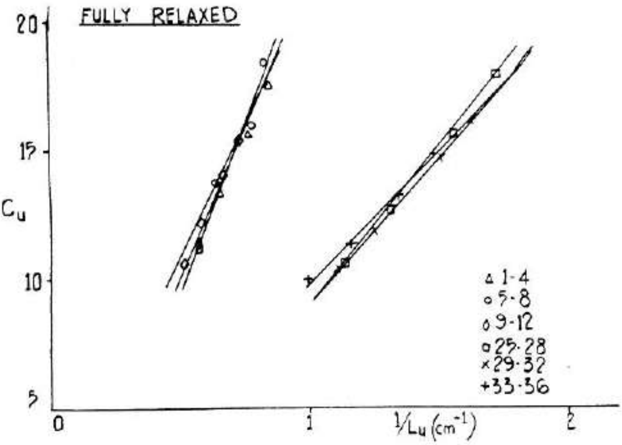

Fig. 7
Relation between structural courses/cm (C_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for fully relaxed interlock fabrics

relaxation considered, therefore appears to be of more practical value to enable one to predict the course-spacing and hence the length of an ihterlock fabric in the wet-relaxed, fully relaxed, and completely relaxed states.

The relation between S_u and $1/L_u^2$ is of a linear form with almost perfect correlation. In all states of relaxation considered, this relation takes the form

$$S_u = b/L_u^2 \pm a,$$

where *a* and *b* approach constants dependent upon the yarn linear density and state of relaxation; the dependence on on yarn linear density is less apparent in the completely relaxed state.

The mean value of U_s is similar for both the 1–4 and 5–8 groups of fabrics and rather greater for the 9–12 group of fabrics. In certain cases, the value of the coefficient of variation is rather low, which suggests that a reasonable prediction

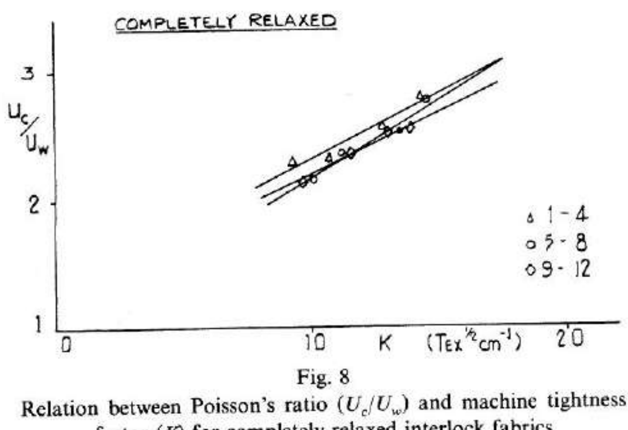

Fig. 8
Relation between Poisson's ratio (U_c/U_w) and machine tightness factor (K) for completely relaxed interlock fabrics

of stitch density, and hence fabric weight, may be achieved for these cases by using an equation of the form

$$S_u = U_s/L_u^2,$$

where U_s approaches a constant dependent upon the state of relaxation and only slightly dependent upon the yarn linear density.

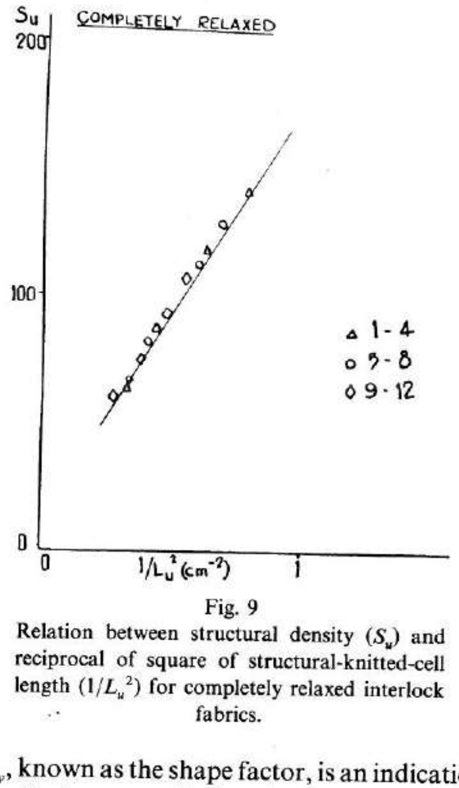

Fig. 9
Relation between structural density (S_u) and reciprocal of square of structural-knitted-cell length ($1/L_u^2$) for completely relaxed interlock fabrics.

The ratio U_c/U_w, known as the shape factor, is an indication of the shape the loop occupies in a particular state of relaxation. For both dry-relaxed and fully relaxed states, U_c/U_w is highly dependent upon the machine tightness factor, K. In the wet-relaxed state, U_c/U_w approaches a constant, mostly independent of K. In the completely relaxed state, U_c/U_w, though approaching a constant, is clearly dependent on K.

The relation between the dial height (H) and the structural-knitted-cell length (L_u) is of a linear form, and perfect correlation exists in the dry-relaxed state, as shown in Table VII. This relation is of the form:

$$L_u = bH + \mathrm{a},$$

where b is a constant independent of yarn linear density and the value of a is significantly different from zero and dependent on the yarn coefficient of friction, as shown in Table VIII.

It is apparent that the shape a loop occupies when in a particular state of

Table VII

Interlock Fabric Parameters (Dry-relaxed State)

Fabric Code No.	Dial Height (Machine)	Dial Height (cm)	L_u (cm)	W_u	C_u	S_u	U_w	U_c	U_s	U_c/U_w
1	−10	0.040	1.186	5.83	16.28	94.91	6.910	19.310	133.500	2.79
2	0	0.075	1.308	6.00	13.83	83.00	7.848	18.089	142.001	2.30
3	20	0.145	1.557	5.79	10.65	61.66	9.015	16.582	149.479	1.84
4	40	0.215	1.775	5.81	8.75	50.84	10.310	15.530	160.180	1.50
5	0	0.075	1.196	5.30	16.33	86.55	6.339	19.531	123.803	3.08
6	10	0.110	1.335	5.50	13.80	75.90	7.343	18.423	135.271	2.51
7	30	0.180	1.579	5.43	10.50	57.02	8.574	16.580	142.165	1.93
8	50	0.250	1.797	5.36	8.63	46.26	9.632	15.508	149.383	1.61
9	10	0.110	1.389	5.94	13.13	77.99	8.251	18.238	150.468	2.21
10	20	0.145	1.509	5.65	11.50	64.98	8.526	17.354	147.965	2.04
11	40	0.215	1.740	5.39	9.50	51.21	9.379	16.530	155.043	1.76
12	60	0.285	1.970	5.46	8.00	43.68	10.756	15.760	169.518	1.47

Table VIII

Yarn			
Cotton Count	Linear Density (tex)	Coefficient of Friction	a
1/36	16.4	0.37	1.309
1/26	19.6	0.39	1.275
1/30	22.7	0.40	1.207

relaxation depends significantly on the tightness of construction of the knitted fabric, with the possible exception of the wet-relaxed state. If the assumption that the shape of the knitted loop approaches the shape of an elastica were true for the knitted-interlock structures, then all intercepts of the line of best fit on the ordinate would approach zero and the slopes of regression lines, tabulated from data held in the University of Strathclyde Library, would approach constants independent of L_u and the yarn linear density; in that case, the value of U_c/U_w would also approach a constant independent of K for a particular case of relaxation. The only state of relaxation for which the elastica assumption is tenable would appear to be the wet-relaxed state. Nevertheless, measurements of the height and width of a true elastica model show that the height of the elastica is always greater than its width. If this statement were translated into knitted-fabric-geometry concepts, the height of the elastica would refer to the course-spacing and the width of the elastica to the wale-spacing, so that the value of courses/cm should always be lower than the value of wales/cm. For the interlock structure, the number of courses/cm is the same as the number of structural courses/cm and the number of wales/cm is equal to twice the number of structural wales/cm. From data held by the authors, it may be seen that, in cases where U_c/U_w is greater than 2, the number of courses/cm is always greater than the number of wales/cm, so that the height of the loop is, in this case, smaller than its width. Only for some slack-knitted fabrics in the dry-relaxed and fully relaxed states is U_c/U_w less than 2, so the assumption that, in the wet-relaxed state, the shape of the loop approaches the shape of an elastica is difficult to accept. When the vlaue of U_c/U_w is less than 2 in the dry-relaxed state, the fabric grows in width after wet relaxation, the opposite happening when U_c/U_w is greater than 2 in the dry-relaxed state. Thus it would appear that, if the knitted-interlock loop were an elastica, then, in the dry-relaxed state, width expansion, rather than shrinkage, could be expected after wet relaxation.

4.1.2 1 × 1-Rib Fabrics

These fabrics were produced on a half-gauge basis on the machine used for the interlock structure. Plots similar to those previously discussed are shown in Figures 1–7. The object of studying the 1 × 1-rib half-gauge structure is seen as an attempt to study interlock as a composite 1 × 1-rib structure and the relation of each rib component to the whole interlock assembly.

With the exception of fabric groups 25–28 and 33–36 on the dry-relaxed state, there is a reasonable linear correlation between W_u and $1/L_u$. The intercepts of the line of best fit on the ordinate are significant, and for the dry-relaxed state the intercepts are rather large. The slopes of the regression lines are dependent on the yarn linear density and state of relaxation, and the mean values of the U_w-parameter also depend on the yarn linear density and state of relaxation. The coefficient of variation of the mean U_w-parameters decreases as the fabric approaches a state of minimum energy. In the fully relaxed state, an equation of the form:

$$W_u = U_w / L_u,$$

where U_w is the mean value of the U_w-parameters, approaching a constant slightly dependent on the yarn linear density, would give a reasonable prediction for W_u, from which the fabric width may be calculated. If W_u for each 1 × 1-rib fabric component of each interlock fabric discussed in the previous sub-section be compared with W_u of an equivalent 1 × 1-rib fabric, it will be noted that there are considerably fewer (but always more than half the number) structural wales in the former than in the latter. The fact that there are always more than half the number of structural wales/cm in the 1 × 1-rib component of an interlock fabric than in its equivalent 1 × 1-rib half-gauge fabric is due to the fact that the loops of one rib-fabric component of interlock are positioned above and under neighbouring loops of the other component fabric, in such a way that the narrowest part or neck of each loop of the former is positioned in the same horizontal line as the widest part of a neighbouring loop of the latter.

The relation between C_u and $1/L_u$ is linear. The mean value of U_w approaches a constant independent of the yarn linear density when the fabric is in the fully relaxed state, and an equation of the form:

$$W_u = U_w / L_u$$

could be used to predict W_u and hence the fabric length in that state.

In the dry-relaxed state, a linear correlation exists between the dial height (H) and the structural-knitted-cell length (L_u). This relation is of the form

$$L_u = bH + a,$$

where b is a constant independent of the yarn linear density, the value of a being dependent on the yarn coefficient of friction.

4.2 Effect on Fabric Geometry of Producing Interlock Fabrics with a Variable Stitch-cam Setting, Constant Dial Height, and Variable Structural-knitted-cell Length

The fabric parameters in the four states of relaxation considered are shown in Figures 10–13. In comparison with Figures 1–7 in the previous section, it will be noted that there is a great similarity in the value of the slopes, this indicating that the method of production, that is, either by having a variable dial height and

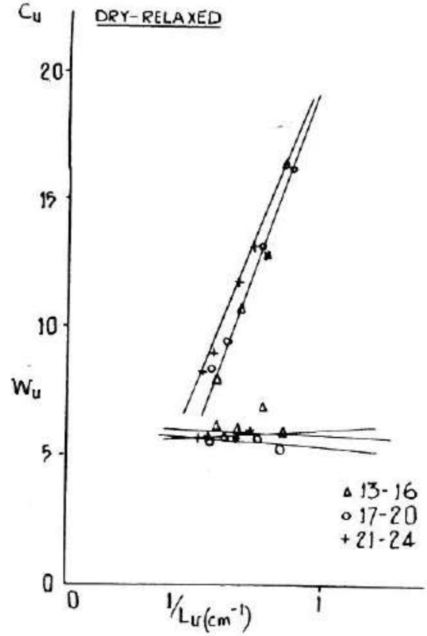

Fig. 10
Relation between (i) structural courses/cm (C_u) and (ii) structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for dry-relaxed interlock fabrics

constant stitch-cam setting or by having a constant dial height and a variable stitch-cam setting (the conventional method), has little ultimate effect on the parameters of the structure. What differences do exist appear to diminish as a state of complete relaxation is reached.

This suggests that the controlling factor among the fabric parameters is the total amount of yarn in the structural knitted cell and not just that in the cylinder or dial loop or both. Within reasonable limitations, it would appear that the ratio of yarn distribution between the cylinder loop, the dial loop, and the 'legs' of yarn joining those loops is not critical provided that the fabric is suitably finished, that is, taken to a state of minimum energy. If a suitable finish is not applied, then yarn movement within the structural knitted cell will cause considerable garment deformation after domestic laundering.

4.3 Fabric Thickness

In considering the relation between the structural thickness at a pressure of 6.888 KN/m^2 (t_c) and L_u, the relation is of an almost linear form for both the dry-relaxed and fully-relaxed states up to a point at which rate of increase of t_c with L_u declines, as can be seen by a flattening of the plot. For fabrics knitted from the same yarn, the effect of loop curvature into the plane of the fabric as the fabric relaxes appears to be the main parameter affecting the thickness of tightly knitted fabrics, whereas yarn-swelling and raising of the fibres on the surface of the fabric also play an important part affecting the thickness of slackly knitted fabrics. When fabrics of the same structural-knitted-cell length but of different yarn linear density are compared, it is clear that the fabric thickness increases with the yarn linear density.

4.4 Fabric Air-permeability

In attempts to assess this parameter, plots of fabric air-permeability (P_a) against the ratio of structural thickness to structural-knitted-cell length (t_c/L_u) and machine tightness factor (K), were produced. It is clear that, for all states of relaxation considered and for each group of fabrics, including the 1×1-rib samples, the relation between P_a and t_c/L_u is linear at a high level of significance and can be defined by the appropriate equation. Related interlock fabrics produced by the two different methods do, in the initial stages, exhibit small differences, but these small differences almost disappear as the fabrics proceed from the dry-relaxed to the fully relaxed state. It may be concluded that there are no significant differences between the air-permeability properties of these fabrics when produced by either method of machine-setting and given the relaxation treatments previously described. Moreover, such differences as do exist will

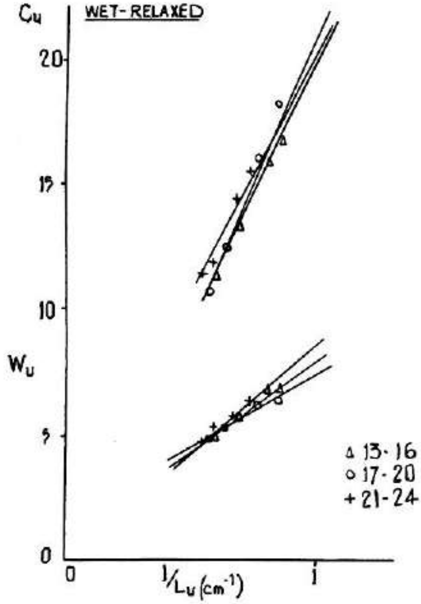

Fig. 11
Relation between (i) structural courses/cm (C_u) and (ii) structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for wet-relaxed interlock fabrics

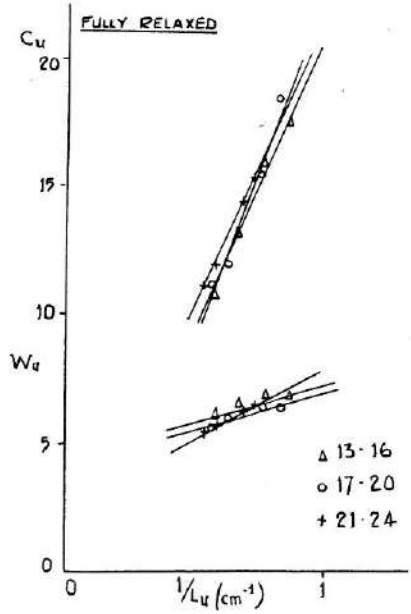

Fig. 12
Relation between (i) structural courses/cm (C_u) and (ii) structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for fully relaxed interlock fabrics

decrease in value as the fabric relaxation proceeds towards a state of minimum energy.

4.5 Elastic Recovery

For each set of fabrics, two forms of tensile elastic recovery, namely, initial elastic recovery (IER) and total elastic recovery (TER), were calculated from cyclic loading and unloading curves.

The tensile elastic recovery of all fabrics was measured at strain levels ranging from zero to 40%. This maximum value was chosen because various researchers have indicated that stretch fabrics, during normal wear, are required to meet extension levels of up to 40%. Rest 4 has given levels of body extension at seat, knee, elbow, and back as 5, 13, 19, and 15%, respectively. It has been noted that, in lifting the arms above the head, the skin on the human back stretches by 13–16%, and elbow- and knee-bending cause localized skin-stretching of up to 40%. Thus, to provide the wearer of the garment with comfort and freedom of movement, and to keep the initial shape of the garment, built-in recoverable extension of certain garments, particularly those for sportswear, must be of the order of 40%.

On all the fabrics produced, measurements of initial and total elastic

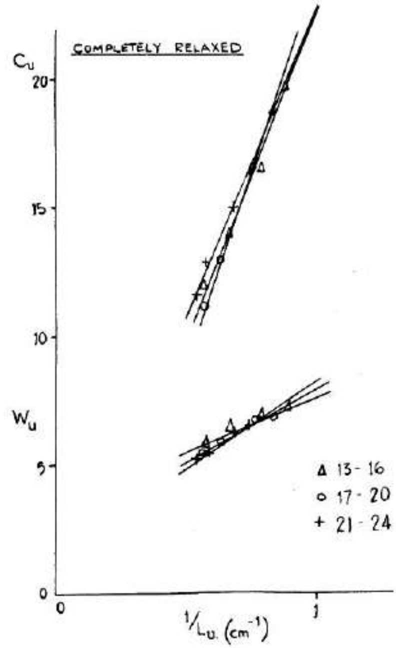

Fig. 13
Relation between (i) structural courses/cm (C_u) (ii) structural wales/cm (W_u) and reciprocal of structural-knitted-cell length ($1/L_u$) for completely relaxed interlock fabrics

recovery were made for the various strain levels and for the first and fourth cycles in both coursewise and walewise directions. Deformation–recovery curves for a tightly knitted and a slackly knitted fabric were compiled, and plots of total elastic recovery (TER) against strain (ε) in the coursewise and walewise directions were obtained. The characteristic of many viscoelastic materials wherein the load required to produce a given state of strain decreases after the first cycle is also exhibited by these fabrics. The characteristic may be explained by the superposition principle attributed to Boltzmann, according to which the deformation at any instance in a body showing primary creep is due not only to the load acting at that instance but also to the entire previous loading history and is given by the summation of the effects of every previous change of load.

The load required to attain a particular strain level decreases as the fabric relaxation increases, the initial and total elastic recovery from any particular strain level increasing as the fabric relaxation increases (particularly in the walewise direction). The reason for this is that, as relaxation proceeds, fabric stresses imposed during manufacture, which act as constraints to both extension and recovery in the dry-relaxed state, diminish in value as the fabrics proceed towards a state of minimum energy, which thus allows extension and recovery to be performed with a greater freedom, so that the load required to produce a given extension decreases and recovery from the applied load increases. Normally, both initial and total elastic recoveries decrease as the strain increases because the amount of permanent deformation or secondary creep increases as the strain increases. In all cases, initial and total elastic recoveries are greater in the coursewise direction than in the walewise direction, this being due to the type of deformation involved in both cases. Only in the coursewise direction and then only at very high levels does the yarn axis commence to accept the effect of deformation load, whereas in the walewise direction the effect of deformation load on the yarn axis takes place at considerably lower extensions. This is related to the basic formation of the knitted loop and to the structural formation of the interlock structural knitted cell.

In the coursewise direction, both the initial and the total elastic recovery increase as the machine tightness factor (K) decreases, the load required to attain a particular extension decreasing as K decreases. These effects are due to the fact that loosely knitted structures are more spring-like than tightly knitted structures and are thus more easily deformable but have greater recovery properties. Nevertheless, because loosely knitted structures are so easily deformable, it is very easy to deform these structures beyond their elastic limit and thus cause permanent deformation. With respect to knitted-fabric performance, a compromise must be reached between stability at the cost of elasticity and elasticity at the cost of bagginess; within reasonable limits, the former is normally preferable.

In the walewise direction and in the dry-relaxed state, it is difficult to appraise the effect of K on the fabric elastic recovery because of the effect of loop distortion during the manufacturing process, particularly the effect of take-down tension, which, if excessive, causes unnecessary elongation of the needle loop at the immediate expense of the yarn link between the cylinder and dial loops. In the fully relaxed state, in which the loops tend to take up a shape more akin to their natural form in the knitted fabric, there appears to be a tendency for both the initial and total elastic recoveries to increase as K increases. This is related to the bending properties of a knitted yarn, whereby the couple required to bend the yarn into a small loop is proportionately greater than the couple required to bend the yarn into a large loop.

It may be stated that, in comparing the elastic-recovery performance of the interlock fabrics produced by the two methods, there is no noticeable difference in the properties of the two sets, particularly when the level of relaxation is increased.

5. CONCLUSION

There appears to be little or no difference in the physical properties of cotton interlock fabrics produced by these two different methods of machine adjustment. For a machine designed to produce simple (plain) interlock, there is no reason why such a machine should not have a linear cam system utilizing a fixed, minimal knock-over position, with stitch-length adjustment given by the dial-height movement. A rearrangement of the angular relation between the cylinder and dial needles could alter the distribution of stress on the fabric at the point of loop formation and fabric passage. There are many garments produced from cotton interlock that do not possess the appropriate stability and recovery properties that they should. That situation is due almost entirely to a lack of understanding of fabric relaxation and an unwillingness by some manufacturers to spend a little more time and finance on producing a garment having superior qualities.

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17—THE DEVELOPMENT OF WOVEN-FABRIC MECHANICS BY MEANS OF OPTIMAL-CONTROL THEORY

By R. Postle and S. de Jong

An energy analysis is formulated with the aid of optimal-control theory and applied to the study of woven-fabric mechanics. The analysis is based on the fundamental principle that elastic structures always assume a configuration of minimum strain energy, regardless of the deformation applied. The resultant minimization of total yarn-strain energy within the fabric (consisting of yarn-bending, torsion, lateral compression, and longitudinal extension) is treated as an optimal-control problem and is subject to certain constraints acting within the fabric.

It is shown how the mechanistic model of relaxed woven fabrics proposed in 1937 by F. T. Peirce may be derived from energy equations for values of weave crimp ranging from low to moderate. For higher values of weave crimp, the introduction of an extra constraint on the curved yarn results in the geometrical model also proposed originally by Peirce and widely used in the textile literature.

The energy and optimal-control analysis is applied to the uniaxial and biaxial tensile deformation of woven fabrics by including the possibility of yarn extension in the theory. Fabric load–extension curves and yarn-decrimping curves are computed and compared with experimental results for cotton and cotton-blend plain-weave fabrics in both the grey and finished states. The computed curves are discussed in terms of the following parameters expressed in dimensionless or normalized form: the applied tension per thread and the interaction force per crossing thread, the relative fabric extension (fabric extension/initial weave crimp), the initial relative fabric tensile modulus, the fabric Poisson's ratio, and the initial tensile modulus of the crimped set yarn unravelled from the fabric.

The pure-bending behaviour of the plain-weave structure is also evaluated as a generalization of the tensile deformation. The ratio of fabric-bending rigidity to yarn-bending rigidity is computed for a range of fabric structures of different values of weave crimp and degree of set by the introduction of inequality constraints on the yarn curvature, a concept borrowed from optimal-control theory. The theoretical results are compared with the pure-bending behaviour of cotton and cotton-blend woven fabrics in both the grey and commercially finished states.

The implications of the work reported in this paper for future theoretical and experimental studies of the structure and mechanical properties of woven fabrics are discussed.

1. INTRODUCTION

The importance of fabric mechanics lies in its direct relation to the objective specification, design, method of manufacture, and functional end-use of textile materials. Hence there is a need to study the fundamental and practical implications for the specification of the mechanical properties of woven-fabric structures, particularly as a consequence of recent developments in the field of fabric mechanics.

The study of woven-fabric mechanics dates back to very early work reported in 1912 by Haas[1] in the German aerodynamic literature at the time of world-wide interest in the development of airships. In the English literature, the paper by Peirce[2] in 1937 presents a purely geometrical and a mechanistic model of the plain-weave structure, both of which have been used extensively and modified by subsequent workers in the field[3,4].

It has been generally argued[4,5] that the two Peirce models of the woven structure represent two fundamentally different approaches to the problem of fabric mechanics, and accordingly each model has its own particular uses and relevance to theoretical and practical problems occurring in fabrics.

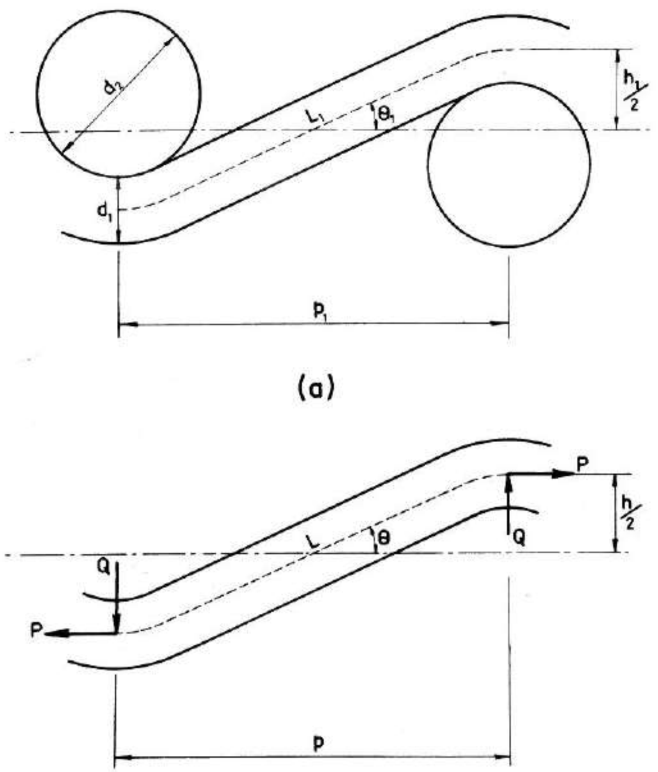


Fig. 1

A schematic representation of: (*a*) Peirce's geometrical model of the plain-weave structure, showing the basic geometrical parameters of the weave crimp (note that the subscripts 1 and 2 are interchanged for the perpendicular cross-sectional view); and (*b*) Peirce's mechanistic model, showing the internal lateral pressure Q between warp and weft yarns and an externally applied tension P

Specifically, the geometrical model shown in Fig. 1(*a*), which is purely descriptive and is based on the initial assumptions of perfect yarn flexibility and circular yarn cross-section of fixed yarn diameter, has been used to derive relations between such woven-fabric parameters as curvilinear or modular yarn length, L, weave-crimp angle, θ, crimp height, h, yarn diameter, d, and thread-spacing, p, for both warp and weft and also to predict the jamming conditions for woven fabrics. On the other hand, the mechanistic model shown in Fig. 1(*b*), which initially assumes perfect linear elasticity for yarn-bending in both warp and weft threads, takes account of the reaction forces Q acting between the warp and weft yarns in the fabric and has been used as the basis for evaluating the internal stresses acting within a relaxed woven fabric[3] (for which the applied tension $P = 0$) and also the stress–strain behaviour of woven fabrics in tension ($P \neq 0$),[5, 6] bendin[7–9], and shear[10].

The present authors[11] have recently proposed a general theoretical analysis of both relaxed and deformed fabric structures by using energy considerations and have applied the concepts of computerized optimal-control theory to the resulting energy-minimization problem. The theory has been successfully applied to knitted[12] and woven fabrics[13,14], and, in this paper, it is shown how both models of the plain-weave structure originally proposed by Peirce may be derived from the general energy equations for different levels of weave crimp in the relaxed woven fabric. It is further shown how the energy and optimal-control theory may be used to derive the uniaxial and biaxial tensile properties and the pure-bending properties of woven fabrics.

This generalized approach to fabric mechanics highlights the important structural parameters and yarn properties that determine the fabric mechanical behaviour as well as its relaxed configuration. These parameters are expressed in normalized form, and their use is illustrated for a set of cotton and cotton–ployester-fibre blended-fibre woven materials.

2. THE BASIC ENERGY–OPTIMAL CONTROL FORMULATION OF FABRIC MECHANICS

The traditional use of force methods to analyse specific problems in fabric mechanics has encountered difficulties[15] because of the inherently complex nature of fabric structure. It is well known that the condition of force and moment equilibrium in static structures, whether relaxed or deformed, is mathematically equivalent to the condition of minimum energy[16–18]. In the textile literature several workers[19–22] have used energy methods to solve specific problems in yarn and fabric mechanics by making an initial set of assumptions about the geometry of the particular textile yarn or fabric under consideration. For this reason, the energy methods used by these workers cannot be readily used to provide a basic formulation for fabrics generally, whether relaxed or subject to deformation.

However, energy methods are widely used to solve complex problems in mechanics[16], where geometric intuition is replaced by algebraic relations deduced from the energy principle. It has been shown by the present authors[11] that the process of minimizing an energy function appropriate to the general solution of problems in fabric mechanics suggests itself as a particular class of optimization techniques, i.e., as a computerized optimal-control problem. Briefly, the optimal-control problem[23–26] is to determine the *control*, $m^*(s)$, that optimizes a given *performance measure*, $J(m)$. As an example, $m^*(s)$ is to be found such that the following integral is minimized:

$$J(m) = \int_{s_0}^{s_1} f(x,m)\mathrm{d}s, \qquad \ldots . (1)$$

subject to:

$$\frac{\mathrm{d}x}{\mathrm{d}s} = \mathrm{g}(x,m). \qquad \ldots (2)$$

It can be seen that $m(s)$ is not a completely independent variable (or set of variables if m is a vector), but it is related to the *state* variable, $x(s)$, and $\mathrm{d}x/\mathrm{d}s$ through the *constraint* equation (Equation (2)). This differential constraint is called the *state* or *system* equation.

To arrive at some very general necessary conditions of the optimal control m^*, we define:

$$F = \mathrm{F}(x,m) + \lambda\left(\mathrm{g}(x,m) - \frac{\mathrm{d}x}{\mathrm{d}s}\right); \qquad \ldots . (3a)$$

$$H = \mathrm{f}(x,m) + \lambda\mathrm{g}(x,m). \qquad \ldots . (3b)$$

The introduction of the Lagrange multiplier, $\lambda(s)$, allows the control variable m to be treated as a completely independent variable. When the constraint equation (Equation (2)) holds, minimizing $\int \mathrm{f}\mathrm{d}s$ is equivalent to minimizing $\int \mathrm{F}\mathrm{d}s$. It can be shown 23–26 that, in conjunction with Equation (2), the necessary conditions for a minimum are:

$$\frac{\delta H}{\delta m} = 0. \qquad \ldots . (4)$$

Moreover, an additional relation can be proved:

$$\frac{\delta H}{\delta x} = \frac{\mathrm{d}\lambda}{\mathrm{d}s} \qquad \ldots . (5)$$

which is called the *costate* equation, H being the *Hamiltonian*.

In problems of fabric mechanics, $\mathrm{f}(x,m)$ may be identified as the total strain energy per unit length of yarn, i.e., the sum of the strain energy due to yarn-bending, torsion, lateral compression, and longitudinal extension; m then becomes the yarn-curvature vector, and x defines the yarn shape within the fabric. Moreover, it has been shown[11] that the Lagrange multiplier, λ, has a very important physical significance in that it represents the forces and couples acting on the yarn within the fabric.

The *State* and *costate* equations and the *constraints* on the yarn within the fabric are presented in their most general form in a previous paper[11], where the total yarn-strain energy is minimized subject to the constraints on the yarn that give rise to internal forces and couples acting within the fabric structure itself. The set of necessary conditions for a minimum is given by Equations (2), (4), and (5) and holds regardless of the boundary conditions imposed, i.e., for different fabric constructions, whether relaxed or deformed. Specific fabric constructions and different modes of deformation can therefore be treated as different boundary-value problems.

3 THE RELAXED PLAIN-WEAVE STRUCTURE

For application to the plain-weave structure (where the crimp is two-dimensional in shape), the general three-dimensional energy equations have been reduced to two-dimensional form and the boundary conditions evaluated [13,14]. The weave-crimp shape, which has the requisite interlacing characteristics for the plain-weave construction, was fed into the computer, whereupon the shape was manipulated systematically to arrive at the minimum-energy or stable weave-crimp shape for a relaxed fabric (i.e., one that is not subjected to any externally applied forces or couples). From this equilibrium crimp shape, it is possible to evaluate the internal forces acting within the fabric itself as well as the relations between the various woven-fabric constructional parameters, e.g., thread-spacings, p, crimp heights, h, weave-crimp angles, θ, and the curvilinear yarn length, L, in both warp and weft directions (see Fig. 1).

The energy and optimal-control analysis has been extended by Knoll[27] to include the effect of continuous contact between crossing threads in a relaxed or tensioned fabric by the introduction of an additional inequality constraint in a manner similar to that employed by the present authors[13,14] in considering the pure-bending properties of woven fabrics. By the application of the energy equations derived for woven fabrics[14], Knoll was able to show that the relaxed-fabric parameters for levels of weave crimp from low to moderate (up to about 11% for a balanced square weave) agree with those predicted by the Peirce mechanistic model shown in Fig. 1(*b*), but, for greater values of weave crimp as structural jamming is approached, the fabric parameters predicted by the energy equations move away from those predicted by the purely mechanistic model of Peirce towards Peirce's geometrical model shown in Fig. 1(*a*). This transition from the purely mechanistic to the purely geometrical model when the maximum yarn curvature is constrained by the diameter of the crossing yarn, as shown in Fig. 1(*a*), was described in Peirce's original paper[2], but, as Knoll[27] points out, this upper limit to the yarn curvature was not considered by subsequent workers in the field before the development of the general energy equations.

To illustrate how the energy equations can be used to derive both of Peirce's models, the values of weave-crimp angle, θ, are plotted in Fig. 2 against h/L (the ratio of crimp height to curvilinear yarn length). These values were obtained by Knoll[27], using the energy equations derived by de Jong and Postle[13] for the plain-weave structure, by assuming various values for the internal reaction force,

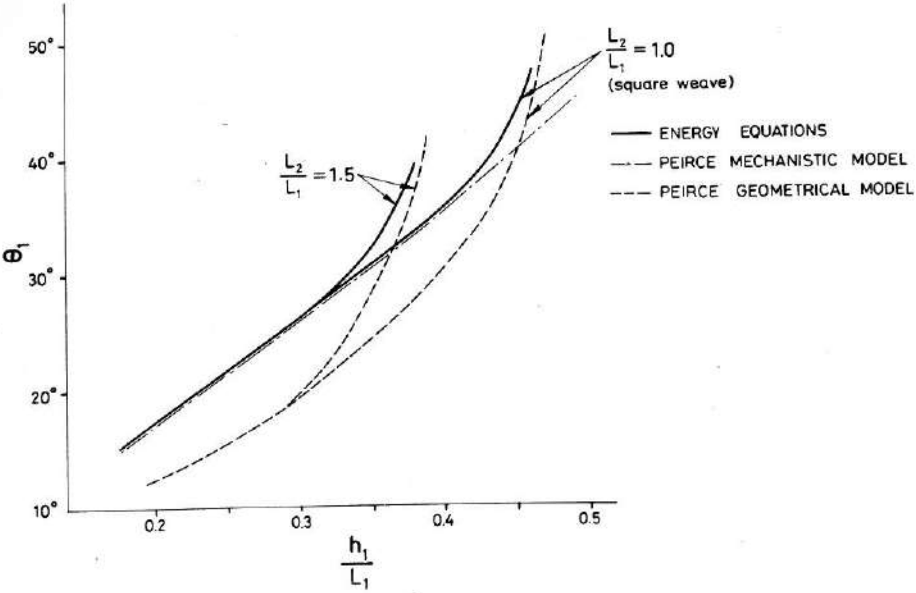


Fig. 2

A comparison of the weave-crimp parameters θ and h/L derived from the energy equations, Peirce's mechanistic model, and Peirce's geometrical model of the plain-weave structure (after Knoll[27])

Q, under conditions of zero external tension ($P = 0$). Two curves were derived from the energy equations, one for the balanced square-weave construction ($L_2/L_1 = 1$) and one for a non-square weave, where $L_2/L_1 = 1.5$. Both curves are compared with the corresponding curves derived from Peirce's mechanistic and geometrical models.

In order to facilitate comparison with Peirce's models, the curves shown in Fig. 2, derived from the energy equations, were based on the assumption of incompressible yarns of circular cross-section, but the analysis can be readily extended to include compressed yarn with flattened lenticular cross-sectional shapes.

On considering the curves for the square-weave structure shown in Fig. 2, it is clear that, for values of $\theta \leq 35°$ (corresponding to crimp values less than 11% approximately), the Peirce mechanistic model based on single-point contact between warp and weft is applicable. As θ increases towards 35°, i.e., as the weave crimp approaches 11%, the warp- and weft-yarn systems make contact over a larger area and the curve derived from the energy equations approaches the limiting case of Peirce's geometrical model (as structural jamming is approached). Complete jamming of the structure occurs at the maximum or limiting value of $h/L = 0.478$; the reaction force Q between the warp and weft threads (not shown) rises steeply as jamming is approached.

For the non-square weave (where $L_2/L_1 = 1.5$), the condition of continuous yarn contact is reached at lower values of crimp and h/L than for the square weave.

Similar curves may be obtained for other crimp ratios (different values of L_2/L_1) and for pairs of fabric parameters other than θ and h/L.

It may be concluded that the basic energy and optimal-control formulation of woven-fabric mechanics can be used to derive the elastic mechanistic model of the relaxed plain-weave structure ($P=0$) for values of the weave crimp ranging from low to moderate. However, the introduction of an inequality constraint, limiting the maximum value of the yarn curvature to that governed by the shape of the crossing thread, means that the energy equations produce results corresponding to Peirce's purely geometrical model as the weave crimp increases and the structure becomes very tight and approaches the jamming condition. The actual value of the weave crimp at which jamming occurs is very dependent on the ratio of curvilinear yarn lengths in warp and weft, L_2/L_1, and on the actual yarn cross-sectional shape.

It is clear from this work that the two models of the relaxed plain-weave structure proposed by Peirce are not mutually exclusive as has often been implied but rather are both applicable at different levels of the weave crimp. The basic energy and optimal-control formulation of woven fabrics has thus provided a unified basis for the detailed study of the mechanical properties of woven fabrics.

4. THE TENSILE PROPERTIES OF WOVEN FABRICS

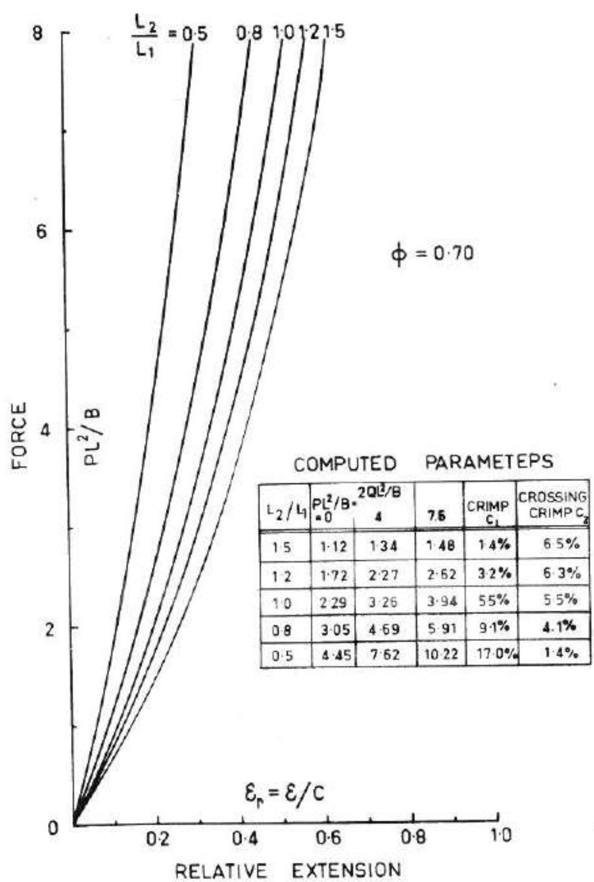
4.1 Parameters and Experimental Conditions

The energy equations have been used to investigate the plain-weave structure in biaxial tension[13, 27] (uniaxial tension merely being considered as the special case where the tension in one of the principal directions of the fabric is zero). An important mechanism of woven-fabric extension is considered in the theory, namely, the possibility of yarn extension.

The fabric load–extension curves and yarn-decrimping curves for the plain-weave construction were computed for a realistic range of input parameters: the yarn-bending rigidity (B), the yarn-extension modulus (Y), the weave crimp (C), the degree of set (ϕ), and the curvilinear lengths of yarn in the two principal directions of the fabric (L_1, L_2). Typical curves are shown in Fig. 3, where it can be seen that the load–extension curves are non-linear.

The computed results are discussed in terms of the following dimensionless parameters: the applied (dimensionless) tension per thread (PL^2/B), the relative extension, $\varepsilon_r (= \varepsilon/c$, where ε is the actual fabric or yarn decrimping extension), the initial relative modulus E_{r2} in the range $0 < PL^2/B < 2$, Poisson's ratio of the fabrics, and the relative extension of the fabric (yarn) ε_{r8} at $PL^2/B = 8$.

Two sets of commercial plain-weave fabrics were obtained, one a pure cotton fabric and the other a 50–50 cotton–polyester-fibre blend (Table II). Each fabric was tested in both grey and finished states. Standard bending-hysteresis tests were carried out on both the yarn and fabric, bent to a curvature of 3 cm^{-1} at a rate of 12 cm^{-1}/min and with a gauge length of 0.5 cm. Tensile load–extension curves on both the unravelled yarns and the fabric were obtained



L_2/L_1	PL^2/B = 0 (2QL²/B)	4	7.6	CRIMP c_1	CROSSING CRIMP c_2
1·5	1·12	1·34	1·48	1·4%	6·5%
1·2	1·72	2·27	2·62	3·2%	6·3%
1·0	2·29	3·26	3·94	5·5%	5·5%
0·8	3·05	4·69	5·91	9·1%	4.1%
0·5	4·45	7·62	10·22	17·0%	1·4%

Fig. 3

Typical uniaxial load–extension curves for plain-weave fabrics in the grey state ($\phi = 0.70$) extended in the L_1 direction; the curves are plotted for different ratios L/L_1 (cloth sett) in terms of the dimensionless quantities PL^2/B, the tension per thread, and the relative extension, $\varepsilon_r = \varepsilon/c$. The inset shows the values of weave crimp c_1 (direction L_1) and crossing crimp c_2 (direction L_2) for each value of L_2/L_1 computed, together with the increase in crossing-thread interaction forces, $2QL^2/B$, with increasing applied tension, $PL^2/B = 0, 2, 7.6$

on an Instron Tensile Tester. The fabric or yarn was in each case loaded to a maximum load of $PL^2/B = 8$. On the two sets of fabrics, an estimate of Poisson's ratio was made.

4.2 Yarn-decrimping Curves

Computed yarn-decrimping curves are shown in Fig. 4 for values of YL^2/B

Table I

Details of Plain-weave Cotton Fabrics

Fabric	Warp Linear Density (tex)	Ends/cm	Warp $c\%$	Warp Modular Length, L(cm)	Weft Linear Density (tex)	Picks/cm	Weft $c\%$	Weft Modular Length, L(cm)
(A) Grey	33	21.2	9.0	0.059	37	18.6	7.0	0.051
Finished		22.4	4.0	0.059		17.6	11.0	0.049
(B) Grey 50–50% polyester-fibre–cotton	30	23.2	9.4	0.051	30	22.5	6.6	0.046
Finished		24.8	3.3	0.045		20.8	10.8	0.050

Table II

Yarn Measurements

Fabric		B (mN mm^2)	Y (N)	YL^2/B	E_{r2}	ε_{r8}	ϕ
(A) Grey	Warp	3.6	16	1500	6.3	0.70	0.87
	Weft	2.1	13	1600	5.0	0.74	0.87
Finished	Warp	2.5		2200	8.7	0.53	0.95
	Weft	2.1		1500	6.3	0.65	0.92
(B) Grey	Warp	3.0	18	1500	5.4	0.81	0.80
	Weft	1.8	18	2200	5.3	0.69	0.82
Finished	Warp	1.8		2500	7.7	0.57	0.88
	Weft	1.5		2500	6.9	0.69	0.94
Mean				1900	6.5	0.67	

and two yarn-crimp levels, $c = 5.5\%$ and 16.6%. It can be seen that, for values of $YL^2/B > 2000$, the yarn extensibility or the crimp value of the yarn makes little difference to the computed curves plotted as the force (PL^2/B) against the relative extension, $\varepsilon_r = \varepsilon/c$, where c is now the retained yarn crimp. This fact justifies the approach of expressing all the load–extension curves in this manner[5].

In Table II, the measurements on the yarns from fabrics A and B are shown. The experimental values of initial relative modulus, E_{r2}, and relative extension, ε_{r8}, at $PL^2/B = 8$ compare very well with the theoretical values $E_{r2} = 6.3$ and $\varepsilon_{r8} = 0.67$ obtained from the decrimping curves of Fig. 4 with $YL^2/B = 2000$ and $c = 5.5\%$.

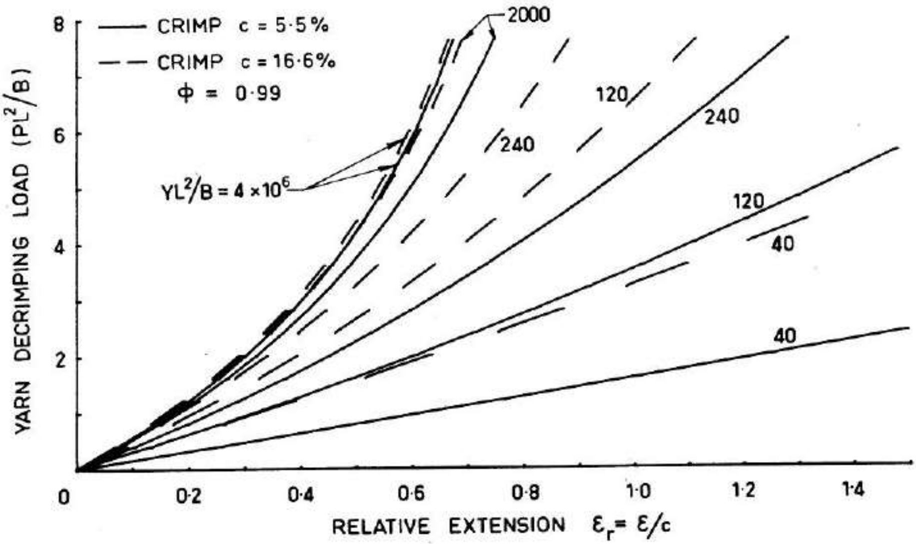


Fig. 4

Theoretical decrimping curves of a set yarn ($\phi = 0.99$) unravelled from a woven fabric for two levels of weave crimp (5.5 and 16.6%) and five levels of yarn extensibility marked on each curve: $YL^2/B = 4 \times 10^6$ (inextensible yarns), 2000 (typical value for cotton fabrics), 240, 120, and 40 (very highly extensible yarns, e.g., textured yarns)

The values of the yarn tensile modulus in Table II are only rough estimates, since the load–extension curves of yarns taken from the cones are non-linear[28]. The value of Y was taken to be the average slope of the initial load–extension curve between loads of 20 and 100 mN. The average slope of this curve between applied loads P, where $0 < P < 20$ mN, was generally 25% of the quoted value in Table II. It is reasonable to assume that the forces during weaving remove this initial region of low modulus. It is interesting, however, to note that, on finishing (commercial bleaching) the fabrics A and B, no increase in yarn extensibility was found in the decrimping curves. It seems likely that worsted woven fabrics do show an increase in yarn extensibility, values of $YL^2/B \simeq 400$ being feasible[13]. Such values of yarn extensibility head to significant yarn extension during fabric extension[13], but this does not appear to be the case with fabrics A and B. For textured yarns, $YL^2/B < 400$ is certainly possible.

4.3 Poisson's Ratio

Poisson's ratio for the fabrics A and B was measured by stretching a 15-cm × 2-cm strip of fabric in steps of 0.09 cm up to 6% extension and noting the corresponding reduction in width of the fabrics. The width measurement is not accurate, but ten measurements give a good reproducible slope and thereby a good indication[13] of ν. It is important to measure Poisson's ratio, since it gives directly an indication of the rounding up of yarn cross-sections. Any yarn compression or appreciable yarn extension would tend to reduce Poisson's ratio because it would reduce the crimp interchange between the stretched and crossing threads.

Table II shows the measured Poisson's ratio of ν and the calculated values of this parameter for $YL^2/B = 2000$ and $c = 5.5\%$ in the range $0 < PL^2/B < 8$. If appreciable yarn compression occurred during tensioning of the fabric, Poisson's ratio, ν, would be significantly less than unity in both warp and weft directions[13]. Because this does not occur, it is concluded that yarn compression does not play a significant part in this deformation. Consequently, the load–extension curves were computed on the assumption that the inter-yarn distances at the cross-over points remained constant. For a square fabric with $c = 5.5$ or 16.6%, Poisson's ratio was calculated[29] to be $YL^2/B = 2000$, i.e., $\nu = 1.1$. This agrees with the mean value in Table III, although the individual measurements are scattered. It would be desirable to devise a better method of measuring Poisson's ratio.

4.4 Relative Extension and Initial Modulus

Table III also shows the measured values of E_{r2}, and ε_{r8} for the fabrics A and B. For square fabrics (with $YL^2/B = 2000$), the theoretical values for E_{r2} and ε_{r8}, with no cross-over constraints or any rounding up of the yarn cross-sections assumed, are, $E_{r2} = 12$, $\varepsilon_{r8} = 0.5$ ($c = 5.5\%$) and $E_{r2} = 13$, $\varepsilon_{r8} = 0.5$ ($c = 16.7\%$). These are respectively, half and double the mean values for E_{r2}, ε_{r8} ($E_{r2} = 25$, $\varepsilon_{r8} = 0.28$) obtained experimentally for fabrics A, B. When the relative extension at $c = 16.6\%$ is computed subject to the constraint that the yarn radius of curvature cannot be less than the inter-yarn distances, a value $\varepsilon_{r8} = 0.12$ is found[27] (for $YL^2/B = 4 \times 10^6$). This is much less than the experimental value in Table III of $\varepsilon_r = 0.28$. It is not yet clear how the constraint on the yarn curvature

Table III

Fabric Uni-axial Tensile Properties

Fabric		E_{r2}	ε_{r8}	ν	L_2/L_1
(A) Grey	Warp	18	0.34	1.0	0.86
	Weft	25	0.30	1.0	1.16
Finished	Warp	25	0.27	2.0	0.83
	Weft	25	0.31	0.4	1.20
(B) Grey	Warp	29	0.28	1.7	1.07
	Weft	33	0.21	1.3	0.94
Finished	Warp	20	0.26	1.6	1.11
	Weft	25	0.26	0.6	0.90
Mean		25	0.28	1.20	

can be quantified owing to the effect of tension on the yarn cross-sections. However, it is clear that the difference between the computed results without the constraint and the experimental values is due to the mixed nature of the fabric as a geometric structure on the one hand and a mechanistic structure on the other.

Extremely tightly woven canvas fabrics show this effect of the yarn-curvature constraint much more, even though their yarn-decrimping curves are again identical to those found here[30]. Values of initial fabric modulus obtained sometimes reach $E_{r2} = 100$, and the relative extension $\varepsilon_{r8} = 0.11$. Clearly, the introduction of further realistic yarn-curvature constraints into the energy model will correct for this discrepancy. It is also worth noting that in cotton fabrics the constraints will generally need to be more rigid than those in woven worsted fabrics, since cotton yarns are generally less compressible and will bulk up less during finishing of the fabrics.

The inset in Fig. 3 shows typically how the yarn reaction forces (Q) rise with the application of tension. The rise in the Q forces is less than the rise in the P forces (applied tension). Also noted on the graph is the effect of L_2/L_1.

From the experimental data in Table III, it is shown that there is no significant effect of setting on the load–extension parameters. This has been verified theoretically for yarns where the finishing treatment ($\phi \to 1$) has no effect on the yarn bulk or cross-sectional shape[13]. The effect of non-square fabrics as measured by the ratio L_2/L_1 is to reduce the fabric modulus E_{r2} as L_2/L_1 increases, becauses the inter-yarn forces acting on the extended yarn (owing to the crossing thread) are reduced[13] by a factor $1/(L_2/L_1)^2$. This effect would be masked by the effect of the yarn-curvature constraints.

4.5 Fabric-bending Properties

The energy analysis of woven-fabric mechanics can be extended by considering the pure-bending behaviour of the plain-weave structure as a generalization of the tensile deformation. The boundary conditions for the plain-weave fabric in bending have been derived, and the ratio of fabric-bending rigidity per thread to yarn-bending rigidity has been computed for a range of fabric structures of different values of weave crimp and degree of set by introducing inequality constraints on the curvature or control variable[14].

Table IV shows the ratio of the fabric-bending rigidity for two values of fabric crimp ($c = 5.5\%$ and 16.6%, and $L_2/L_1 = 1$) and for three different values of set ($\phi = 0.0, \phi = 0.70, \phi = 0.99$). Table IV was computed by first calculating the solution of the fabric free from external couples or tensions and then computing the solution with two different values of M_B ($M_B L/B = 0.3, 0.6$), which gave varying (dimensionless) fabric curvatures of up to $L/\rho = 0.7$, where ρ is the radius of curvature. The ratio of the fabric-bending rigidity. B_F per thread, to the yarn-bending rigidity, B, was very nearly equal at these two values of M_B, which showed that, if yarns behave linearly in bending, the fabric-bending rigidity, B_F, is also constant. Only the mean values are given in Table IV. It is a well-known

Table IV

Ratio of Fabric-Bending Rigidity per Thread to Yarn-bending Rigidity, B_F/B

Curvature Constraint*	B_F/B			Crimp %	Percentage Contact†
	$\phi=0$	$\phi=0.70$	$\phi=0.99$		
	Unset	Grey	Set		
None	1.30	1.05	0.95	5.51	0
2.0	1.33	1.08	0.97	5.15	0
1.5	1.59	1.27	1.15	5.54	20
1.25	2.52	1.81	1.38	5.46	47
None	2.14	1.14	0.87	16.63	—
2.5	2.27	1.39	1.03	16.73	20
2.0	4.27	2.58	1.36	16.06	60

*For inequality constraints on the curvature or control variable, e.g., $m_1 <$ constraint, the first of Equations (5)[13] applies unless the constraint is violated, in which case the solution of m_1 at point s is equal to the constraint[24]

† Percentage of yarn length during which curvature constraint was active.

experimental fact woven fabrics have a constant bending rigidity after the frictional hysteresis has been subtracted.

If there is no curvature constraint on the yarn, i.e., if the yarns are free to bend around each other subject to point between them, and the yarn is also completely

Table V

Bending Parameters of Yarns and Fabrics

Fabric		M_{0F} (mN mm)	M_0 (mN mm)	B_F (mN mm^2)	B (mN mm^2)	$\frac{M_{0F}}{M_0}$	$\frac{B_F}{B}$	
(A) Grey	Warp	0.38	0.16	5.9	3.6	2.4	1.6	0.87
	Weft	0.27	0.09	3.8	2.1	3.1	1.8	0.87
(A) Finished	Warp	0.38	0.19	4.5	2.5	2.0	1.8	0.95
	Weft	0.22	0.15	2.6	2.0	1.5	1.3	0.92
(B) Grey	Warp	0.79	0.17	6.2	3.0	6.1	2.1	0.80
	Weft	0.54	0.10	4.4	1.8	5.4	2.5	0.82
(B) Finished	Warp	0.27	0.11	3.5	1.8	2.5	2.0	0.88
	Weft	0.16	0.07	2.3	1.5	2.4	1.6	0.94
Mean	Grey	0.50	0.13	5.1	2.7	4.3	2.0	0.84
	Finished	0.26	0.13	3.3	2.0	2.1	1.7	0.92
	Over-all	0.38	0.13	4.2	2.3	3.2	1.8	0.88

Legend: M_{0F}, M_0 are fabric and yarn coercive couples, respectively; B_F, B are fabric- and yarn-bending rigidities (expressed per thread), respectively; ϕ is fabric set.

set ($\phi = 0.99$), then the ratio $B_F/B \simeq 1/(1 + c)$, a result that is in agreement with the literature.[9] When $\phi = 0.0$, 0.70, however, $B_F/B > 1$ even when there is no constraint imposed on the yarn curvature. With increasing constraint for either of the two yarn crimps, the ratio B_F/B increases sharply, the ratio B_F/B being always greater for smaller degrees of set, ϕ. Consequently, the inter-yarn forces have a very significant effect on the fabric-bending rigidity, as noted experimentally by Grosberg[7].

Comparison of the theoretical results with the experimentally obtained values (Table V) shows that, according to the energy model, the yarns in the fabric are in contact for over 50% of their length. (More contact gives higher values of B_F/B.) This agrees with microscopical examination of the fabric. The grey and finished fabrics have degrees of set $\phi = 0.84$ and 0.92 (mean), respectively. A slight reduction in the ratio of B_F/B was found experimentally, as predicted. These results are in agreement with the literature.[7]

For very tight canvas-type fabrics (not shown), ratios as high as $B_F/B = 18$ have been found[30]. The reason here is again that the fabric is acting as a geometric model, i.e., one with a severe curvature constraint active on the yarn during bending.

4.6 Future Work

It is clear that the energy and optimal-control formulation of fabric mechanics is extremely powerful. It needs to be developed further, particularly in quantifying the constraints on the yarns during fabric deformations. This may be done by evaluating the yarn constraints necessary to obtain the high values of B_F/B as noted for the canvas-type fabrics and then to feed this constraint into the tensile deformations. A further improvement in the model will be to include inelastic mechanisms. No complete analysis has yet been presented of the tensile-recovery properties of woven fabrics. A preliminary study of the inelastic deformation of woven fabrics has yielded a result as in Fig. 5, where typical initial-recovery and recycle tensile curves of a woven fabric are shown, as well as the elastic deformation. Clearly, any friction effects will tend to reduce the fabric extension. The friction parameters used in Fig. 5 were actually obtained experimentally from fabric-bending measurements. The elastic curve was computed from present energy considerations.

5. CONCLUSION

An energy analysis, based on the fundamental principle that elastic structures always assume a configuration of minimum strain energy, has been formulated for fabric mechanics with the aid of optimal-control theory. The analysis has been applied to a study of cotton plain-woven fabrics and has been compared with experimental results.

It has been shown how the two models of fabric structure originally proposed in 1937 by Peirce[2], namely, the geometric model and the mechanistic

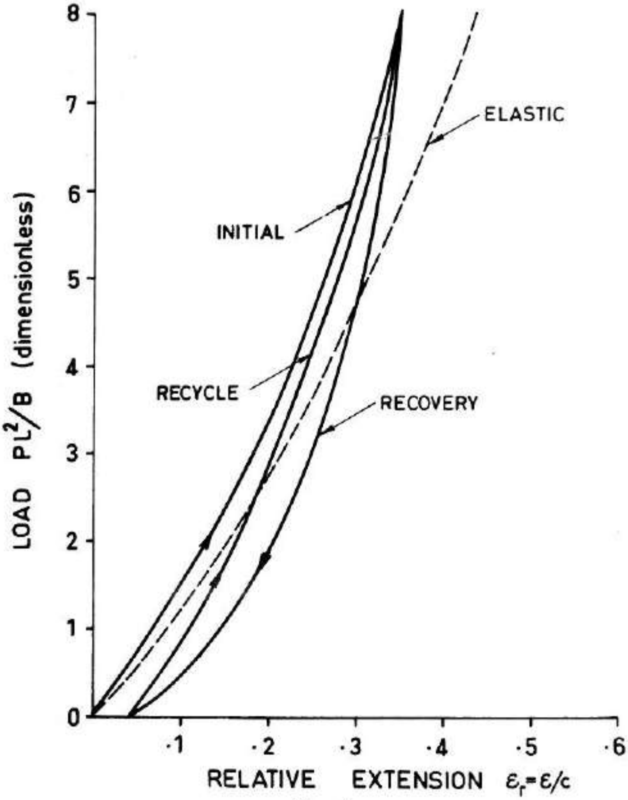


Fig. 5
Typical tensile-recovery curve with friction parameters from experimental bending-hysteresis curve calculated from the energy model of the present paper

model, may be derived from the energy analysis. Comparison of the experimental results on a series of cotton fabrics and theoretical results calculated on the basis of both curvature constraints on the yarn (geometric model) and no curvature constraints (mechanistic model) shows that cotton fabrics during both uniaxial-tension and pure-bending deformations act as a mixture of the geometric model and the mechanistic model.

Yarn-decrimping results show that, in the set of fabrics studied, yarn extensibility plays only a small part in the load–extension behaviour. Comparison of yarn- and fabric-bending rigidities shows that the yarn-bending rigidity is not appreciably increased when the yarn is in the fabric, but rather that the increase in fabric-bending rigidity is due to the imposition of yarn-curvature constraints.

The energy analysis provides a unified approach to the study of both woven and knitted fabrics and has been shown to be a very powerful tool in the interpretation of experimental results on fabrics. Work on the application of the energy analysis to other fabric structures and deformations is continuing.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contribution made by their colleague, Dr. R. C. Dhingra, who offered his advice regarding the experimental work associated with this paper.

The authors are also indebted to Mrs. Z. Peselson, who carried out the experimental work.

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18—THE PROCESSING OF COTTON TEXTILES TO IMPROVE THEIR COMPETITIVENESS

By H. U. MEHTA

Improved retained properties of resin-treated cotton textiles are shown to have been obtained by pad–flame-dry–oven-cure, pad–sandwich–dry–cure, and pad–dry–cure–viscous-media–acid-hydrolyse–wash methods. Controlled preparatory processing as against conventional processing is shown to retain all the properties of the untreated as well as the treated fabrics at a higher level. The effect of processing on fabric-surface damage was examined by using a scanning electron microscope. Plain-, twil, crêpe-and basket-woven fabrics are compared for the retained properties after durable-press resin-finishing.

1. INTRODUCTION

Cotton textiles face heavy competition from synthetic-fibre materials, which have provided new properties for textile consumers. Some chemical and mechanical treatments to cotton textiles are expected to impart new properties. The International Institute for Cotton (IIC) and United Nations Development Programmes (UNDP) have promoted research efforts to increase the competitiveness of cotton. Under one such UNDP-assisted project, extensive work has recently been carried out at the Ahmedabad Textile Industry's Research Association (ATIRA) to improve the smooth, crease-free-drying character of cotton textiles by cross-linking treatments. The more cross-links there are in cotton textiles, the higher are their resiliency, dimensional stability, and shape-retention characteristics, but proportionately lower are their tearing strength, tensile strength, and durability. Attempts are therefore generally directed to the improvement of retained properties by increasing cross-links. In the present paper, a variety of such approaches (some of them quite new) are discussed. The migration of resin to the fabric surface during drying gives an uneven distribution of cross-links. It results in greater losses in strength properties than a finish with less migration. Experiments have therefore been conducted to reduce migration and to achieve an even distribution of cross-links. The pre-history of fabric preparation is further found to affect the properties of the fabrics before and after resin-finishing. The better the initial properties of the fabric, the higher is the level of retained properties after finishing. Attempts to pre-toughen the fabrics by controlling the preparatory chemical processes are also described.

2. EXPERIMENTAL

2.1 Fabric

A cotton poplin fabric with 120 ends/in. (47 ends/cm) of 40s-cotton-count

(14.8-tex) yarn and 64 picks/in. (25 picks/cm) of 40s-cotton count (14.8-tex) yarn was used for the pad-cure, pad-flame-dry-oven-cure, pad-dry-cure-acid-hydrolyse-wash, and pad-sandwich-dry-cure processes. A cotton poplin fabric with 112 ends/in. (44 ends/cm) of 30s cotton-count (19.7-tex) yarn and 72 picks/in. (28 picks/cm) of 36s-cotton-cotton-count (16.4-tex) yarn was used for the mill and laboratory investigations of controlled preparatory processing.

2.2 Testing

All tests were made in accordance with ASTM method[1]. The energy to rupture was calculated from strength–elongation curves obtained on an Instron Tensile Tester.

2.3 Chemicals

A commercially available resin, dimethylol dihydroxy ethylene urea in a 45% solution, was used for resin-finishing. Catalyst DC[2] was used in all cases except where otherwise specified. Polyvinyl alcohol of fully hydrolysed (FH) grade was used after preparing a stock solution (10%w/v in boiling water. All other chemicals were of reagent grade.

2.4 Scanning Electron Microscopy

Scanning-electron-microscopy investigations were made on a Cambridge S 4–10 model. All the samples were examined after vacuum-coating with either gold or silver.

3. RESULTS AND DISCUSSION

3.1 The Pad–Cure Process

The higher the temperature of drying, the greater seems to be the migration of resin to the surface. Subsequent curing then leads to the fixation of cross-links on the surface. A low temperature of drying, preferably with simultaneous drying and curing, would be expected to yield a better balance of properties. A pad–cure process was therefore investigated extensively in order to bring about desired improvements in resilience at 60, 80, or 100°C. Very strong acid catalysts, namely, hydrochloric acid, phosphoric acid, and sulphamic acid, were employed. The concentrations of the catalysts were selected to give pH values of the solution ranging from 0.5 to 2.5. Padded and squeezed samples were immediately dried (i.e., cured). The kinetics of curing were studied by varying the periods of curing.

Various properties of the treated fabrics plotted against their corresponding dry crease-recovery angles are shown in Figures 1,2 and 3. In these figures, vertical broken and solid lines represent easy-care and durable-press levels of dry crease-recovery angles, respectively, and the horizontal solid line shows the

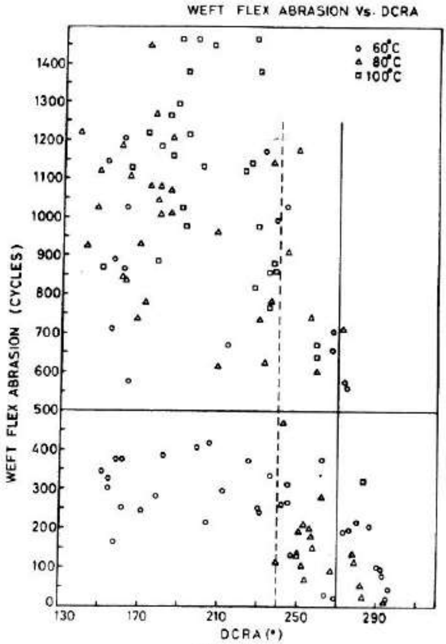

Fig. 1
Dry crease-recovery angles plotted against tensile-strength data for pad–process

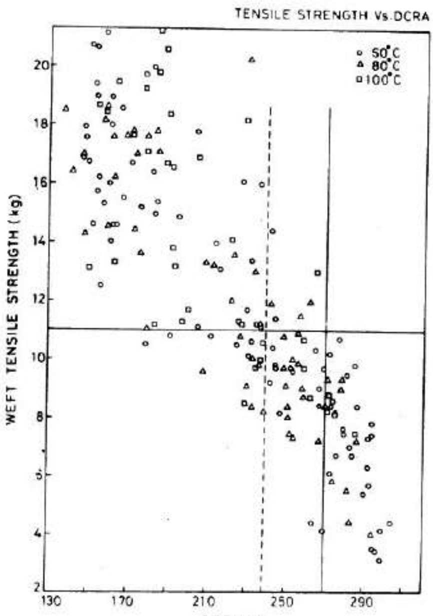

Fig. 2
Dry crease-recovery angles plotted against tearing-strength data for pad–cure process

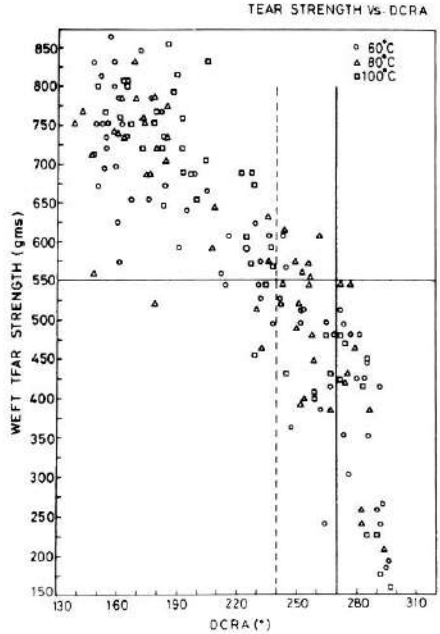

Fig. 3

Dry crease-recovery angles plotted against flex-abrasion-resistance data for pad–cure process

minimum retained value of the property desired for the satisfactory durability of a garment made from the treated fabric. Despite such a large variation in the experimental conditions of time, temperature, recipe pH, catalyst type, etc., none of the samples shows retained properties significantly above the desired level at the crease-recovery angles for durable-press treatments, and only a few samples show retained properties above the desired level for easy-care treatment. However the sample that may pass in one property at the easy-care level may not pass in another property at the same easy-care level. Obviously, the satisfactory sample is one that shows significantly higher levels of all three retained properties. Clearly, therefore, the commonly employed strong-acid catalysts cannot yield a cross-linked fabric with desired durable-press performance characteristics by the pad–cure process, even though the temperature of curing is kept low to minimize the migration of resin to the surface. The mild-cure process further suffers from formaldehyde odours during and after finishing, greater strength loss after chlorine bleaching, scorching, and other disadvantages.

3.2 The Pad–Flame-dry–Oven-cure Process

Another attempt to reduce resin migration was aimed at very rapid drying of the fabric in a direct flame within a few seconds, followed by conventional curing in baking ovens. Such a rapid flame-drying procedure is

Table I

Physical-test Data for Flame-dry–Oven-cure Processed Fabrics

No.	drying Time (Sec)	Oven-cure (°C/min)	Crease-recovery Angle (deg) Dry (W+F)	Wet (W+F)	Warp Tensile Strength (kgf)	(N)	Weft Flex Abrasion-resistance (cycles)	Warp Tearing Strength (gf)	(N)
1	10	100/2	221	212	30	294	2880	870	8.53
2	30	100/2	249	234	29	284	2300	800	7.85
3	50	100/2	268	249	23	226	—	680	6.67
4	—	(100/2) 150/4	280	264	14	137	150	430	4.22
5	Untreated		145	163	36	353	3200	1120	10.98

expected to dry the fabric before resin molecules migrate to the surface, on the assumption that the rate of drying in this case is much more rapid than the rate of migration of resin molecules. Results obtained are shown in Table I.

The use of phosphoric acid served two purposes, since it acted both as a catalyst and as a temporary flame-retardant during flame-curing. With the increase in dry crease-recovery angles, the decreases in tearing strength, tensile strength, and abrasion-resistance are relatively low. However, flame-drying of cotton textiles with a naked flame is an extremely risky operation, so that elaborate safety and precautionary measures would be required before such a process was made practicable.

3.3 Immerse–Hydroextract–Dry–Cure (IHDC) Process

When a wet cotton fabric is subjected to a centrifugal force, all loosely bound water is rapidly removed, only about 40–45% imbibed water being retained. One reason advocated for the increased resin migration on the surface is that there may be as much as 60–70% retained water after the best squeezing between the rolls of the padding mangle. It is difficult to lower the pick-up below 60% with mangles. The IHDC process was therefore tried in an attempt to retain only about 45% pick-up. The hydroextracted fabric was dried and cured conventionally. The results of the experiments are compared with those of a conventional pad–dry–cure (PDC) process in Fig. 4. The IHDC-treated fabrics, when compared with PDC-treated fabric, did not show any advantage in terms of retained tensile strength but showed a significantly higher level of retained abrasion-resistance. Since the abrasion-resistance is largely a surface-friction phenomenon, the low pick-up obtained with the IHDC process presumably helped in reducing the cross-link density at the fabric surface. The significance of the IHDC process cannot be realized in conventional-wet processing plants, but the process may find application in loose-stock and ready-made-garment treatments.

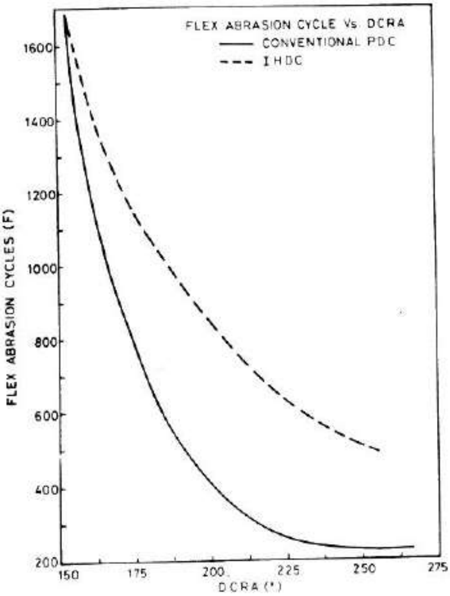

Fig. 4
Dry crease-recovery angles plotted against flex abrasion cycles for IHDC process

3.4 Pad–Sandwich Process

A fabric squeezed to 70–75% pick-up on conventional padding mangles, is squeezed again after sandwiching it between two dry absorbent layers of cotton fabric to reduce the retained pick-up to 40–45%. The middle fabric is subsequently dried and cured conventionally. The retained properties and compared in Fig. 5. Compared with conventional processing, the sandwich

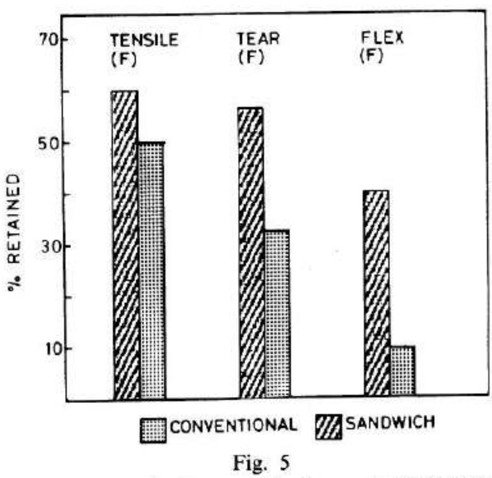

Fig. 5
Percentage retained properties for sandwich process and conventional process at durable-press level

process leads to the retention of better tensile strength, tearing strength, and flex abrasion-resistance at the durable-press level of resin treatment. The second squeeze between two absorbent fabrics clearly helps to blot out the resin solution trapped in the yarn interstices and fabric surface. As a result, the cross-linking predominantly take place within the fibre structure to give a better balance of properties. The blotting operation consumes more chemicals and needs endless fabrics, so, commercialization of this process may encounter some difficulties.

3.5 Acid Hydrolysis for Core Cross-linking

Viscous-media acid hydrolysis (VMAH) of the conventionally cross-linked fabric was attempted to preferentially remove the surface-migrated and cross-linked resin.

High-molecular-weight 3.0% poly(vinyl alcohol) solutions form the viscous media because the polymer is resistant to dilute-acid hydrolysis, and it does not show greatly altered viscosity under the experimental conditions. Hydrolysis is effected in the short duration of 10 min. Several acid concentrations were used. The results are shown as bar charts in Fig. 6. The fabric loses about 20–25° in dry crease-recovery angle after the hydrolysis but gains substantial improvements in flex-abrasion-resistance and tearing-strength values. The tensile strength also increases. The results thus confirm that the removal of surface-migrated and cross-linked resin by partial hydrolysis of the cross-link leaves the core-cross-linked fabric with very much improved surface properties. A continuous process consisting in PDC–P (VMAH)–batch–wash–dry, may find some practical applications, but the cost of processing may increase substantially.

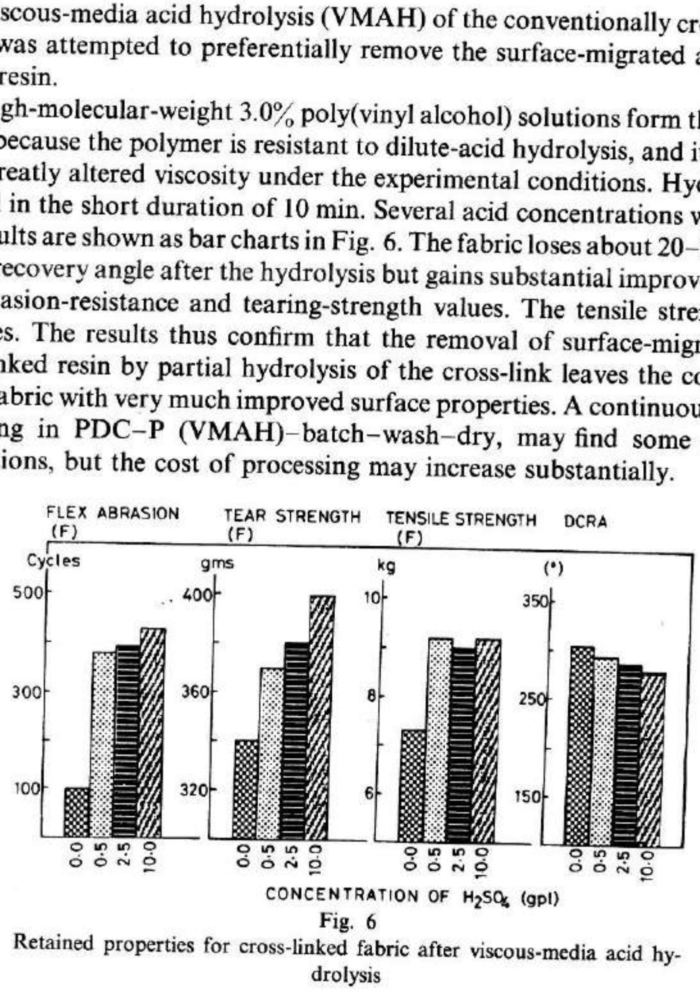

Fig. 6

Retained properties for cross-linked fabric after viscous-media acid hydrolysis

3.6 Controlling Preparatory Processing

Earlier studies by the author[3,4] showed that chemical preparatory processing has a significant effect on the properties of the fabric before and after

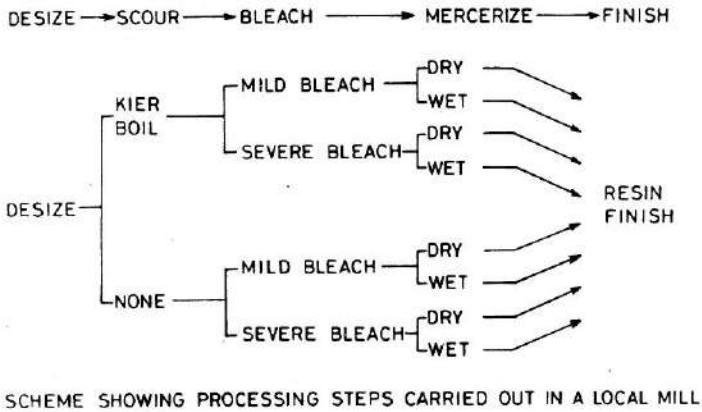

Fig. 7
Scheme showing processing steps carried out in a mill

resin-finishing. The loomstate fabrics, when desized and analysed, show higher dry crease-recovery angles, flex abrasion-resistance, tearing strength, and tensile strength than the same fabric analysed after scouring, bleaching, and mercerizing. Mild conditions of preparation give the fabric much better retained properties before being finished as well as after the finishing stage. One such experiment conducted in a local mill is shown schematically in Fig. 7. The loomstate poplin fabric was desized and kier-boiled under pressure. The desized fabrics after the kier-boil and one without any kier-boil were bleached under two conditions, namely, mild and severe. The fabrics were further mercerized by two processes: (*a*) under normal (dry) conditions with 52°Tw caustic soda solution and (*b*) after water-mangling to 65% water pick-up and mercerizing the wet fabric by using 68°Tw caustic Soda solution.

Table II shows physical-test data for the most severely and most mildly processed fabrics before the mercerization stage. The fabrics that had been processed after kier-boiling all show a lower tearing strength and number of flex-abrasion cycles than those processed without kier boiling. Tensile strengths and dry crease-recovery angles are also lower for the former fabrics than the corresponding ones in the latter group, though less significantly. The energy to rupture remains practically unaltered for the mildly processed fabric, whereas it decreases by about 15% for the severely processed one. Figures 8, 9, and 10 show results for tensile strength, tearing strength, and flex abrasion-resistance for the most mildly and the most severely processed fabrics after resin-finishing at several levels. The fabric processed under the milder conditions not only has higher initial physical properties but also retains them to a greater extent after resin-finishing than that the severely processed fabric.

A scanning-electron-microscopical examination of the fabrics at various stages of processing showed that severe conditions of processing lead to greater damage to the fibre surface, particularly in the warp-crown regions. In order to ascertain the damage and to find out whether it occurs as a result of mechanical

Table II

Physical-test Data for Mill-processed Fabrics

No.	Process	Crease-recovery Angle (deg) Dry (W + F)	Crease-recovery Angle (deg) Wet (W + F)	Warp Tensile Strength (Kgf)	Warp Tensile Strength (N)	Warp Tearing Strength (gf)	Warp Tearing Strength (N)	Warp Flex Abrasion-resistance (cycles)	Energy to Rupture* (A.U.)
1	Desized–caustic soda Boil–severe bleach	179	127	29.8	292	820	8.04	690	162.5
2	Desized–no scour–mild bleach	199	132	32.7	321	1130	11.08	1450	191.4

* Area under strength × elongation curve; A.U. = arbitrary units; for desized fabric, energy = 189.3Au.

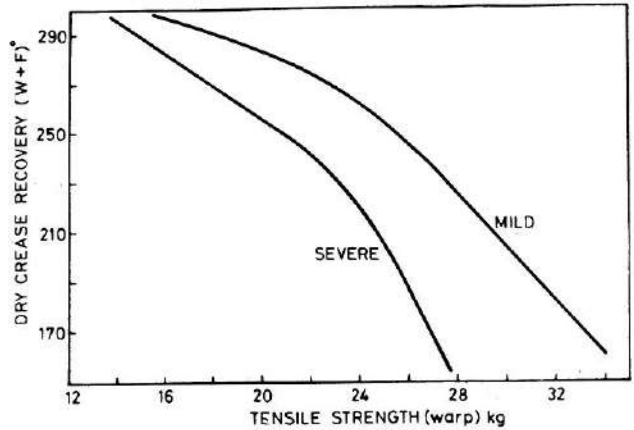

Fig. 8

Dry crease-recovery angles plotted against tensile-strength data for the severely and mildly processed fabrics

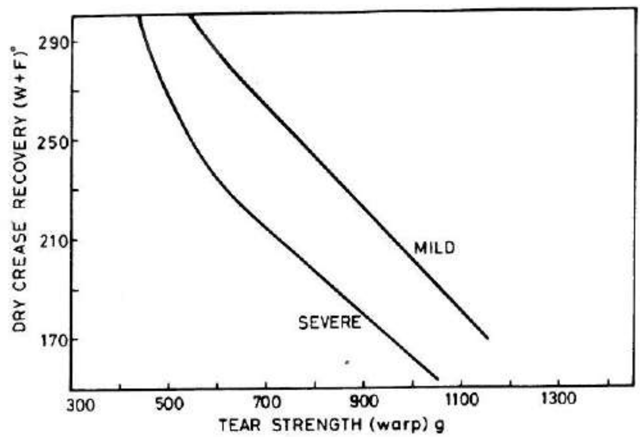

Fig. 9

Dry crease-recovery angles plotted against tearing-strength data for the severely and mildly processed fabrics

treatment, chemical treatment, or both, a systematic study of chemical processing was conducted in the laboratory. The grey goods were desized, scoured, bleached, mercerized, and resin-finished as shown schematically in Fig. 11.

Except mercerization, all the processing steps were carried out in the laboratory, due care being taken to avoid any mechanical handling or damage. Mercerization was done in a local mill. An analysis of physical properties confirmed earlier observations. Solvent-scouring, which removed all the wax, reduced the flex abrasion-resistance and tearing strength drastically. The mildly processed fabrics showed better retained properties before as well as after resin-finishing. In the investigations with the scanning electron microscope, the kier-boiled samples showed greater warp-crown damage than the soda-boiled, which

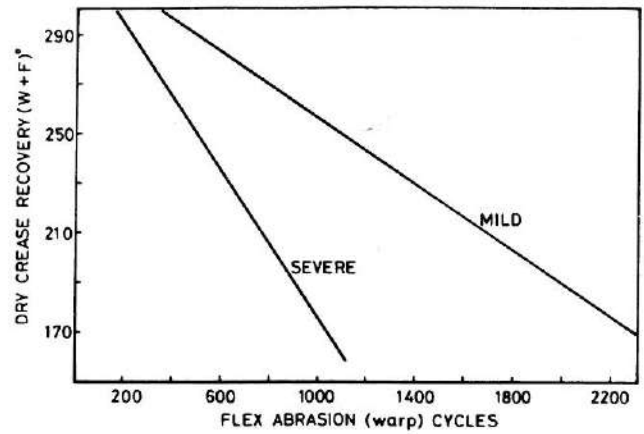

Fig. 10
Dry crease-recovery angles plotted against flex abrasion cycles for the severely and mildly processed fabrics

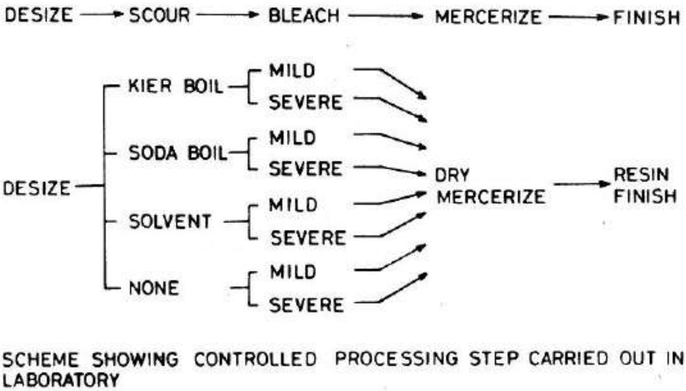

Fig. 11
Scheme showing processing steps carried out in the laboratory

were followed by solvent-scoured and unscoured fabrics. Severe bleaching and mercerization both increased the warp-crown damage. Under the most severe conditions of processing, when warp crowns were severely damaged, all the weft yarns remained practically undamaged. A typical scanning electron micrograph at the desized stage is shown in Fig. 12, and a sample after the kier-boil–severe-bleach–mercerizing stage is shown in Fig. 13. The damage follows the order: desized $<$ solvent-scoured $\ll$ kier-boiled; and also desized $\ll$ scoured $<$ bleached $<$ mercerized. Fig. 14 shows the clean weft for the fabric that had been desized, kier-boiled, severely bleached and mercerized. Under the most severe conditions of processing, when a large number of warp-crown fibres had been damaged, weft fibres remained clean and undamaged. If chemical damage were the cause of the warp-crown damage, both warp and weft should have been damaged equally.

Fig. 12
Scanning electron micrograph of the desized fabric

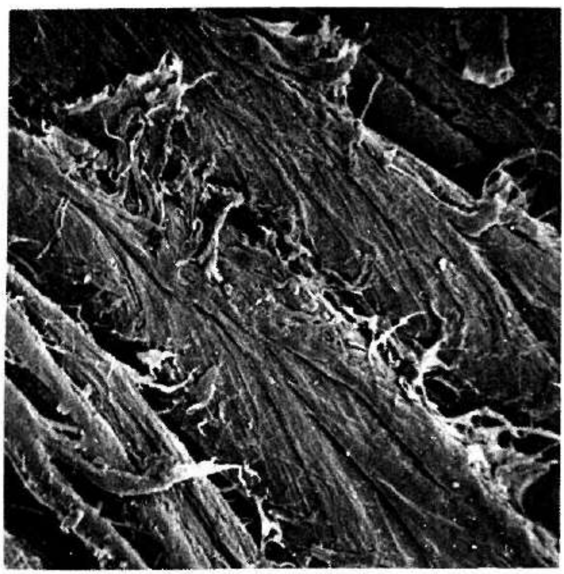

Fig. 13
Scanning electron micrograph of the kier-boiled, severely bleached, and mercerized fabric, showing extensive damage

Preferential damage on warp-crown fibres suggests that these fibres have undergone some mechanical surface damage or have suffered irreversible strains. The strained and damaged zones are preferentially extracted out during chemical processing.

Fig. 14
Scanning electron micrograph showing clean weft for the same fabric as in Fig. 13

3.7 The Effect of Construction and Weave

Various shirting fabrics were woven from Giza 45 cotton. The same yarn, of 44s count (linear density 13.4 tex), was used for warp and weft. Plain, twill, crêpe, basket, and certain modified weaves on dobby were woven, processed under controlled conditions, and resin-finished. Data are shown in Fig. 15. The basket weave shows the highest retained tearing-strength and the twill weave the highest retained tensile strength, whereas the plain weave gives the highest retained flex abrasion-resistance at the durable-press level. All the fabrics show initial crease-recovery angles between 180 and 210° (W + F, i.e., the sum of the warp and weft angles).

4. CONCLUSIONS

The investigation reported in this paper of the cross-linking reactions of cotton fabric by the pad–cure, pad–flame-dry–oven-cure, immerse–hydro-extract–dry–cure, pad–sandwich–dry–cure, and pad–dry–cure–acid-hydrolyse–wash–dry methods to improve the retained properties of the finished fabrics has shown that milder preparatory processing conditions improve the properties of the fabrics before and after resin-finishing. A scanning-electron-microscopical study of variously processed fabrics revealed increased fibre-surface damage due to increased severity of the conditions of processing. The effects of plain, twill, basket, and crêpe weaves on the retained properties of cotton fabrics have also been outlined.

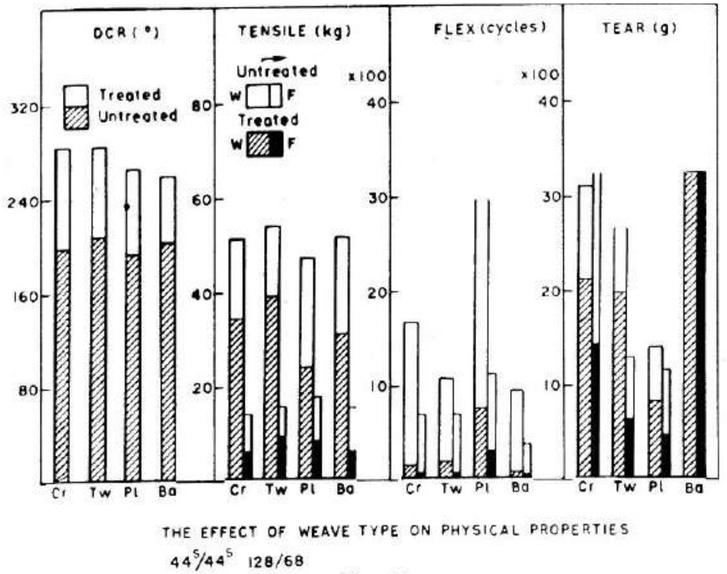

Fig. 15

Properties of crêpe-, twill-basket, and plain-weave fabrics at the durable-press level of finishing

ACKNOWLEDGEMENTS

UNDP assistance in the course of the work reported in this paper is gratefully acknowledged. The author acknowledges help from his colleagues, Dr. P. C. Mehta, and Dr. J. J. Willard, Senior Consultant, UNDP. Scanning electron micrographs were taken by Dr. P. Neelakantan and Dr. J. T. Sparrow (United Nations Expert at ATIRA).

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19—SOURCES OF SHADE VARIATION IN THE DYEING OF COTTON FABRIC

By J. G. ROBERTS, M. G. CORLESS, and PAULINE F. WALTON

The main objectives of the work described in this paper are to locate the important sources of shade variation arising in dyed cotton fabrics and to seek ways that will lead to their minimization and ultimate elimination. In this way, improved reproducibility of the dyeing process will be achieved and a more consistent substrate provided for garment manufacture.

1. INTRODUCTION

The added value to textile products accruing as the result of dyeing processes was almost £142M in the U.K. in 1976[1]. In the course of colouration processes, a sizeable element of the cost involved results from the need for adjustments in shade or the need for critical examination of fabrics for consistency and correctness of shade, both within a piece and between pieces in a batch. Improvements in control and consistency of shade offer a potential for saving that is large and open up possibilities for increasing production and lowering costs, both with the consequent effect of improvement in profitability.

Batch-dyeing processes are frequently operated in such a way that the required shade in a textile material is approached from the weaker side, with adjustments made in the later stages of the dyeing sequence to bring the dyeing onto shade. As a consequence, dyeing times are extended, and this adversely influences the efficiency of machine usage. The need for this approach arises from two main factors:

(i) insufficient control over the dyeing process; and
(ii) non-uniformity of the substrate to be dyed.

These can equally apply in continuous processing, though the factors influencing the dyeing process will not be the same. In this case, the dyeing is essentially non-competitive with respect to the substrate, and the key factors lie in the application of the dye and in particular with the state of the substrate and its uniformity.

Factors requiring control in the dyeing process and their influence on the shade of the fabrics dyed are generally well understood. With reasonable care on the part of the dyer, this source of shade variation in dyed fabrics can be eliminated. Nevertheless, all that can be done to this end is frequently neither realized nor practised. The reasons for this arise through the complexity of interaction of a very large number of factors that can influence shade and the difficulty in relating the variation in a single factor to a variation in shade in the course of a commercial dyeing operation.

A major item in the Shirley Institute's Finishing Division programme is a project to investigate sources of shade variation in dyed fabrics. This project has been running for two years and is still in progress, but it is appropriate to make an interim report of the main findings to date.

In defining this project, the major target was an examination of shade variation in polyester-fibre–cotton woven fabrics, and as a first step the two components of the blend were examined separately. The processing routes for cotton, polyester-fibre, and polyester-fibre–cotton blended-fibre fabrics were considered and possible points at which shade variation could be introduced identified. (This is illustrated in Table I for polyester-fibre–cotton blends.) The individual stages were then considered in greater detail (by way of an example, the section dealing with the scouring of cotton is shown in Table II.) These factors were considered by an industrial panel for their relative importance in the light of their practical experience. As might be expected, the preparation

Table I

Processing Route for Polyester-fibre–Cotton Blends

<table>
<tr><th>Cotton</th><th>Polyester Fibre</th></tr>
<tr><td>Ginning
Blending at source
Selection by spinner
Opening
Blending
Carding
Combing
Drawing</td><td>Polyester-fibre production
Merging by producer
Opening
Carding
Drawing</td></tr>
<tr><td colspan="2">Combing cotton and polyester-fibre slivers
Drawing
Spinning
Steaming or dry-heat stabilization
(Lubrication)</td></tr>
<tr><td>Wind for warp
Sizing
Beaming</td><td>Wind for weft
Pirning</td></tr>
<tr><td colspan="2">Weaving
(Pre-heat-setting)
Singe
Desize
Scour
Bleach
(Mercerize)
Dry
Dye, polyester fibre
Dye, cotton
Dry and finish
(Post-heat-setting)</td></tr>
</table>

Table II

Factors Affecting the Shade to which Cotton Fabric is Dyed: The Influence of the Scouring Step in a Preparation Sequence

Scouring

(*a*) Pressure caustic
Alkali concentration, temperature, and duration of the process; possible oxidation of the cellulose due to non-removal of air from the equipment
Open-width or rope processing
Surface-active agents

(*a*) Mild caustic
Alkali concentration, temperature, and duration of the process
Open-width or rope processing
Surface-active agents

(*c*) Solvent: choice of solvent and the condition of its use
Efficiency of removal of solvent after scouring

(*d*) Emulsion
Conditions of application, and removal of the non-aqueous component after scouring

All these factors are considered of great importance.

General

(1) The nature and concentration of the surfactants used as scouring auxiliaries, and the thoroughness of their removal afterwards
(2) Selvedge-to-centre differences in open-width scouring
(3) Mechanical creases and abrasion
(4) Incompatability of surfactants with following processes
(5) Tension during scouring, especially on the beam

All the above factors are considered important.

Washing after Scouring

(1) Thoroughness of the operation, especially with regard to removal of residual alkali
(2) Acid scouring
(3) Use of sequestrants
(4) Removal of Ca^{++} and Mg^{++}
(5) Lapse of time between impregnation and washing in scouring continuously

All these factors are improtant; factor (1) is considered crucial, especially when reactive dyes are to be used.

sequence was seen to be of major importance, and this, being an area generally under the control of the dyer, was selected as a main item for study.

At this point, it is worth examining an example taken from an experiment set up with a commercial dyer. A dye-lot of 100 pieces of cotton fabric was followed through the dyehouse, and each piece of fabric was sampled at each end on three occasions:

(i) in the grey state,
(ii) after the preparation sequence, and
(iii) after dyeing.

The last set of samples was then examined for shade, colour measurements being made on the Harrison–Shirley Digital colorimeter (Fig. 1). The shade

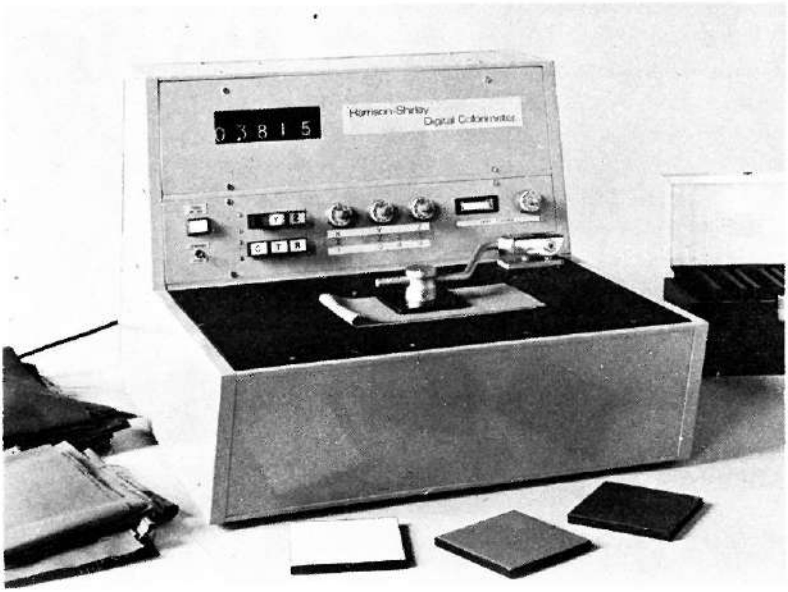

Fig. 1
The Harrison–Shirley Digital Colorimeter, used for measurements of shade differences

variations found were expressed in terms of total colour difference (ΔE in ANLAB 40 units) between patterns or between a pattern and the mean of the set. The value of ΔE that corresponds approximately to a shade tolerance within a garment varies with the basic colour (Table III). In this experiment, the fabrics were dyed a blue shade, and hence a value of ΔE of 0.8 corresponds to the desired limits of variation in shade.

Differences in shade corresponding to ΔE values of 2 units were found within pieces. Examples showing significant total colour differences (ΔE) between ends were selected for further experiments. Grey samples were prepared and dyed by laboratory versions of the commercial processes, and the commercially prepared samples were also dyed in the laboratory. Colour

Table III

Approximate Representative Values of Total Colour Difference Corresponding to Tolerance Limits of Shade Variation within Garments of Different Colours

Colour	Approximate ΔE Value (ANLAB 40 units)
Navy Blue	0.8
Grey	0.8
Green	1.0
Royal Blue	1.5
Red	1.5
Orange	2.0
Bright Yellow	2.5

measurements were then made and total colour differences between pairs of samples computed (Table IV). It is clear that, by careful preparation and dyeing, the end-to-end shade variation can be contained within acceptable limits. This shows that any inherent differences in dyeing behaviour of the fibre itself or arising in the fabric-making stages are not the major causes of the observed end-to-end shade variation. The samples that were commercially prepared and laboratory-dyed showed a partial improvement in end-to-end shade variation, which in turn suggests that both the commercial preparation sequence and the commercial dyeing are contributing to the observed shade variation between ends of fabric pieces.

Table IV

End-to-end Variation in Shade: Comparison between Commercial and Laboratory Processing

	ΔE between Ends of Fabric		
	Commercial Preparation		Laboratory Preparation
Sample	Commercial Dyeing	Laboratory Dyeing	
1	1.75	0.39	0.79
11	1.65	0.25	0.13
23	1.40	1.18	0.62
31	1.55	0.09	0.24
34	1.60	0.83	0.22
60	0.80	0.64	0.21
61	1.95	1.07	0.77
83	1.10	1.75	0.37

Further examination of fabric samples after preparation revealed that size removal was incomplete. In the commercial preparation, residues equivalent on average to 5% of starch were found, whereas only 3% remained on the laboratory-prepared samples. Some correlation between individual amounts of starch residue and shade was found, but this was not completely consistent. However, it seems likely that the generally higher levels of size residue are, at least in part, responsible for some of the shade variation found.

2. FACTORS INFLUENCING THE DYEING OF COTTON

The nature of the cotton fibre influences its dyeing behaviour. This has long been recognized, and for this among other reasons care is taken in blending cotton fibre before spinning. Although shade variation arising from differences between the fibres within fabrics does not occur frequently, the likelihood of mixed batches of fabric containing different fibres is greater. In either case, there is little that can be done except to redye. Whereas control of this variable is not in the hands of the dyer, it was considered of interest to determine the size of potential shade variations that might arise from this source.

Samples of nine different cotton fibres were prepared for dyeing by passing them through the Shirley Analyser, scouring in a caustic soda solution, and bleaching with hydrogen peroxide. The loose fibre was dyed with Chlorantine Fast Green 5BLL (1%) in the Pretema laboratory-dyeing unit. The fibre was then reprocessed through the Shirley Analyser before colour measurements were made on a pad of fibre with the Harrison–Shirley Colorimeter. A considerable variation in shade was found (Table V).

Table V

The Influence of Cotton Type on Shade after Dyeing of Fibre with Chlorantine Fast Green 5 BLL (1%)

Cottong Type	Staple Length (in.)	Staple Length (mm)	x	y	Y	ΔE
Pakistan Dessai	$\frac{5}{8}$	15.9	0.2369	0.2984	9.85	0
Middling American	$1\frac{1}{16}$	27.0	0.2399	0.2971	9.60	1.47
Ashmouni	$1\frac{3}{8}$	34.9	0.2382	0.2985	11.15	2.08
Bengal	$\frac{1}{2}$	12.7	0.2360	0.2971	10.70	1.46
Malaki	$1\frac{1}{2}$	38.1	0.2359	0.2966	12.95	4.93
El-Paso	$1\frac{3}{16}$	30.2	0.2377	0.2967	12.05	3.50
Karnak	$1\frac{5}{16}$	33.3	0.2385	0.2967	11.20	2.24
Sudan Sakel	$1\frac{1}{4}$	31.8	0.2381	0.2976	11.00	1.87
Tanguis	$1\frac{1}{4}$	31.8	0.2353	0.2967	10.40	1.05

X, Y, and Z are tristimulus values.
Y is the lightness.

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z}$$

ΔE is the total colour difference computed on the ANLAB 40 system.

Similar results were obtained when yarns were prepared from four cottons. In this case, after preparation, the yarns were dyed with a trichromatic grey mixture (Table VI). It should be noted that these yarns were dyed competitively, i.e., competing for the same dyestuff in a single dye batch, whereas the loose cotton samples had been dyed individually. The base colour of these yarns varied considerably, but examination of the two showing the greatest difference (Deltapine (lightest) and Short American (darkest)) showed little difference after dyeing to the grey shade competitively and even small differences when dyed non-competitively. Thus it can be seen that considerable shade variations can arise between cotton types but that the base of the fibre is not necessarily responsible; rather it is a function of the dyeability of the fibre itself.

The next step considered to have a possible major influence on the dyeing

Table VI

Shade Variation in Yarns of Various Cottons Dyed Competitively to a Neutral Grey% Shade after Scouring and Bleaching

Cotton Type	x	y	Y	ΔE
Coker	0.3184	0.2883	15.00	0.78
Deltapine	0.3210	0.2896	16.58	1.76
Middling American	0.3180	0.2883	16.55	1.40
Short American	0.3201	0.2875	15.99	1.43
Tanguis	0.3156	0.2875	15.61	0

* Chlorantine Fast Yellow 2GLL 0.15%, Fast Red 5 BRL 0.15%, and Fast Blue 2RLL 0.30%.

behaviour of cotton materials is the sizing of warp yarns or, more importantly, the factors that influence the removal of the size. An important factor here is any heat treatment to which sized materials are subject, and the first point at which this needs attention is in the drying of the sized yarn.

A sample of cotton yarn was sized with four different size formulations, each containing 10% of tallow, as follows:

Size A	Sago starch;
Size B	Sago starch–Elvanol 51-05 (2/1);
Size C	Cellofas 350;
Size D	Elvanol 51–05.

The drying of the sized yarn was done either normally passage at 2.5 m/min over five heated cylinders (at 90, 120, 130, 130, and 90°C) or by overdrying at a speed of 10 m/min over the cylinders when drying occurs at an early stage with consequent overheating in the later stages. Several other factors were incorporated in a skeleton factorial design of experiment. These included:

(i) singeing before or after desizing;
(ii) three types of scouring (soda ash, caustic soda, and pressure caustic soda);
(iii) three types of bleaching (peroxide, hypochlorite, and chlorite);
(iv) operator variable in preparation; and
(v) operator variable in dyeing.

The skeleton factorial design enabled the experiment to be carried out with 144 samples, whereas the full factorial design would require no fewer than 1296 experimental dyeings. The factors of size type, drying treatment, and singeing before or after desizing were treated fully factorially, which required 16 groups of experiments. In each of these groups, the remaining factors required nine experiments by suitable choice of a skeleton factorial scheme. (The methods used in the design of experiment were taken from the schemes discussed by Bell, Gailey, and Oglesby[2].)

After being processed, the hanks of yarn were dyed in a Marney laboratory-dyeing machine, the trichromatic mixture of direct dyes being used to give a neutral grey shade as previously. Colour measurements were made with the yarn wound on plastics cards, and directional effects were eliminated by rotating the samples while the measurements were made.

From the analysis of the colour measurements, it is possible to determine the influence of each of the factors considered in the design of the experiment, and in this case the analysis shows that there are no significant sources of shade variation in the preparation sequence employed in this experiment. No variation other than experimental scatter was found for the variables of singeing before or after desizing, the type of scouring employed, or the type of bleaching (Table VII shows typical results). On the other hand, a consistent difference was noted when

Table VII

Colour Differences (ΔE–ANLAB 40) for Yarns Sized with Starch and Starch-Poly(vinyl alcohol)* Mixtures

Differences between: \ Process	Size with Starch				Sized with Starch–Poly(vinyl alcohol)*			
	Mild Drying		Harsh Drying		Mild Drying		Harsh Drying	
	Singe before Desize	Singe after Desize	Singe before Desize	Singe after Desize	Singe before Desize	Singe after Desize	Singe before Desize	Singe after Desize
Scour								
Soda and pressure caustic	0.51	1.41	0.59	0.60	0.73	0.46	0.56	0.31
Soda and caustic	0.51	0.93	0.26	0.41	0.37	0.32	0.36	0.21
Pressure caustic and caustic	0.10	1.55	0.58	0.31	0.37	0.64	0.23	0.10
Bleach								
Hypochlorite and chlorite	0.90	0.27	0.18	0.44	0.14	0.38	0.45	0.18
Hypochlorite and peroxide	0.69	0.65	0.31	0.44	0.35	0.17	0.10	0.34
Chlorite and peroxide	0.28	0.27	0.24	0.73	0.24	0.33	0.31	0.40

* Elvanol.

the analysis was based on the method of drying after sizing with the starch containing size (Table VIII). Starch and starch–Elvanol sizes show a shift to a more yellow shade from the basic grey with no over-all change in lightness. This change occurs with a more than adequate level of scouring and bleaching and stems from the higher drying temperature in sizing that results from the lower processing speed. At the higher speed, the yarn emerges first dry, whereas at the lower speed it dwells for between 5 and 10 sec at 130°C. When starch is present in the size, this is sufficient to influence subsequent dyeing, which produces in this experiment shade changes approximately three times those visually perceptible.

This sensitivity of starch-containing sizes to heat treatments is clearly important, and confirmation of these results was sought in experiments involving the heat treatment of grey starch-sized cotton fabric. Experiments with a cotton

Table VIII

Colour Differences (ANLAB 40 units) between Grey-dyed Cotton Yarns*

Size	Differences between Harsh and Mild Drying				
	A	B	C	D	E
Starch	0.88	1.51	1.75	0.05	1.75
Starch–Elvanol	0.81	1.32	1.55	0.03	1.55
Cellofas	0.03	0.47	0.47	0.23	0.53
Elvanol	0.06	0.51	0.52	0.11	0.53

* Analysis of results based on differences in drying treatment after sizing, average values derived from samples with varying preparation treatments being used.

sheeting containing maize starch size (18% on the weight of warp yarn) lubricated with tallow involved heating in the grey state at a range of temperatures (40–240° C for 50 sec) and a range of times (25–300 sec at 160°C). Samples were then desized (enzyme at 60°C for 45 min) and washed and next scoured (20 g/l. caustic soda at 100°C); this was followed by rinsing and bleaching in peroxide at 95°C with final rinsing, scouring, and air-drying. Fabric samples after preparation were dyed either with the direct grey mixture of:

0.15% Chlorantine Fast Yellow 2GLL,
0.15% Chlorantine Fast Red 5BRL, and
0.30% Chlorantine Fast Blue 2RLL, by exhaustion, or in a reactive grey mixture of:

9.5 g/l. Procion Blue MX2G,
4.8 g/l. Procion Yellow MX4R,
3.2 g/l. Procion Red MX5B,
17.7 g/l. Sodium carbonate (anhydrous), and
0.5 g/l. Lissapol NX, by a pad–batch technique.

Colour measurements were made on the Harrison–Shirley Colorimeter.

The shade of both dyeings was influenced by the heat treatments. However, the direction of the shade change was different in the two systems. Increasing the temperature and time of baking had an additive effect in the case of the reactive dyeings and the shift was towards green on the violet–green axis in the chromaticity plot. The shift in the case of the direct dyeings was smaller and was towards blue on the blue–yellow axis. Calculations of total colour difference (ΔE Anlab 40) showed maximum values of about 1.5 for the direct-dyed samples and values approaching 4 for the reactive-dyed samples (Fig. 2(a) and (b)). In each case, both the difference in chromaticity (ΔC) and that in brightness (ΔL) contributed almost equally to the total colour difference observed.

These results confirm those from the yarn experiments and show that sized fibres are sensitive towards heat at all times and not only at the time of drying of the size. This indicates that the fabric is at risk in any heat treatment before the

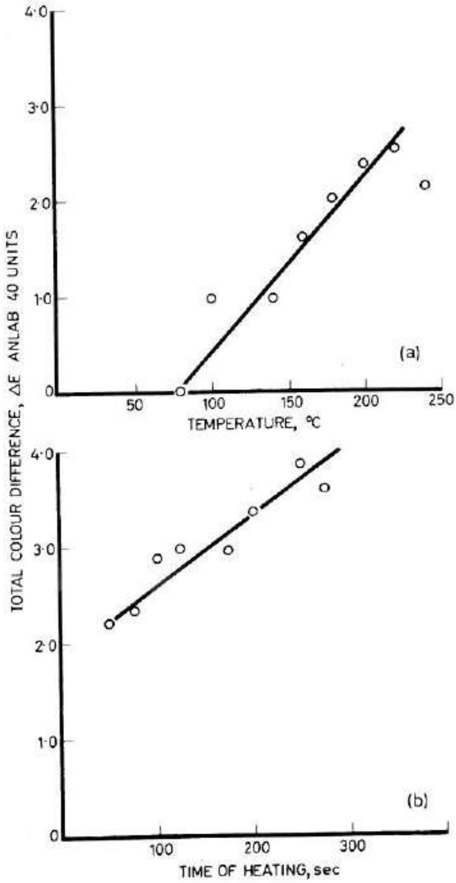

Fig. 2
The influence of heat treatments on the reactive dyeing of cotton fabric: total colour difference (ΔE) for 50 sec at various temperatures and (*b*) at 160°C for various times

preparation sequence. Thus singeing and pre-heat-setting are revealed as processes where fabric-temperature control is of importance if uniformity of shade is to be achieved in subsequent dyeing.

3. CONCLUSIONS

This report of work on the sources of shade variation in dyed cotton fabrics reveals the importance of the control of heat treatments at all stages of processing. It was a matter of some surprise that preparation processes were found to have such a relatively small influence. In commercial practice, variations in the level of preparation are more frequent than would be expected from laboratory results.

Table IX

Critical Factors in the Processing of Cotton

Stage of Processing	Recommendations	Control Limits
Fibre-blending	Keep fibre type constant	± 3% of blend Composition
Yarn production	Avoid contamination with metals	
Sizing	Choose easily removable size; avoid overdrying after sizing with starch-containing size	± 10% of yarn speed in drying
Weaving	Avoid contamination with oils	
Singeing	Avoid excessive heating	
Desizing	Ensure effecient removal of size	
Scouring and bleaching	Ensure efficient removal of lubricants, products of singeing, and metal and metal-ion impurities to obtain good uniform whiteness of fabric at neutral pH	
Dyeing	Maintain good control of dye-bath-component concentrations, of pH, and of the temperature programme	
Fishing	Ensure good control of liquor pH and select catalyst carefully	

A summary of results is shown in Table IX. It should be remembered that, where factors work simultaneously, even tighter limits of control will be necessary than has been indicated.

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20—THE APPLICATION OF SCIENTIFIC TECHNIQUES FOR INCREASED PRODUCTIVITY, IMPROVED QUALITY, AND REDUCED COST IN THE PROCESSING OF TEXTILES CONTAINING CELLULOSIC FIBRES

By M. D. Dixit and S. M. Doshi

As in any other industry, increased productivity, improved quality, and reduced cost of the ultimate product have become very important in the textile industry. Unlike, however, many other industries, the chemical wet processing of textiles is greatly influenced by theoretical considerations of pure and applied chemistry, which include the important factors of time, temperature, and concentration. In addition, the application of many simple chemical laws and the use of basic chemical theory enable a discerning textile chemist to achieve these aims with comparative ease. This paper describes in detail several instances in each of which basic chemical principles have been applied to attain the desired results. In many of the cases, new methods of chemical processing are shown to have been evolved.

1. INTRODUCTION

As in any other industry, increasing productivity, improving quality, and reducing costs of production have become important aims in the wet-processing sector of the textile industry. This sector uses large quantities of various chemicals, dye, and other utilities, such as water, steam, power, and labour. In fact, the field of textile wet processing is very closely related to the chemical industry in the sense that it is characterized by a series of unit operations, which are a feature of any branch of the chemical industry. The series of unit operations in the wet processing of textiles constitutes what is commonly known as a *wet-processing sequence* for the textile material to be treated. The wet-processing sequence may be either a batchwise operation or a continuous operation, depending upon the nature of the textile material and the equipment used. Productivity in the textile wet-processing sector depends upon several factors. Continuous operations are more conducive to higher productivity than batchwise operations. Apart from the mode of processing, maintaining a consistent quality and its improvement play a very important role, not only from the viewpoint of consumer satisfaction but also for withstanding competition in the present situation. Such quality control in the wet processing of textiles include a judicious choice and careful testing of raw materials, quality controls at different stages in the process, and the assessment of the final quality of the finished product. In addition to increased productivity and improved quality, cost reduction is also of great importance, especially in the present era of competitive markets for cellulosic textiles, including cotton, which still enjoy a lion's share of the world's usage of textile fibres. In this paper, some of the applications of scientific techniques for increased productivity, improved quality, and reduced cost in the wet processing of textiles containing cellulosic fibres are therefore discussed.

The wet-processing sequences adopted in the textile industry are many and varied.[1,2] For the sake of convenience, the aspects of increased productivity, improved quality, and reduced cost are therefore discussed separately under the individual headings of the unit operations involved in the wet processing of textiles.

2. BLEACHING AND MERCERIZING

2.1 Desizing

A typical wet-processing sequence starts with the operation of desizing. In some cases, grey mercerizing is resorted to, which serves the dual purposes of desizing and mercerizing. In all other cases, the fabric is subjected to a normal desizing operation, which may be carried out by using enzymes, acids, or oxidative chemicals. The general trend in the textile industry is to use enzymes for desizing. In using the enzymatic desizing process, due consideration should be given to the following aspects:

(i) The amount of sizing ingredients present on the weight of the fabric (o.w.f.);

(ii) the type of enzyme used;

(iii) the quantity of enzyme used (o.w.f.);

(iv) the pH and temperature of the desizing bath; and

(v) the dwell time of the fabric in the desizing liquor.

An important aspect that is often forgotten is that there is a considerable quantity of antiseptic or mildew-proofing agents, which are added to the sizing ingredients. These preservatives, while serving their intended purpose, can also obstruct the action of enzymes during the course of desizing. It is therefore desirable to reduce their concentration on the fabric by a preliminary hot-water quench. This preliminary treatment also helps in gelatinizing the dried starch film for the subsequent better action of enzymes, as can be seen from table I.

Table I

Effect of Hot Pre-quenching on Desizing Efficiency

Fabric	Percentage Starch (o.w.f.)	Percentage Desizing Efficiency
Grey	8.5	—
Straight desized	2.55	70
Desized after hot pre-quenching	0.85	90

Thus, the hot pre-quenching helps towards improved desizing efficiency, which in turn, leads to an improvement in the efficiency of subsequent wet-processing treatments. If the hot-quenching operation is synchronized with the subsequent desizing operation, the productivity of the unit operation of desizing as such is also not affected.

It has also been observed that desizing by means of mineral acids instead of enzymatic desizing gives comparable results, with a reduced time of treatment and consequent increased productivity, as well as a reduced chemical cost. Besides reducing the ash content in the fabric, the acid desizing also helps in reducing the problems of metallic contaminants during subsequent bleaching. The economy in the desizing operation that could be realized by acid desizing in place of the enzymatic process, as tried in actual practice, was as shown in Table II[3].

Table II

Economics in Acid Desizing in Place of Enzymatic Desizing

	Mills' Practice of Ensymatic Desizing				Suggested Practice of Acid Desizing			
Particulars	Mill A	Mill B	Mill C	Mill D	Mill A	Mill B	Mill C	Mill D
Fabric quality	Poplin	L.c	Mulls	Cambric	Poplin	L.C.	Mulls	Cambric
Desizing efficiency	70	78	82	85	75	82	85	90
Chemical cost of desizing (per 1000 kg fabric)	8.30	15.60	11.45	19.60	2.00	3.00	2.50	4.00
Time of desizing (hr)	12	8	10	8	6	6	6	6
Residual ash content %	0.280	0.250	0.272	0.310	0.050	0.060	0.041	0.068

Acid desizing, if carried out properly, is thus not only economical but also conducive to increased productivity of this unit operation.

2.2 Scouring

2.2.1 Outline of Process

After the fabric has been thoroughly desized, it is taken to be scoured for the removal of the natural impurities associated with cotton fabrics. This is done by using dilute solutions of caustic soda and boiling, either the kier system or the J-box system being used. For fabrics containing synthetic fibres, the scouring generally consists in treating the material with mild alkali, preferably in open width. On the other hand, fabrics containing man-made cellulosic fibres, such as viscose and polynosic fibres, can be treated in rope form, preferably by using soda ash for the purpose[4]. In all other cotton goods, a thorough boiling with caustic soda solution is imperative to obtain a well-bottomed fabric. A survey of scouring practices followed in different mills has shown that wide variations exist in such treatments[1].

2.2.2 *Scouring in the J-box*

In general, the scouring operation is governed by the parameters of concentration, temperature, and time of reaction, which are typical of any chemical reaction. By altering one or more of these parameters, it is possible to obtain increased productivity of the unit operation without any adverse effect on the material processed. This is exemplified by the operation of the J-box for the purpose of scouring whereby the conventional batch-scouring time of 16–24 hr is reduced to about 2 hr by using a lower material-to-liquor ratio and a higher concentration of alkalis[5]. This relationship was observed in actual shop-floor working as shown in Table III.

Table III

Effect of Caustic Soda Concentration on Scouring Time with J-Box System

Caustic Soda (o.w.f.) %	Scouring Time Required (hr)
2	2.00
3	1.25
4	1.00
5	0.75
6	0.50

Although the scouring time can be decreased considerably, as can be seen from Table III, the optimum concentration from economic considerations is found to be about 4%, which gives a well-scoured fabric within about an hour's steaming time. A further reduction in time, however, does not give rise to significant benefits of additional economy. In earlier work, it has been shown that the reduction in the time of scouring from 2 hr to 1 hr also helped to reduce steam and power consumption to the tune of Rs. 22 per 1000 kg fabric on this account alone.

2.2.3 *Scouring in the Kier*

The kier is a pressure autoclave further illustrates the relationship of time, temperature, and concentration. It is surprising that the important operation of kier-boiling is still carried out under empirical conditions and that, in this case also, there are widespread fluctuations in kier-boiling practices. Since these parameters have not so far been studied in detail, further work was done to study them. The effect of varying alkali (caustic soda) concentration on the time required for kier-boiling under a pressure of 20 lbf/in^2 (95.8 Pa) is shown in Table IV.

It can be seen from Table IV that a considerable reduction in kiering time and consequent increase in productivity can be obtained without any adverse effect on the quality of the material scoured by using an increased concentration of caustic soda. The gain in productivity, however, is less pronounced at caustic soda concentrations above 15 g/1.

Table IV

Effect of Varying Caustic Soda Concentration on Kier-boiling Time

Caustic Soda, (g/l.)	Kiering Time (hr)	Cuprammomium Fluidity (P^{-1})
1	2	3
4	16	3.0
6	12	3.0
8	10	3.1
10	8	3.2
15	6	3.2
20	4	3.5

* At pressure of 20 Ib/in^2 (95.8 Pa); L.M.R. = 4:1; absorbency required = 3 sec.

Table V

Kier Pressure (lbf/in^2)	(kPa)	Kiering Time (hr)	Cuprammonium Fluidity (P^{-1})
10	68.9	12.0	3.0
15	103.4	10.0	3.1
20	137.9	8.0	3.2
25	172.4	7.0	3.2
30	206.8	6.5	3.3
40	275.8	6.0	3.4

The effect of the pressures used in kier-boiling on the kiering time when 10-g/1. caustic soda and an L.M.R. of 4:1 are used is shown in Table V.

From Table V, it can be seen that, as the kier pressure is increased, the time required for kier-boiling is decreased; however, increasing the kier pressure beyond 20 lbf/in^2 (137.9 kPa) does not offer any significant advantage. From a consideration of Tables IV and V simultaneously, it can therefore be concluded that the optimum conditions for kier-boiling could be as follows:

concentration of caustic soda	10g/l.;
kier Pressure	20 Ibf/in^2 (137.9 kPa);
time of boiling	8 hr.

2.3 Bleaching

2.3.1 Bleaching of Cotton Fabrics

Bleaching in the cotton sector of the textile industry is generally carried out by using mainly either sodium hypochlorite or hydrogen peroxide. The different aspects of bleaching with hydrogen peroxide have been fully dealt with earlier[3], where it has been shown that it is important to give due consideration to the formulation of the peroxide bleach bath, including the addition of buffers and stabilizers. It is desirable to introduce a souring treatment prior to hydrogen peroxide bleaching in the sequence to reduce the catalytic effect of metallic contaminant, which otherwise would be harmful during peroxide bleaching by giving rise to hole formation[5]. These precautions would ensure improved quality of the bleached material.

In the hypochlorite bleaching of cotton fabrics, a considerable amount of work has been reported. However, special mention may be made of the work reported on the accelerated hypochlorite bleaching of cotton[6], on the basis of which it is possible to reduce the time required for hypochlorite bleaching by a factor of 2.7 for each 10-degC rise in temperature of the hypochlorite bath. A process based on this is already in operation in India[7].

2.3.2 *Bleaching of Polyester-fibre–Cotton Blended-fibre Fabrics*

Sodium chlorite is generally used for the bleaching of synthetic-fibre blends with cotton. However, it is possible to obtain equivalent bleaching results by the use of potassium permanganate, especially with polyester-fibre blended-fibre fabrics. The results of a mill trial were shown to be as follows:

Table VI

Comparative Economics (Chemical Cost of Polyester-fibre Bleaching with Sodium Chlorite and with Potassium Permanganate*

Chemical	Cost/kg (Rs)	Bleaching with: Sodium Chlorite Quantity (kg)	Sodium Chlorite Cost (Rs)	Potassium Permanganate Quantity (kg)	Potassium Permanganate Cost (Rs)
Sodium chlorite	30.00	1.500	45.00	—	—
Acetic acid	10.00	1.500	15.00	—	—
Potassium Permanganate	20.00	—	—	1.500	30.00
Sulphuric acid	1.00	—	—	1.500	1.50
Oxalic acid	20.00	—	—	1.000	20.00
Hydrogen peroxide	10.00	1.500	15.00	1.500	15.00
Total Cost	—	—	75.00	—	66.50
Cost/kg of Fabric	—	—	0.75	—	0.65

* Figures as obtained from mill; batch size 100 kg; L.M.R. 5:1.

(*a*) it is economical;
(*b*) the ambient atmosphere is pleasant compared with that of sodium chlorite bleaching;
(*c*) $KMnO_4$ does not noticeably corrode the equipment used; and
(*d*) tenacious stains due to coloured specks incorporated at the time of blending are removed.

The bleaching of the cotton component has already been discussed in Section 2.3.1.

2.4 Souring

Souring is found to be a very useful operation, leading to the following desirable effects in the wet processing of textiles containing cellulosic fibres and cotton in particular:

- (i) it helps in reducing the ash content;
- (ii) It reduces the problems of metallic contaminants in subsequent bleaching, where they are otherwise likely to give rise to hole formation due to the considerable catalytic activity exerted by these impurities in the bleaching action of hydrogen peroxide;
- (iii) it can serve as the desizing treatment whenever grey souring is done.

Souring is generally accomplished by using mineral acids, which are necessarily required to be removed from the treated material before any other chemical treatment in the sequence. The neutralization of such acids is effected generally by using soda ash followed by washing with a plentiful supply of water. However, if the souring treatment is the final treatment, it is likely that the quantity of neutralizing soda-ash alkali used will be inordiantely high, which results in residual alkalinity in the fabric. This residual alkalinity is found to be undesirable for the following two considerations:

- (*a*) for white goods, it causes yellowing of the fabric, if not immediately, then after some time in storage;
- (*b*) if the material were to be dyed with those classes of dyes sensitive to alkalinity, e.g., reactive dyes, it may give rise to undue hydrolysis of the dyes, making them ineffective as a reactive dye application; in such cases, therefore, it is always advisable to use sodium acetate for the neutralization of mineral acids used in the final souring treatment, so that any organic acidity formed during double decomposition is removed from the fabric during drying owing to its volatile nature without causing any deleterious effect of chemical degradation of the cellulosic fibres; the usefulness of sodium acetate for the neutralization of mineral acids used in souring can be seen from the results of pH and cuprammonium fluidity of fabric given such a treatment in the mills' former normal wet-processing sequence[8].

2.5 Mercerizing

The mercerization of textile fibres is mainly carried out to improve the lustre of the fabric and the dyeability of native cotton fibres so that they match the same properties of regenerated cellulosic fibres. This is generally achieved by a treatment with 25–30% caustic soda solution (w/v), followed by stretching, washing, neutralizing and washing, etc. However, whenever regenerated cellulo-

Table VII

Use of Sodium Acetate for Neutralization on Soured Fabric and its Effect on pH and Cuprammonium Fluidity of the Treated Fabric

No.	Sample Particulars					pH of water Extract	Cupr-ammonium Fluidity (P^{-1} at 20°C)
	Distilled Water Used					6.8	—
1	Untreated Fabric (Bleached)					8.3	3.89
2	Pad I	Wash	Wash	Dry Final		7.0	4.72
3	Pad I	Wash	Dry Final			6.6	6.47
4	Pad I	Dry IA	Wash	Dry Final		6.4	8.33
5	Pad I	Dry IB	Wash	Dry Final		6.3	9.61
6	Pad I	Pad II	Dry IA			7.3	4.14
7	Pad I	Pad II	Dry IB			7.4	4.22
8	Pad I	Pad II	Dry IA	Wash	Dry Final	7.6	4.05
9	Pad I	Pad II	Dry IB	Wash	Dry Final	7.9	4.26
10	Pad I	Pad II	Wash	Dry Final		7.2	4.01

Processes: Pad I: 2 g/1 sulphuric acid.
Pad II: 5.66g/1 sodium acetate
Wash: with MLR(1:10) for 5 min
Dry IA: intermediate drying for 2 min at 120°C
Dry IB: intermediate drying for 4 min at 120°C
Dry Final: 7 min at 80°C

sic fibres are included in blended material, a less drastic treatment has to be used to prevent any damage to these alkali-sensitive fibres. The spent caustic lye and the wash waters that can be collected should be effectively reutilized, either in the mercerizing operation again and again after proper concentration in the evaporators of caustic-soda-recovery plants or in other unit operations requiring dilute solutions of caustic soda, e.g., scourings, etc. The concentration of dilute caustic soda from the mercerizing wash waters, can be done for the mills by several commission concentrators, especially in industrialized areas like Bombay, or alternatively the mills can have their own recovery plants. However, taking into account the cost of getting caustic soda recovered from outside parties and the cost of the mills' own recovery system (including the cost of equipment as well as the recurring cost of labour, supervision, and utilities such as steam) and the quantity of dilute wash waters available for recovery, BTRA's recent survey has worked out a break-even point as 1500kg/day of caustic soda as the justifiable level for the mills to do for their own recovery and thereby avoid the problems of transportation, delivery, etc.[9]

Acids such as hydrochloric acid are normally used for the neutralization of residual caustic alkalinity from the mercerized material. This, however, entails control of the feed of the acid and a plentiful supply of water in the subsequent washes to ensure that there is no hydrolytic damage to the cellulose. For this purpose, some work done at BTRA has revealed that such neutralization of residual alkalinity can safely and effectively be accomplished by the use of ammonium chloride giving rise to common salt (NaCl) and volatile ammonia, both of which are harmless, as the products of double decomposition. Even if the ammonium chloride used for the purpose is inadvertently in excess of the stoichiometric quantity required for the purpose, it has been found to be much less harmful, as can be seen from the results of cuprammonium fluidity given in Table VIII, for experiments in which as 10 g/l. of salt in excess was used and the material was dried at temperatures of 120 and 150°C for durations of 5 and 3 min, respectively.

Table VIII

Effect of Residual Ammonium Chloride on Fluidity Values on Drying of Mercerized Cotton Fabrics

Fabric Sample	Cuprammonium Fludity (P^{-1}) of Sample Dried at:	
	120°C for 5 min	150°C for 3 min
Untreated	3.2	3.5
Control	3.7	3.9
Treated with 1% NH_4Cl (w/v)	4.4	4.8

It can be seen from Table VIII that the drying operation itself has only a very marginal effect on the cuprammonium-fluidity values, even in the presence of ammonium chloride. In actual practice, after the neutralization has taken place, it is but to be expected that the quantity of ammonium chloride will be much lower than that used in the above experiments and consequently no deterioration in fabric properties is expected.

3. DYEING

In dyeing, the scope for economy in dyes is limited, since most of the dyes are fixed on the fabric either by the exhaustion technique or by the padding technique, where the possibilities of dye fixation are governed by the technique adopted. However, there exists some limited scope for increased productivity by reducing the operational time. This is examplified by the development of vat dyes on jiggers with sodium bicarbonate in intermediate rinsing before chemical oxidation[10] and by disperse-dye fixation with an H.T.–H.P. steaming technique in place of the conventional beam-dyeing used for the purpose. The comparative economics of such pressure-steaming compared with H.T.–H.P. beam-dyeing as tried out in a few mills[11] were as shown in Table IX.

Similarly, the use of an alkali mixture of soda ash and sodium acetate together in the final drying or finishing operation (or both) helps to prevent subsequent acid damage in fabrics dyed with sulphur dyes.

Table IX

Comparative Economics Involved in Dyeing by the Pressure-steaming and H.T.-H.P. Beam-dyeing Methods

Item	Normal	Modified
(1) Expected production per shift	$2 \times 100\,kg = 200\,kg$	$8 \times 40\,kg = 320\,kg$
(2) Cost of labour: Rs. 25 per worker	Rs. 25 × 3 = Rs. 75.00	Rs. 25 × 4 = Rs. 100.00
(3) Cost of steam: Rs. 0.10 per kg	Rs. 0.10 = 5.5 × 200 = Rs. 110.00	Rs. 0.10 × 8 × 320 = Rs. 256.00
(4) Cost of water Rs. 30 for 10 000 litres	$\frac{\text{Rs. } 30 \times 50 \times 200}{10000}$ = Rs. 30.00	$\frac{\text{Rs. } 30 \times 320 \times 7}{10000}$ = Rs. 6.72
(5) Cost of power Rs. 0.30 per kW hr	Rs. 0.30 × 75 × 2 × 100 = Rs. 45.00	Rs. 0.30 × 0.625 × 320 = Rs. 60.00
(6) Total for items 1–5	Rs. 260.00	Rs. 422.72
(7) Cost per kg	Rs. 1.30	Rs. 1.321

4. PRINTING

4.1 Advantages of Printing

Compared with dyeing, the field of printing offers greater scope for economy from the point of cost reduction and increased productivity and also for improved quality in view of the number of styles of printing, the different classes of dyes employed, and the different methods used by the printer. A few typical examples are given below.

4.2 Resist Under-reactive Dyes

For the purpose of printing resist under-reactive dye, either citric acid or tartaric acid is used. It has been shown in mill-scale trials that ammonium chloride acts equally as an alkali-binding or neutralizing agent. The cost reduction resulting from the use of ammonium chloride in place of citric or tartaric acid in the resist print paste alone is shown in Table X.

4.3 Substitution of Kerosene Oil in Pigment Printing

Kerosene oil is the main ingredient in the formulation of emulsion print paste for pigment printing. In the event of a scarcity of kerosene oil, it has been shown that it is possible to substitute up to 50% of the kerosene oil used in pigment printing or roller printing with a low-solids gum paste, together with an emulsion of ammonium stearate. The latter serves to prevent dulling of the prints by the gum used[13].

4.4 Development of Rapidogen Dyes by Dry-heat Fixation

It has been shown by one of the authors (S.M.D.) that it is possible to

Table X

Cost Comparison of the White Resist Print-paste Formulation as in BTRA's Recipe and the Conventional Recipe

		Conventional*		Modified	
		With Citric or Tartaric Acid		With NH_4Cl + Sodium Acetate	
Chemical	Cost/kg Rs. P.	Mass (kg)	Cost Rs. P.	Mass (kg)	Cost Rs. P.
Citric or tartaric acid	40.00	10	400.00	—	—
Ammonium chloride	2.50	—	—	12.5 (10–15)	31.25
Sodium acetate	4.00	—	—	2.5	10.00
Titanium dioxide (1:1)	19.00	10	95.00	10	95.00
Glycerine	18.00	2	36.00	—	—
Fluorescent brightening agents	40.00	0.5	20.00	1 (0–2)	40.00
Rongalite	20.00	—	—	1	20.00
Wax emulsion	5.00	—	—	5	25.00
British gum (60%)	3.00	77.5	232.50	59	177.00
Total for 100 kg			783.50		398.25
Cost of resist printing paste per kg			7.84		3.98

* As obtained from a mill printing a substantial proportion of its printed fabrics in the resist style.

develop Rapidogen dyes by dry-heat fixation without the use of the organic acid vapours that are normally effective when acid ager is used. The process, which is now well established in the Bombay Textile Mills, enables the printer to print other classes of dyes together with the Rapidogen prints, e.g., pigment, reactive, disperse dyes, etc., and to do the fixation of all such dyes in a one-step operation[14,15]. The other advantages offered by this process include freedom from ambient acid vapours, partial development at the plaiter of the printing machine, and adaptability for using Rapidogen and disperse dyes together in the same print paste in printing on polyester-fibre–cotton blended-fibre fabrics.

4.5 Brighter Carbonized Prints

At the outset, it may seem to be rather out of place to discuss in a paper dealing with the processing of cotton and man-made cellulosic fibres and their blends with man-made synthetic fibres the production of printed fabrics in which the cellulosic component is removed by the process of dissolution with 70% sulphuric acid. However, the demand for such prints in recent years has increased so much that a short discussion of the subject is worth while. These fabrics are popular because of their light handle, supple feel, and silky appearance. However, the successful production of such prints poses several problems, such as dulling and flushing of the prints and excessive tinting of the white background. These problems can be successfully overcome by curing followed by pressure-steaming and direct carbonizing without an intermediate hot-rinsing operation[16] and by the incorporation of urea or sulphamic acid in the carbonizing acid bath. These additives efficiently overcome the defect of the dulling of disperse prints by neutralizing the contaminating impurities of nitrous and nitrosyl sulphuric acid[17], as shown below:

$$2HNO_2 + H_2NCONH_2 \rightarrow 3H_2O + CO_2 + N_2 \quad (1)$$

$$HNO_2 + H_2NSO_3H \rightarrow H_2SO_4 + H_2O + N_2 \quad (2)$$

5. FINISHING

The finishing operation is largely governed by the requirements of feel, handle, and other subjective parameters, especially in conventional finishes. A judicious selection of finishing ingredients is often found useful in effecting a cost reduction without adversely affecting the finish of the fabric. A typical example is the use of mixed starches in place of single-component starches, e.g., the use of maize and tapioca in place of either maize or tapioca alone. For the finishing of pigment-printed and resin-cross-linked fabrics, the use of sodium acetate has been found to be useful to deal with the residual acidity of the catalyst used. Similarly, it has been shown that the use of urea in the final finishing of resin-treated goods helps to overcome the problems of formaldehyde release in storage to a great extent[18].

Similarly, the heat-setting of blended-fibre fabrics containing synthetic fibres, which is carried out with a view to obtaining dimensional stability, is generally assessed by such measurements only, and no exact quantitative assessment is established for the purpose. In this respect, the Bombay Textile Research Association has recently developed and standardized a quantitative volumetric method for the purpose that is based on iodine absorption and enables of over- or under-heat-setting of such materials to be avoided. The original method suggested by Moncrieff[19] was modified as far as extraction of iodine absorbed by the polyester-fibre component of the fabric was concerned by using chloroform in place of phenol for obtaining a consistent and sharp end-point.

6. CONSERVATION AND REUTILIZATION OF PROCESS CHEMICALS AND WATER

6.1 Introduction

In view of the varied processes followed and the diverse types of chemicals used, requiring copious supplies of clean soft water, this field affords challenging opportunities to a discerning textile chemist to explore ways and means of conserving and reutilizing processing chemicals and water in the textile industry.

The Bombay Textile Research Association in the last two decades has helped its member mills, not only in effecting economies in this field but also by increasing their production by reusing the utilities such as water and other process chemicals. A brief account of the work done is given below.

6.2 Reuse of Water in Continuous J-box System

Besides counter-current washing in continuous processing on a J-box range, mercerizing and soaping operations, etc., reduced water consumption per unit of production in a washing machine is possible in a counter-current manner even in slack rope-washing machines in which the incoming loose strands of fabric conform to the contours of a compartmentalized washing machine[8].

In the continuous J-box system of processing, the reuse of water in the preceding washers is governed by the type of chemical treatment received by the fabric before such washing by reusable waters.

By taking these factors into consideration, it has become possible to reuse the water in the J-box system as follows.

Fresh water passes to the washers after the caustic J-box and peroxide J-box, and water from the peroxide-J-box washer is used in the washer after the chemic J-box (first reuse). Reused washer water from the chemic J-box is again reused in the washer of the desizing unit (second reuse).

In this manner, instead of four points of intake of fresh water, only two such points are necessary, which thereby saves about 50% of the water required for processing in the J-box. This system of reuse, first introduced in 1966, is now in operation in many of the member textile mills of the Bombay Textile Research Association.

6.3 The Effective Reutilization of Wash Waters in Discontinuous Processing

In the discontinuous systems of processing, such as are normally found in conventional rope-form processing with kiers, the use of the counter-current-flow principle of washing from the following washing machines to the preceding one becomes rather difficult. In such cases, however, it is much more practicable and easier to resort to the collection of such reusable waters in a common sump and to pump them in the appropriate preceding washing machines, which thereby reduces the consumption of fresh water to that extent. In doing so, it has been found that neutralizing and equalizing effects on acidity–alkalinity and chlorine–antichlorine, etc., become possible, with the added advantage that water collected in this way is as good as fresh clean water except for the increased amount of dissolved solids that it contains[20].

In this manner, reuse of 30–40% of the fresh-water intake in conventional rope-form processing is possible.

6.4 Reclamation and Reuse of Process Chemicals

Treating chemicals, such as those used for souring, chemicking, and peroxide bleaching, can conveniently be reused for almost indefinite periods provided that effective filtering systems are used to remove floating fibres and appropriate replenishment by means of concentrated feed is effected.

Regeneration of Caustic Soda from Spent Kier Liquors

The kier liquor at the end of a kier-boiling operation is always drained off. This is because the kier liquor is intensely coloured and contains impurities such as fats and waxes removed from the cotton material. In addition to these impurities, the kier liquor has great polluting propensity in view of the high B.O.D., C.O.D., and T.O.S. impurities, which are objectionable from the aspect of effluent disposal. In the early days of kier-boiling, attempts were made to regenerate caustic alkali from the spent kier liquors[21], but these were subsequently not pursued in view of the abundant water supplies, the availability of cheaper caustic soda, and the absence of pollution-prevention laws. In the context of the present world situation relating to effluent disposal, fresh attempts were experimentally made at BTRA to reutilize the discharge kier effluent after giving it a suitable treatment with a lime suspension. The caustic is regenerated as follows:

$$Na_2CO_3 + Ca(COH)_2 \rightarrow 2\,NaOH + CaCO_3$$

After the precipitated $CaCO_3$ has been filtered, the kier liquor is ready to be reused by suitable replenishment with the necessary quantities of caustic soda and other ingredients. It has been found that in this manner it is possible to reuse the kier liquor several times without adversely affecting the quality of kier-boiling.

6. CONCLUSIONS

It has been shown in this paper that, by the application of scientific techniques, it is possible to attain increased productivity, improved quality, reduced cost, and better utilization of process chemicals and water in the wet processing of textiles containing cellulosic fibres.

These techniques enable a reduction to be made in the time taken for the scouring and bleaching of fabrics containing cellulosic fibres. In the neutralization of alkaline fabrics, e.g., mercerized goods, ammonium chloride has been found to be very effective. For the neutralization of acidic fabrics, e.g., soured or sulphur-black-dyed goods, sodium acetate has been found to be equally useful. In addition, both these chemicals have enabled a reduction to be made in the water consumption in final washes. The use of pressure-steaming techniques in dyeing has made possible better and quicker fixation of dyes on the fabric. Dry-heat-fixation techniques for Rapidogens have dispensed with conventional acid-steaming for the development of such dyes. Ammonium chloride has been found to be an effective chemical resist for reactive dyes. Partial substitution of kerosene oil in pigment printing enables air pollution to be reduced. BTRA recommendations have allowed brighter carbonized prints to be obtained without flushing of prints and tinting of the white background. In finishing, the use of sodium acetate helps in overcoming the residual acidity of pigment-printed and resin-treated fabrics. In the reclamation and reuse of process chemicals and water, it has been shown that considerable economies are possible in addition to the reduction of effluent-disposal problems.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the co-operation extended by several mill technicians and colleagues in the Bombay Textile Research Association in collecting relevant information and carrying out the necessary trials. They also wish to thank Mr. T. V. Ananthan, Director, BTRA, for his kind permission to present this paper.

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21—A NOVEL CONCEPT IN THE CROSS-LINKING OF COTTON CELLULOSE

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Magnesium chloride hexahydrate and zinc nitrate are the common catalysts used in the cross-linking reactions of *N*-methylol reactants with cellulosic materials. It is believed that magnesium chloride hexahydrate decomposes at a higher temperature, i.e., nearly 150–160°C, and produces hydrogen chloride, which acts as a cross-linking catalyst. It is also known that the strength losses of cotton fabrics given a durable-press treatment with *N*-methylol reactant and magnesium chloride or zinc nitrate catalyst arise from molecular degradation caused by the catalyst in addition to cross-link embrittlement caused by the cross-links. This implies that, if cross-linking is achieved in the absence of an acid-liberating catalyst or in the presence of a metal-salt-supplying cation (other than proton) necessary for the cross-linking reaction, at least those strength losses that arise out of the molecular degradation of cotton cellulose can be avoided. A few examples of experimental evidence are presented that support the hypothesis that, for the cross-linking reaction, the presence of proton is not essential and that sufficiently activated cations can also bring about the cross-linking reaction. It is further observed that durable-press cotton materials produced by exploiting the above principle preserve to a large extent the strength characteristics of the original material.

1. INTRODUCTION

From the very early days of the application of resin treatments, it has been known that good crease-resistance can be obtained by increasing the amount of resin applied to the cellulosic-fibre fabric. However, when such an approach was attempted, it was found that the tensile strength, tearing strength, and abrasion-resistance were rapidly reduced to such a degree that the fabrics were no longer serviceable.

Magnesium chloride hexahydrate and zinc nitrate are the common catalysts used in the cross-linking reactions of *N*-methylol reactants with cellulosic materials. It has been found that the temperature of curing is critical (about 150–160°C) when magnesium chloride hexahydrate is used as a catalyst and that *N*-methylol reactants are not efficiently fixed to the cellulosic materials below this temperature. It is believed that magnesium chloride hexahydrate decomposes at the higher temperature (nearly 160°C) and produces hydrogen chloride, which acts as a cross-linking catalyst. However, the literature shows contradictory results regarding the decomposition of magnesium chloride hexahydrate[1,2].

Segal and Timpa[3] observed recently that the strength losses of cotton fabrics given a durable-press treatment with dimethylol ethylene urea (DMEU) and zinc nitrate catalyst arise from molecular degradation caused by the catalyst in addition to the cross-link embrittlement caused by the cross-link. They further observed that, although the hydrolytic reaction proceeds in the dry state, the molecular degradation of cotton cellulose by the catalyst increases with the curing time.

Similarly, in order to account for the excessive strength losses of cotton fabrics given a durable-press treatment with DMEU and magnesium chloride hexahydrate, it appears probable that both degradation of the molecular chain length and the formation of ether cross-links take place. Both these reactions may occur via the formation of complexes between magnesium chloride and the hydroxyl groups. Hence, in resin cross-linking reactions in the presence of magnesium chloride, besides the formation of cross-links due to the cross-linking agent, degradation of the cellulose molecular chain may also take place, both of which result in a loss of strength.

The other metal-salt catalysts, such as zinc chloride, most probably behave in a similar manner to magnesium chloride and zinc nitrate in cross-linking reactions.

On the basis of the foregoing, it can be argued that, if cross-linking is achieved in the absence of an acid-liberating metal-salt catalyst, at least those strength losses that arise out of the molecular degradation of cotton cellulose can be avoided.

According to Vail[4], the acid-catalysed reaction of *N*-methylol agents with cotton proceeds through a series of reversible steps in which the formation of a resonance-stabilized intermediate is considered to be the rate-determining step. Thus, the formation reactions are:

$$=\text{N-CH}_2\text{OH} + \text{H}^+ \rightleftharpoons =\text{N-CH}_2\text{-O}^+\text{H}_2$$

$$=\text{N-CH}_2-\text{0}^+\text{H}_2 \rightleftharpoons =\text{N-C}^+\text{H}_2 + \text{H}_2\text{O}$$

$$=\text{N-C}^+\text{H}_2 + \text{Cell-OH} \rightleftharpoons =\text{N-CH}_2\text{-}\underset{\text{H}}{\text{O}}{}^+\text{-Cell}$$

$$=\text{N-CH}_2\text{-}\underset{\text{H}}{\text{O}}{}^+\text{-Cell} \rightleftharpoons =\text{N-CH}_2\text{-O-Cell} + \text{H}^+.$$

From the above mechanisms, it appears that, in principle, all metal cations can behave as Lewis acids. The acid strength depends upon the amount of positive charge on the ion and the electro-negativity of the metal. It also appears, on extending the hypothesis further, that any latent Lewis acid may be able to catalyse the above reaction, provided that it fulfils the following requirements:

(i) a cation is generated that has a small ionic radius;
(ii) the cation generated possesses vacant orbitals, which are in a position to overlap constructively with the lone pair of electrons on the oxygen atom of the *N*-hydroxymethyl group;
(iii) such an overlap becomes feasible from geometrical as well as energy considerations; and
(iv) the cation has a wide spectrum of oxidation states as well as the ability to accommodate the oxygen atom of an *N*-hydroxymethyl group in its co-ordination sphere.

In order to check the validity of the above hypothesis, a series of cations was selected for use as catalysts in the cross-linking reactions of DMEU with cotton cellulose.

2. EXPERIMENTAL

2.1 Fabrics

The fabrics used for laboratory experiments and commercial trials were desized, scoured, bleached, mercerized, and dyed or printed poplin or sheeting fabrics, the constructional and other particulars of which are given at appropriate places.

2.2 Chemicals

The cellulose cross-linking agent used in this study was a commercial product, namely, dimethylol ethylene urea (DMEU). The wetting-out agent was of the non-ionic type, and the catalysts used were the ones developed by the authors. The softener was again a commercial product based on polyethylene.

2.3 Recipe

The pad-bath recipe was formulated by using DMEU reactant, a non-ionic wetting agent, a catalyst, polyethylene emulsion, and the required quantity of water.

2.4 Method

Before application of the finishing treatment at both the laboratory and the large-scale level, the fabrics were given 0.1% acetic acid treatment in order to remove residual alkaline impurities from them. The pad-bath recipe was applied to fabrics by means of a three-bowl padding mangle giving two dips and two nips. The pad-roll pressure was adjusted to give approximately 50–60% wet pick-up. The padded fabrics were then flash-cured in a stenter under conditions indicated at the appropriate places. Thus the usual curing in a polymerizer at 150°C for 4 min of resin-padded and dried fabric was eliminated. This was followed by the normal process of washing and drying.

2.5 Testing

The resin-finished and control fabrics were conditioned for 24 hr at 65% r.h. and 25 ± 2°C and then tested by standard methods. Each result given is the average of tests on ten samples. The dry crease-recovery angles of the conditioned samples were determined by using a Monsanto Tester and the ASTM method[5]. The tensile strength of the fabric was measured according to the

ASTM method on a 20-cm. × 5-cm revelled strip on a constant-rate-of-traverse machine[6] operated at 18 in. (45.7 cm)/min. The tearing strength of the fabric was measured according to the ASTM method on a Elmendorf tearing-strength tester[7]. The resin add-on of the resin-treated fabric was determined by the method recommended by Tootal[8].

3. RESULTS AND DISCUSSION

As reported by numerous scientists, the strength losses of cotton fabrics given a durable-press treatment with conventional *N*-methylol-type cellulose-cross-linking agents and such conventional catalysts as magnesium chloride and zinc nitrate, arise from the molecular degradation caused by the catalyst (or by acid liberated from it) in addition to the cross-link embrittlement caused by the cross-links. To understand the effect of a metal-salt catalyst on fabric properties at the elevated temperature at which a metal-salt catalyst is believed to liberate acid (which is thought to be a catalyst for the cross-linking reaction), experiments were designed in which the fabric was treated with a 2.7% magnesium chloride hexahydrate solution. (For about 4.5% resin add-on on fabric, one would use 9.0% resin solution at 50% wet pick-up. The concentration of metal-salt catalyst, which is generally 30% on the weight of solid resin, works out to be 2.7% for 9.0% resin concentration in the pad bath.) The fabric was then dried and baked at 150° C for 4 min and was next given a process wash followed by water-rinsing. In the final rinsing, distilled water was used to eliminate the possibility of salt deposition on the fabric and its subsequent adverse effect on tearing strength. Similarly, fabric was treated under identical conditions except that the catalyst was the one developed by the authors in 2.7% concentration. The fabric treated in this manner was flash-baked (i.e., by drying and baking combined) at 150°C for 1 min—the conditions largely employed for the experiments reported in this paper. The results are summarized in Table I.

One may think that in the above experiments two factors are operating to tender the fabric, i.e., (i) heat treatment and (ii) hydrolytic attack (reaction) by the catalyst or acid liberated from it. In order to ascertain which of these is solely or largely responsible for fabric-tendering, an experiment was designed where by fabrics were padded with distilled water and then in one case subjected to drying followed by baking at 150°C for 4 min and in the other flash-baked (by drying and baking combined) at 150°C for 1 min. The results are summarized in Table II.

The following conclusions can be drawn from the results contained in Tables I and II.

(i) Heat treatment of the magnitude employed in the resin-finishing of cotton textiles does not contribute much towards tendering of the fabric.

(ii) Such widely accepted catalysts as magnesium chloride hexahydrate and other metal-salt catalysts do tender the fabric by hydrolytic

Table I

The Effect of Cross-linking Catalyst on Fabric Properties*

Fabric Treatment	Tensile Strength†				Elmendorf Tearing Strength				Resistance to Abrasion on Ring-wear Tester (rev)	Cuprammonium Fluidity (P^{-1}) (Rhe)
	Warp		Weft		Warp		Weft			
	(lbf)	(N)	(lbf)	(N)	(gf)	(N)	(gf)	(N)		
Padded with 2.7% solution of $MgCl_2.6H_2O$ at 50%	137	609	87	387	764	7.49	696	6.83	1158	9.5
Pick-up, dried and baked at 150°C/4 min; process-washed.	(95)	(95)	(89)	(89)	(79)	(79)	(82)	(82)		
Padded with 2.7% solution of Catalyst A, flash-baked at 150°C/1 min; process washed.	143	636	96	427	938	9.20	873	8.56	3125	6.4
	(99).	(99)	(98)	(98)	(97)	(97)	(100)	(100)		
Control	144	641	98	436	968	9.49	852	8.26	3640	3.0

Figures in brackets indicate percentage strength preserved.
*Fabric particulars: Yarn 16 tex × 21 tex; 47 ends/cm × 28 picks/cm; bleached and mercerised poplin; 145 g/m^2.
†Tests on ravelled strip, 20 cm × 5 cm.

Table II

The Effect of Heat Treatment on Fabric Properties*

Fabric Treatment	Tensile Strength†				Elmendorf Tearing Strength				Resistance to Abrasion on Ring-wear Tester	Cuprammonium Fluidity (P^{-1})
	Warp		Weft		Warp		Weft			
	(lbf)	(N)	(lbf)	(N)	(gf)	(N)	(gf)	(N)	(rev)	(Rhe)
Padded with distilled water at 50% pick-up, dried and baked at 150°C/4 min	144	641	98	436	944	9.26	853	8.37	3460	3.2
Padded with distilled water at 50% pick-up and flash-baked at 150°C/1 min	143	636	98	436	1000	9.81	896	8.79	3643	3.0
Control	144	641	98	436	968	9.49	852	8.36	3640	3.0

*Fabric particulars as for Table I.
†Testing conditions as for Table I.

reaction, probably by liberating acid at the elevated temperature generally employed for curing and baking.

(iii) The catalyst developed by the authors is quite innocent in the sense that, under the flash-curing-baking conditions employed, it does not liberate acid and does not do any appreciable harm to the fabric in terms of loss of tensile and tearing strengths and reduction in abrasion-resistance.

To check the second phase of the hypothesis, i.e., whether or not the sufficiently activated cation can bring about a cross-linking reaction under the flash-curing condtions described, catalyst A was tried together with DMEU. The results are summarized in Table III.

Table III

Properties of Fabrics Treated with DMEU in the Presence of Non-acid-liberating Catalyst and in the Presence of Free Acid Based on Anion of the Catalyst*

Catalyst	Dry Crease-resistance (deg) (Monsanto: W + F)	Percentage Tensile Strength Retained		Percentage Tearing Strength Retained	
		Warp	Weft	Warp	Weft
A	286	77.6	64.4	88.1	88.0
A′ (free acid based on anion of catalyst A)	198	95.7	95.6	98.0	97.3
A′ (free acid based on anion of catalyst A); flash-curing conditions 205°C/30 sec	269	59.7	68.6	78.4	75.0
Control	170	100.0	100.0	100.0	100.0

*Fabric particulars as for Table I.
Recipe: Prepared to give 4% resin add-on on fabric.
Catalyst concentration: 20% on weight of solid content, of resin solution.
Flash-curing conditions: 150°C/1 min (unless otherwise mentioned).

The results contained in Table III clearly indicate that catalyst A does contribute to the formation of cross-links between adjacent cellulose molecules or micro-fibrils even under very mild flash-curing conditions, such as those indicated at the head of Table III. Catalyst A raised the dry crease-recovery (i.e., the sum of the crease-recovery angles for warp and weft (W + F)) from 170 to 286°. In other words, catalyst A brought about an improvement in crease-resistance of 116° and made it reach DP level at the same time and preserve the strength of the fabric to a large extent.

In order to study the contribution of free acid (on the assumption that catalyst A decomposes into free acid under the flash-curing conditions employed), the fabrics were given a resin-finishing treatment under identical conditions except that the free acid based on the anion of catalyst A (i.e., catalyst A') replaced catalyst A in the pad-bath recipe. The properties of fabrics treated in this way are given in Table III for catalyst A'. It is very clear from these data that this particular acid alone makes very little contribution to the formation of cross-links and that it was not able to life the crease-recovery property to the extent that catlyst A had done. In other words, catalyst A supplies enough cations (other than proton H^+) for cross-linking to occur, and, in the absence of cations (when the free acid based on the anion of catalyst A is used as catalyst), sufficient protons are not made available for the cross-linking reactions to occur, as a result of which the improvement in crease-resistance is very marginal. The strength data reported for catalyst A' are indicative of the fact that it is quite harmless since it had not attacked the cellulose substrate and had not degraded it to an appreciable extent. However, the same free acid under the flash-curing conditions of 205°C for 30 sec was able to lift the crease-recovery to an appreciable extent (Table III). This finding probably reveals that either a proton or a cation other than a proton can bring about cross-linking between adjacent cellulose molecules or microfibrils provided that they are sufficiently activated. The results recorded in Table IV further substantiate this observation.

For this study, fabrics were treated with DMEU in the presence of catalyst A under various flash-curing conditions. The idea was to find out whether it was possible to lower the flash-curing temperature further by increasing the curing time. In other words, the idea was to ascertain whether catalyst A could also furnish sufficient activated cations at a lower temperature for the cross-linking reaction to occur to an appreciable extent.

The results given in Table IV indicate that the improvement in crease-resistance is very marginal under the mildest flash-curing conditions employed, i.e., 80°C at 4 min. However, this gradually improves as the flash-curing conditions, particularly the temperature of curing, become more and more drastic. This is probably due to the fact that, as the temperature of flash-curing increases, the effective concentration of cations and their activity also gradually increase, which progressively improves the cross-linking reaction, the resin fixation on the fabric, and hence the crease-recovery property of the treated fabric. The flash-curing conditions of 110°C for 1 min, for instance, made catalyst A liberate enough cations for the cross-linking reaction, which lifted the crease-recovery to the wash-and-wear level. The liberation and activation of cations further increase when the flash-curing conditions become more drastic, say, 160°C for 1 min, which raised the crease- recovery to a high degree to reach DP level.

The results of percentage retained tensile and tearing strengths indicate that these properties of the treated fabric gradually fall as it crease-recovery properties improve. This is the normal experience. However, one point that deserves mention here is that the strength retained after treatment with catalyst A for a particular level of crease-resistance is certainly higher than that normally observed in the conventional pad-dry-cure process to obtain the same level of crease-resistance.

Table IV

Properties of Fabrics Treated with DMEU in the Presence of Catalyst A under Various Flash–curing Conditions*

Flash–Curing Conditions	Dry Crease-resistance (deg) (Monsanto: W + F)	Percentage Tearing Strength Retained		Percentage Tensile Strength Retained		Resin Content of Treated fabrics		
		Warp	Weft	Warp	Weft	Resin Content (%)	Loss on One Standard Wash (%)	Fixation (%)
80°C/4 min	217	84.8	87.0	98.7	98.0	2.9	6.2	93.8
90°C/3 min	213	84.1	86.0	98.7	98.0	2.9	5.0	95.0
100°C/1 min	209	82.5	88.0	98.7	98.0	2.8	7.6	92.4
100°C/2 min	213	83.6	86.0	98.7	98.0	3.0	10.1	89.9
110°C/1 min	240	79.1	84.0	98.7	98.0	3.3	5.4	95.6
120°C/1 min	240	78.0	75.0	96.5	98.0	3.2	4.4	95.6
130°C/1 min	252	70.6	75.0	96.0	97.0	3.5	2.9	97.1
140°C/1 min	261	70.0	72.0	95.5	96.0	3.5	5.7	94.3
150°C/45 sec	259	76.1	76.0	95.5	97.0	3.6	3.5	96.5
150°C/1 min	276	77.6	64.4	88.1	88.0	3.7	7.1	92.9
160°C/1 min	285	68.0	64.0	86.0	80.0	3.8	7.8	92.2
170°C/45 sec	288	67.2	62.0	85.5	81.5	3.9	5.6	94.4
180°C/30 sec	281	76.8	73.0	86.0	84.2	3.7	7.4	92.6
Control	163	100.0	100.0	100.0	100.0	—	—	—

*Fabric particulars as for Table I; recipe and resin concentration as for Table III.

A careful look at the data obtained under curing conditions, particularly those for 150°C and 1 min and for 160°C and 1 min reveals, that, once the crease-recovery level reaches a reasonably high value, say, 276°, further efforts to make flash-curing conditions increasingly drastic, say, 160°C and 1 min, do not give a proportionate advantage in terms of improving the crease-recovery. In other words, a further improvement in crease-recovery is only very marginal.

However, the treatment required to give this improvement has a considerably adverse effect on the strength characteristics of a fabric. The optimum number of cross-links to raise the crease-recovery properties to a DP level is achieved under flash-curing conditions of 150°C and 1 min. A further increase in the number of cross-links does not contribute significantly to raising the crease-recovery level. However, this does increase the cross-linking embrittlement of a cotton cellulose substrate and leads to undesirable strength losses. In other words, by selecting a catalyst that does not liberate acid and the optimum cross-linking conditions, strength losses due to the molecular degradation of the cellulose substrate have been eliminated and the number of cross-links necessary to raise the crease-recovery to the DP level has been maintained at the optimum level and undue cross-linking embrittlement has been avoided. The resin fixation brought about in the presence of cations is quite fast to washing as indicated by the data for the resin content of treated fabrics. Lastly, the experiments were designed with a view to finding out whether or not all previous experiments on cross-linking reactions that had given encouraging results had really been brought about by cations.

For this purpose, two catalysts, A and E, were selected out of several that were tried. The former has already been discussed, and catalyst E which has not yet been considered, proved to be more promising in laboratory experiments, the results of which will be discussed later in this paper.

Resin recipes were prepared that consisted of DMEU reactant and catalyst A or E (20 and 30% on the weight of the solid reactant, respectively). These are referred to as fresh recipes, stock recipes, or ready-to-use recipes, and they were preserved at room temperature. The ready-to-use recipes were diluted before fabric treatment with the necessary amount of water so as to achieve a particular resin add-on on the fabric (as mentioned at the appropriate places). Parts of these recipes were used immediately for fabric treatments, and parts were used after they were four, ten, fifteen and sixty days old (as indicated at the appropriate places). The properties of the fabrics treated in this way are given in Table V.

Experiments Nos. 1–7 are carried out with the recipe containing catalyst A and Experiments Nos. 8–10 with the recipe containing Catalyst E. Experiments Nos. 1 and 6 are carried out with the fresh ready-to-use recipe containing Catalyst A. As expected, Experiment No. 1, which was designed to give 3% resin add-on on the fabric, had a crease-recovery angle of 245°, whereas Experiment No. 6, which was designed to give 5% resin add-on on the fabric, had a crease-recovery angle of 282°. However, these recipes, when preserved for four and ten days and then used for fabric treatment, led to very low crease-recovery angles. In Experiments Nos. 2 and 3, the crease-recovery angles fell from 245° to 201° and

Table V

Stability of Ready-to-use Recipe Made from DMEU and Catalyst A or E*

Experiment No.	Age of Ready-to-use Recipe	Crease-resistance (deg) (Monsanto: W + F)
	Catalyst A, Adjusted Resin Add-on on Fabric: 3%	
1	Fresh recipe	245
2	4 days	201
3	10 Days	186
4	Recipe 4 days old with fresh DMEU added in quantity to give 4% resin add-on on fabric	226
5	Recipe 4 days old with fresh catalyst A—20% on weight of resin originally taken	198
	Catalyst A, Adjusted Resin Add-on on Fabric: 5%	
6	Fresh recipe	282
7	10 days	208
	Catalyst E, Adjusted resin add-on on fabric: 5%	
8	Fresh recipe	271
9	15 days	268
10	60 Days	236

*Fabric particulars as for Table I.
Recipe: Prepared to give 3 and 5% resin add-on on fabric.
Catalyst concentration: 20% catalyst A or 30% catalyst E on weight of solid content of resin solution.
Flash curing conditions: 150°C/1 min.

186°, respectively, whereas, in Experiment No. 7, the crease-recovery angle fell from 282° to 208°. These experiments revealed that, if conventional reactants such as DMEU are sorted with a compound such as Catalyst A for few days, they lose their cross-liking efficiency and, if used for fabric treatment, bring about very little improvement in the crease-recovery property. This could possibly be due to the fact that the DMEU molecules undergo self-condensation (since no cotton cellulose is available) in the presence of Catalyst A at room temperature, at which a ready-to-use recipe is stored. Catalyst A cannot liberate acid at room temperature and therefore cannot furnish protons for self-condensation. It is thus the cations released by the catalyst that initiate self-condensation in the bottle in which the ready-to-use recipe is stored. The self-condensation probably proceeds according to the mechanism given in Section 1 of this paper whereby the cation replaces the proton and the DMEU molecule in the absence of cellulose, condenses with another molecule of DMEU, and ultimately becomes converted into a molecule that cannot form a cross-link between adjacent cellulose molecules or microfibrils when tried on a cellulose substrate.

In order to check whether Catalyst A and DMEU mutually 'destroy' each other (when kept together for a long time in the form of a ready-to-use recipe in a bottle) or it is the destruction of one of the these chemicals that occurs, experiments were designed in which fresh DMEU in one case and fresh Catalyst A in the other were added to four-days-old ready-to-use recipes, and fabric treatments were applied by using such recipes. The results are given in Table V for Experiments Nos. 4 and 5. The results reveal that it is mutual destruction that occurs and the fresh addition of one of the chemicals to four-days-old recipes could not bring the crease-recovery level to that obtained with parent fresh recipe. Similarly, Experiments Nos. 8, 9, and 10 are designed to check the stability of the recipe containing Catalyst E. It can be said, in the light of the results obtained, that Catalyst E is not in a position to supply sufficient active cations at room temperature to initiate the self-condensation and thereby destroy DMEU. However, the same catalyst provides enough active actions under the flash-curing conditions to bring about the cross-linking and give more or less the same level of crease-resistance as that given by a fresh recipe. This explains why Catalyst E was considered promising and why a statement to this effect was made earlier.

On the basis of the foregoing, a large-scale trial (on over 100,000 metres of fabric) was made with Catalyst E, the results of which are given in Table VI.

The results contained in Table VI are self-explanatory and prove the superiority of the flash-cure technique employing Catalyst E over the conventional pad-dry-cure process employing magnesium chloride hexahydrate. This technique was also tried on other types of fabric. The results again prove the superiority of the authors' process over the conventional one.

Lastly, one very important observation, which has great significance from both the theoretical and the practical points of view, is that of the residual-formaldehyde content of resin-finished goods produced by employing the authors' process. Meyer *et al.*[9] have proved that the cross-linking of cotton with formaldehyde is a proton-catalysed reaction. Since the authors' catalyst is a non-acid-liberating type, it is to be expected that formaldehyde cross-links will be absent in fabrics resin-finished by their process. This was confirmed as follows.

The resin-finished fabrics produced both by the pad-dry-cure method and the authors' flash-cure process were subjected to acid-stripping, a method widely employed to determine the resin content of resin-finished fabrics. It was observed that fabric resin-finished by the pad-dry-cure process and acid-stripped were still insoluble to some extent in cuprammonium solution, which indicated the presence of formaldehyde cross-links. Compared with this, the fabrics resin-finished by the authors' process and then acid-stripped dissolved completely in cuprammonium solution, which indicated the absence of formaldehyde cross-links in it. This supports the non-acid-liberating nature of their catalyst. In addition to this, it was observed that the formaldehyde-odour problem was considerably less in fabrics resin-finished by the authors' process compared with those processed by the pad–dry–cure process. Moreover, at the same level of crease-resistance, the ratio of nitrogen fixed on the fabric to formaldehyde (both expressed in gram mole) fixed on fabric for the pad–dry–cure process was found

Table VI

Result of Large-scale Trials: Properties of Treated Fabrics Comparison of Flash-Cure Technique Employing Catalyst E and Pad-Dry-Cure Technique Employing Catalyst $MgCl_2.6H_2O$

Process	Fabric Particulars: Yarn Linear Density (tex) Warp	Weft	Ends/cm	Picks/cm	Mass/Unit Area (g/m^2)	Type of Fabric	Adjusted Resin Add-on on Fabric (%)	Dry Crease-resistance (deg) Monsanto: W+F)
Flash-cure	20	20	32	32	150	Sheeting	5.0	280
Pad-dry-cure	20	20	32	32	150	Sheeting	7.0	284
Control	20	20	32	32	150	Sheeting	—	165
Flash-cure	20	20	25	27	115	Sheeting	5.0	282
Control	20	20	25	27	115	Sheeting	—	149
Flash-cure	30	30	22	19	132	Sheeting	5.0	268
Control	30	30	22	19	132	Sheeting	—	181
Flash-cure	17	20	47	28	150	Poplin	4.0	227
Control	17	20	47	28	150	Poplin	—	138

Recipe and other conditions: *Flash-Cure Technique*
Resin concentrations: given in the table.
Catalyst E concentration: 30% on weight of solid content of resin solution.
Flash-curing conditions: 150°C/1 min.

to be 1.1, whereas that for the flash-cured fabric was 1.4, indicating the smaller extent of fixation of formaldehyde on the fabric. However, the work described in the last two paragraphs is under further investigation.

4. SUMMARY AND CONCLUSIONS

4.1 A new flash-cure catalyst has been discovered.

4.2 Appropriate flash-curing conditions employing the new catalyst have been established.

4.3 It is generally accepted that, for the cross-linking reaction to occur, the presence of proton (H^+) is necessary. This theory is further extended by providing experimental evidence that sufficiently activated cations can also bring about the cross-linking reaction.

4.4 Under the appropriate flash-curing conditions, the new catalyst preserves to a large extent the strength characteristics of cotton cellulose at the DP level of crease-resistance.

4.5 The probable reasons for the preservation of strength at a high level are proposed. They are (*a*) the non-acid-liberating nature of the new catalyst, which prevents the molecular degradation of the cotton cellulose substrate and (*b*) the selection of an appropriate combination of catalyst and flash-curing conditions to supply just sufficient active cations for the cross-linking reaction to proceed and raise the crease-recovery property of the

Percentage Tensile Strength Retained		Percentage Tearing Strength Retained		Resistance to Abrasion				
				Flex Cycles		Accele-rotor (6 min) (weight loss %)	Ring-wear Tester (rev)	Appea-rance Rating
Warp	Weft	Warp	Weft	Warp	Weft			
65.5	68.3	96.7	83.3	—	—	17.2	4852	3.5
54.0	56.8	64.7	51.6	—	—	—	1700	3.5
100.0	100.0	100.0	100.0	—	—	—	8602	2.0
79.3	84.6	84.4	96.6	597	587	6.3	2120	3.5
100.0	100.0	100.0	100.0	2006	1082	3.3	5698	2.0
90.0	98.0	85.0	86.0	—	—	—	—	3.5
100.0	100.0	100.0	100.0	—	—	—	—	2.0
87.0	73.3	96.4	92.1	—	—	—	—	—
100.0	100.0	100.0	100.0	—	—	—	—	—

Pad–Dry–Cure Technique:
Resin concentration: given in the table.
Catalyst concentration: 30% $MgCl_2 . 6H_2O$ on weight of solid content of resin solution.
Pad–dry–cure conditions: drying at 110°C/1 min; curing at 150°C/4 min.

cotton fabric to the DP level. This keeps the number of cross-links at an adequate level.

ACKNOWLEDGEMENT

The authors are grateful to the management of The Arvind Mills Ltd. for granting permission to publish some of the data obtained in their project.

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22—THE MARKETING AND DISTRIBUTION OF FINISHED SHIRTING FABRICS AND GARMENTS IN THE UNITED KINGDOM AND EUROPE

By W. BARNES and J. OGDEN

It is shown that shirt consumption in Europe has been declining since 1973, owing partly to economic recession and partly to displacement by more casual garments, and that shirt production in Europe has declined dramatically as imports from outside the E.E.C. have increased their share of the market from 20% in 1970 to 60% in 1978. In the U.K. polyester-fibre–cotton blends amount for nearly 70% of the market compared with about 15% in 1970, and the share of the market taken by cotton and particularly nylon has fallen very considerably.

The remaining European shirt production is increasingly in the hands of large-scale producers, in many cases vertically linked to textile operations, and the new structure is shown to be beginning to provide stability based on high quality in the middle and upper market sectors, excellence of design, and rigid and consistent control of quality from yarn to garment. Of the final selling price of a garment, 50% is accounted for by retailers, and countries with the greatest concentration of retailing have the highest levels of import penetration. In these countries, retailers' own brands have significnatly increased their share of the market at the expense of manufacturers' brands.

1. INTRODUCTION

One of the attractions of giving a paper on the European shirting market is that it is a subject which, however narrowly defined, embraces all the great changes that have taken place in European textiles. It will be necessary to bear in mind, in reviewing this subject, such economic, political, and social forces as, for example:

the aspirations of the less-developed nations;

the formation of the European Economic Community;

the emergence of international companies;

increased consumer aspirations;

the concentration of retailing; and

close to the authors' own heart, the successful struggle for a continued and prosperous existence by the textile industry of the United Kingdom.

The last ten or fifteen years have seen much dramatic change in all aspects of the textile industry, and this occasion gives one an opportunity to stand back, to review the stage that has been reached, and to give some thought to likely future developments. This will be approached by looking first at market trends, which will set the scene; then by looking at the structure of the industry and seeing how it has reacted to market developments; and finally by concentrating on the distribution and retailing scene, where so much of the pressure for change has originated.

The paper will be restricted to what may be described as the formal shirt and will not cover T-shirts and other such garments, which have risen in popularity so dramatically in the past few years. These garments will not be included in the statistics given, although obviously the influence they have had cannot be ignored.

2. THE MARKET

The demand for shirts in Europe grew at a respectable rate up to 1973 but, as the years of economic stagnation have set in, there has been virtually no growth since then. The pervading economic pressure to reduce personal consumption has, of course, been only one of the many influences at work. This would, anyway, have been a difficult time for the formal-shirt producer, with the strong move towards more casual wear and, associated with this, the rising influence of the young buyer.

Within Europe, though, the pattern has been very mixed. If one takes, for example, the trends in shirt consumption on a per-capita basis, it is found that the average Germany citizen buys more than four shirts per year, the average Italian fewer than two. This may be partly determined by income differences but is probably also a reflection of urban as against rural societies: those countries such as Germany, the U.K., and the Benelux countries, which have a high density of population, tend also to be the high consumers of shirts.

Just as we have had to contend with slow growth, so we have also had to contend with dramatic changes in shirt types. During the 1960s, the warp-knitted shirt soared in popularity and dealt cotton a very severe blow in the process. Eventually, the weaver hit back with a polyester-fibre–cotton blend, which since 1970, has more than emulated the success of the knitter and has dealt him, in turn, an equally severe blow. For the United Kingdom, these dramatic changes are summarized in Fig. 1.

It is unfortunately not possible to give the same details for other European countries, and too much should not be inferred from this figure. The U.K. has certainly seen more dramatic changes in this context than anywhere else. Similar trends have been apparent everywhere, but on a smaller scale. In continental Europe, the warp-knitted shirt never reached the same market penetration that occurred in the U.K., and polyester-fibre–cotton blends have subsequently been displacing the pure-cotton shirt at a rather more sedate pace. Climate, of course, is another important factor. In Italy, for example, cotton remains the dominant fabric and is unlikely to be rapidly displaced.

Thus, in a period of relative stagnation, the market has seen technological change on a considerable scale. But by far the major influence on the industry has been the rapid increase in international trade: so far as Europe is concerned, this has meant one thing only—the loss of a large part of the market to imported goods. In 1970, imports accounted for 20% of the European market; to-day, they

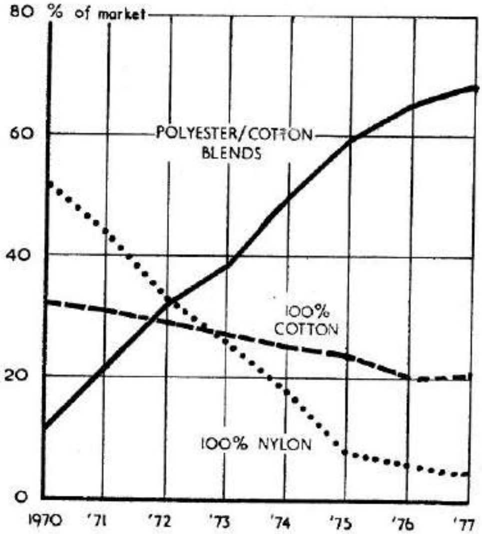

Fig. 1
The market share in the U.K. of shirts of different fibre content, 1970–77

are nearer 60% and in the U.K. the trends have been stronger still. Figures 2 and 3 demonstrate this clearly and illustrate the considerable pressure on local shirt producers.

Again, by trying to describe the position in Europe, the very considerable variations that do occur within it are disguised. Import penetration in France, Belgium, and Italy is markedly less than that in the U.K., Germany, and Holland. Naturally the reasons for this wide disparity have been the subject of much discussion, and no firm conclusions seem to have been reached. The most frequently quoted 'causes' are:

(i) nationalism, and a built-in desire to purchase locally made products,

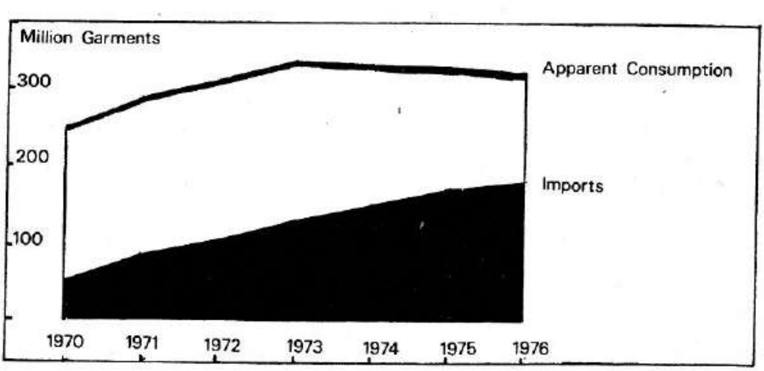

Fig. 2
Consumption trends of formal shirts in E.E.C. countries, 1970–76

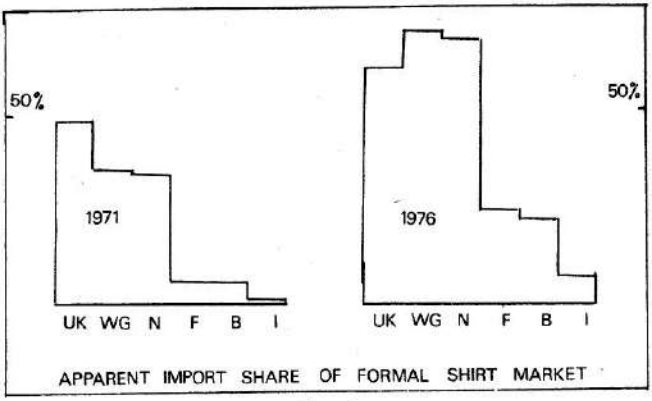

Fig. 3
The apparent import share of the formal-shirt market, 1971 and 1976 (UK = United Kingdom, N = Netherlands, F = France, B = Belgium, I = Italy)

a more prevalent feature of buyers and importing officials in France and Italy than it is in Germany and Britain;

(ii) large-scale retailing in Germany and Britain gives a far more accessible market to importers than do the small and scattered distributors of France and Italy; and

(iii) similarly, the more competitive retailing systems encourage buyers to look further afield in their search for value-for-money products.

The retailing systems will be discussed further later in this paper, but it will be noted that these frequently heard reasons for import growth, put forward by members of the European shirt industry, do not lay any blame on themselves. One cannot believe, however, that the European industry can avavoid responsibility for the loss of its markets, and this will be discussed further in a later section on the structure of the industry.

The Far Eastern shirt producers have taken by far the largest slice of the import business, with 69% of European imports in 1976 plus another 12% from India, as may be seen in Fig. 4. Hong Kong is the U.K.'s major supplier and also West Germany's, though it is followed closely by South Korea in West Germany. South Korea is the main supplier to the Dutch and Belgian markets; India is Italy's major source and Macao France's. However, areas other than the Far East are important in some countries; Yugoslavia is an important source for Holland, Belgium, and West Germany, Eastern Europe for West Germany and Italy, and the Mediterranean area for France. These trading links, some of them related to colonial history, are slowly being widened, and a very much more varied pattern of importing can be expected from a larger number of source countries, with a more even distribution throughout Europe.

This mention of shirt imports cannot be allowed to pass without reiterating the British view of the Multi-Fibre Agreement (MFA), in the light of the controversial attitude of the EEC.

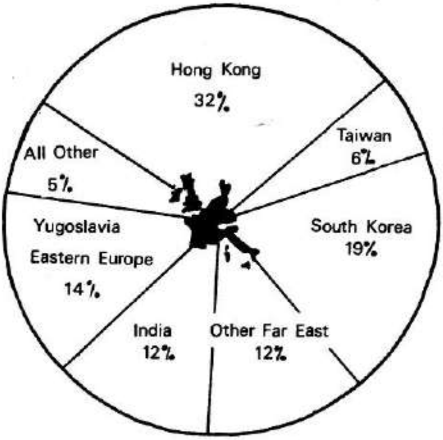

Fig. 4
Sources of formal-shirt imports into E.E.C. countries, 1976

The following logic is recognized:

(i) that the textile and garment-making industries are the favourite industries of developing nations; they are relatively labour-intensive, earn foreign exchange, and can use local raw materials;
(ii) that the wealthier nations have a responsibility to give real help by encouraging industrial development in the developing countries;
(iii) that free trade is an economic necessity in the long term for an improving world economy.

Accepting all of this, U.K. arguments have been concerned only with means, not with objectives. One of the most disturbing features of recent years has been the way in which a world overcapacity in sectors of the textile and clothing industries has created violent movements in prices and hence in international trade. The results have been, too often, to put parts of the European industry out of business and to create unemployment and hardship. Just as often, the pattern has subsequently changed, but by then the damage has been done, the factory has been closed, and there is no alternative but to continue to import. Thus all of the arguments have been aimed not at disturbing the natural and logical underlying trend, but rather at effecting a more orderly process of change. It has also been recognized that, in the rapid technical and commercial changes that have affected the European industry in recent years, the producers there have in turn to alter their business policies and to adapt to a new environment. Through the revised MFA, an attempt has been made to give them a breathing space to make those changes. Imports have been allowed to continue to rise, but at a more controlled pace, and these imports have been spread more equitably through the community. This seems a most rational policy, and, if some of the detailed legislation is unfair to some, then forbearance from all must be requested.

To return to the main theme, the rapid growth in imports has naturally led to sharp cutbacks in domestic shirt production. For the fabric producer, the situation has been made worse by the rise in imports of shirting cloths. The cotton weaver has been the hardest hit and has lost on all fronts to imported garments, imported fabric, and displacement by polyester fibre–cotton blends.

Among the blends of cotton with synthetic fibres, although the bulk of greige cloth continues to originate in the Far East, there has been a trend towards importing finished cloth, and here the origins are far more diverse. In Northern Europe in particular, the trend has been to upgrade fashion and design, particularly in the polyester-fibre–cotton sector. The remaining shirt producers in Europe are now buying finished fabric from all over the world, and the economics of production are less sharply defined on a geographical basis than in many other sectors of textiles. On the one hand, the shirt maker is buying design and quality. On the other hand, weavers of polyester-fibre–cotton fabrics in Europe and America, operating efficient large-scale plants and working with the synthetic-fibre producers, are more competitive with producers in the lower-cost countries.

Hand in hand with this development has been the demand for increased patterning. In the U.K., for example, the patterned-shirt market, whether the shirts were printed or colour-woven, accounted for only about a quarter of total consumption in 1970. To-day, however, a half of all shirts sold in the U.K. are patterned. The shirt-maker, with all the other problems he has had to cope with, has become involved in a much more fashion-oriented world than hitherto. This is a most important element and the next section will demonstrate the opportunities that this trend has created and how some companies at least are using this to counter the other influences that have been working against them.

One last point must be made, though, on the market picture. Knitted shirts, i.e., the formal style of knitted shirt, not the T-shirt, have had a very chequered career recently; in Europe, the weft-knitting sector of the textile industry has been in the doldrums for some time and has never fully recovered from the demise of polyester-fibre ladies' wear. One of the possible salvations has been the development of knitted cotton and polyester-fibre–cotton shirtings. Few would deny the attractiveness of these fabrics. They offer a unique blend of comfort and performance, which in theory should fit well with the general trend towards more casual clothing. To date, however, their success has been limited. Perhaps they have fallen between the stools of casual and formal styles. Probably more important is that here is another area where the shirt-maker has to adapt: to be effective, he must set up a discrete production unit, learning the skills of stitching a fabric with very different properties from those of his traditional woven fabrics. It is not surprising that, with all the other problems in the industry, a few shirt-makers have been tempted to accept the risks involved. Thus, for the moment, the knitted shirt has a low market share, and that almost exclusively in the casual sector. This will surely change, and the time will come when knitted shirts have a stable share of the market, although probably never large one.

3. THE STRUCTURE OF THE INDUSTRY

In this section the influence of the market developments described above on the industry that has remained in Europe will be considered, and the discussion will concentrate particularly on the United Kingdom in this respect. This is not chauvinism; it is because the forces of change have been as pronounced in the U.K. as anywhere, and the response has been rapid and far-sighted. The largest textile and shirting companies in Europe are based in the U.K., and their move towards vertically integrated and large-scale production of quality fabrics and garments is the process that will be described.

The market forces described above have induced many commentators to make the generalization that the clothing industry, because it is labour-intensive, must eventually shift towards low-cost producing countries. They went on to argue that the textile industry must then follow it. It would be difficult to dispute this for those sectors of the trade that are:

(*a*) highly price-sensitive, and
(*b*) not fashion-oriented.

Indeed, over the past decade, this is very much what has happened.

With textiles still one of the largest employers even in the developed countries, there are very strong social pressures to resist this logic and to establish a viable industry. Let nobody underestimate the considerable human hardship and disruption that have already resulted from the contraction in the European textile and garment industries.

But, quite apart from the social pressures, there are very sound economic and business reasons to maintain a firm industrial base for European textiles, and the theme that will be developing later in this paper, with the shirt-manufacturing section of the industry as an example, is that well-equipped and efficient textile and garment industries are a sound investment for a prosperous future so long as they determine a clear market policy. This will involve recognizing the great potential of the developing world in the textile industry and not attempting direct competition with it but rather supplementing it by specializing in clearly defined areas of the market. The end-result will be that the consumer will have abundant choice between both lower-cost products and high fashion, advanced-technology products.

The shirt and shirting sector of the industry provides a clear and useful example of the way in which viability can be and has been established, and the policies on which this success has been built are:

(i) excellence of design;
(ii) a fast response to market developments as well as innovation to direct and to influence the market;
(iii) a rigid control of quality at all stages from yarn production through to the production of the final garment; and
(iv) increasing capital intensity to secure the maximum productivity gains from the latest technology.

The point should here be made, and stressed quite firmly, that it is the mass-produced sector of the trade that is being discussed. This is a most important consideration because this in turn means that the large and forward-looking shirt-manufacturer must have a local source of supply for these shirting fabrics, and his supplier of shirtings must in turn have a local source of supply for his yarn. Indeed, it can be argued that a common ownership through all these stages of production is necessary for success. Only by establishing this structure can the essential control of quality and, more importantly, the maintenance of continuity be provided. Furthermore, the more this logic is followed, the more important it is to plan ahead for new development, and this in turn requires close liaison at all stages of supply.

If the production chain is considered initially, the first requirement is that the basic production routes should be standardized to the highest possible extent. This has meant, in the developments that have occurred to date, that yarn production and fabric-weaving are concerned with a very restricted range of products and qualities because these are the most capital-intensive sectors of the chain, where the benefits of large-scale production must be achieved. The further one moves from the capital-intensive operation through fabric-finishing and garment-making, so can one undertake increased patterning and variety.

As has already been noted, in the major markets of middle and northern Europe, a polyester-fibre–cotton blend has become the dominant yarn in shirtings because it combines easy care and long life with a crisply tailored appearance and comfortable wearing properties. To maximize the production economies, spinning mills, in the U.K. in particular, are therefore increasingly becoming concentrated around the production of one or two yarn qualities for supply to vertically linked weavers.

The weavers in turn have become much more specialized. In one mill, there were, in 1970, over 150 different shirting products and qualities in stock. To-day that mill produces just three shirting qualities, all for plain dyeing and printing. An associated mill produces exclusively colour-woven fabrics, again in three different qualities. Both are tied to one yarn supplier, both operate only one loom type, and both are geared to a relatively small number of large customers. The colour-weaving operation is the leading forces in this particular marketing operation. As an efficient production unit, it requires customers to pay only a small premium over the prices of cheaper suppliers of comparable fabrics. In turn, though, it can adequately justify this premium by effectively guaranteeing consistency of quality and delivery on a long-term basis. Even this, however, is not sufficient in the fast-moving world of high-fashion shirts. Excellence of design is of paramount important, and geography is an important factor in achieving this. No matter how well organised he is, the distant producer has problems in overcoming the local manufacturer's advantage in this context. It is he who can establish and service the garment-maker and the retailer with continuous discussion and testing of new designs.

The fabric finisher is an important element in this process. More than the spinning–weaving interface, it is vital that weaving and finishing should be under central control. It is at this part of the chain, the adding of colour, that the elements of quality and design become all-important. Of course, changing fashions, with patterns and plains alternating, necessitate flexibility, but this can be accommodated within an integrated unit set up either at a level marginally below weaving capacity or with an established commission-finishing business. The economic advantages of continuous preparation and dyeing ranges, particularly of the savings in energy costs, are well known, and these all become attainable when vertically linked to large-scale production of a limited range of qualities.

In the United Kingdom, successful production of shirting fabrics is well established, despite all the trends in the market, and it is based on the principles of vertical integration and specialization that have been described. It is dependent for this success, though, on the fact that there is a large demand for shirts at the middle-to-higher end of the market. This is the niche that the local producers have created, with imported shirts largely catering for the bottom end.

Finally, the making-up sector must be considered. There is no doubt that, without success in this area, the fabric sector would have declined dramatically. But, despite an over-all decline in European shirt production, several companies have established profitable businesses and are continuing to do so. Again their success is based on aiming at the middle-to-higher end of the market, servicing large customers, and establishing a reputation for quality. Even so, and despite all the latest developments in garment-manufacturing techniques, they must remain, on an international scale, relatively high-cost producers.

One would not advocate vertical integration from fabric production through to shirt-making to anything like the same extent as at the textile end. It is simply impracticable in view of the much wider product range that the garment producer must offer and the vast scale of shirt-making that would be needed to take off all production from a large-scale fabric mill. Nevertheless, many of Europe's vertical textile companies own some shirt-making capacity, which provides them with some continuity of off-take and, more importantly, that direct contact with the market which is such a useful source of design trends.

The final stage of the process is distribution and retailing, and it will help to put everything in context to describe how shirt costs are made up. Only a rough breakdown is possible, but, for a typical branded, plain-dyed polyester-fibre–cotton shirt, which would retail in the U.K. for the equivalent of around $15, the costs would be approximately:

fibre	4%
spinning	5%
weaving	4%
finishing	4%
making-up	33%
retailing	50%
	100%

Thus the spinning, weaving, and finishing areas, where verticality confers the greatest benefits, account for only 13% of the selling price. The greater the degree of verticality, the more will the arguments rage over transfer prices. the decision on transfer-pricing must be based on whether or not each business area is an autonomous profit centre and thus would charge an arms-length market rate for its services. In reality, the financial theory tends to be tempered by commercial considerations, and, if the shirt-making-up activity is to compete efficiently, it may be necessary for it to obtain its fabric at cost rather than at a true market price in order that the company maximizes its over-all profitability in obtaining contracts. The greater the proportion of intra-company activity, the more likely it is that a market price will not be sacrosanct.

4. THE DISTRIBUTION PROCESS

Shirts in the U.K. are typically sold through two main channels. Firstly, branded shirts are sold in a variety of outlets throughout the country, typically backed by advertising campaigns in the media to create a national image, where the retail price is recommended by the manufacturer, although it may be discounted by the retailer. Secondly, shirt-manufactuers are commissioned by retailers to produce shirts to sell in that outlet under the retailer's label, and the selling and pricing decisions are taken by the retailer. Recent years have seen the growth of contract-label shirts in the U.K. at the expense of branded garments, owing to three main factors, as detailed below:

(i) There has been a major change in the distribution of shirts, with the gradual erosion of the traditional High Street outfitter (tending to stock the more select and expensive branded shirts) and a growth in the number of retail outlets not previously relying on clothing, e.g., Tesco, Sainsbury, and Woolworth, or else concentrating increasingly on clothing, notably Marks & Spencer. Crucially, these outlets have concentrated on their own-label shirts, and their aggregate size has meant a major change in the U.K. shirt industry.

(ii) This movement has accompanied a squeeze in living standards in the last couple of years, reducing both the over-all consumption of shirts and the share held by the more expensive branded garments. Increasing price-consciousness on the part of the consumer, added to the fact that around 40% of shirts are bought by women, has further hardened the move toward the purchase of own-label shirts in department stores and variety chains.

(iii) A growing proportion of the shirt market is accounted for by imports—currently over 60%—and this has inevitably had a major effect on the domestic shirt-making industry and forced it to fight for a diminishing share of the pyramid. Whereas some retailers have traditionally preferred U.K.-produced garments, the price differential has increasingly put pressure on this loyalty, with a move towards imports gaining retailers' contracts.

Although this movement in retailing methods has been gradual, its over-all effect has been to pose problems for U.K. shirt-manufacturers. The branded-shirt market is undoubtedly under pressure, and manufacturers are attempting to increase their share of a shrinking market through advertising and design in order to differentiate their product from others. The pricing of branded shirts tends to be within specific ranges, and manufacturers only reluctantly break through psychological barriers of £10, etc., with the result that cost increases are not passed on if it means exceeding the price bands.

The contract side presents fewer marketing problems for the shirt-manufactuers, who are commissioned to produce a given quantity at a fixed price. This area is also becoming increasingly competitive, with importers gaining a growing share largely on price considerations. There has been a trend towards domestic manufacturers using the contract trade as a marginal business in order to keep factories fully active, with a subsequent reduction of margins.

The changes in the retailing methods in the U.K. that have been discussed above have largely been mirrored in the rest of the E.E.C. The most significant movement throughout Europe has been the rise of the department stores and variety chains at the expense of the independent outfitters. In the U.K., the last-named have seen a market share of 36% in 1974 decline to 32% in 1977, a level that is typical of the E.E.C., particularly France and Germany. Specialized shirt shops, often selling accessories, account for around 10% of sales around Europe and embrace the fashion-oriented boutique. Market stalls hold a stable 5% market share, and mail order has become an increasingly popular outlet, particularly in the U.K., where the share has double to 5% within three years.

The major development, however, has been the growing importance of the department stores, variety chains, and hypermarkets, retail outlets that have been either introducing clothing for the first time or else developing more lines of garments. Shirts have become a major items for this type of outlet since they are a more homogeneous product and thus face less need for changing facilities than outerwear garments. It is estimated that in Germany these outlets account for perhaps 50% of shirt sales, in France 35%, and in the U.K. 30%. In these three countries, nearly all large retail stores sell shirts as staple lines.

The economic recession since 1974 has produced a tightening of living standards throughout the E.E.C. and, as mentioned above, in the U.K. has resulted in greater price-consciousness among consumers. The proportion of shirts purchased by females is even higher on the Continent than that in the U.K., with perhaps only a quarter of shirts bought by men on their own. The over-all change in retail distribution towards general stores and away from traditional outfitters has thus seen clothing-purchasing increasingly become a family phenomenon conducted as part of general shopping in the same store.

It is not only the retailing industry that has been affected by these developments. The wholesaling of shirts has become an increasingly less important phenomenon as the department stores tend to deal either directly with the shirt-manufacturers themselves or directly with importers and thus avoid the wholesaling activity. However, wholesalers still provide an important function for the independent, often financially weak, retailers, and perhaps 15–20% of shirt sales in the E.E.C. involve a wholesaler. It is likely that this share will further diminish as the retail outlets tend to concentrate further into large central buying organizations, able to negotiate directly with domestic or foreign manufacturers. The development of contract-label shirts is one manifestation of this trend.

To return to the relationship between imports and retail concentration, large-scale retail groups are a very significant factor in the United Kingdom, where import penetration is high, and are very insignificant in Italy, where penetration is lowest. Fig. 5 compares the share of all non-food retail sales among large-scale retail companies on the one hand and smaller independent shops on the other in each European country. This should be compared with Fig. 3, showing import penetration into each country. Although the comparison is between retail sales on the one hand and shirt imports only on the other, it is still apparent that a strong correlation does exist.

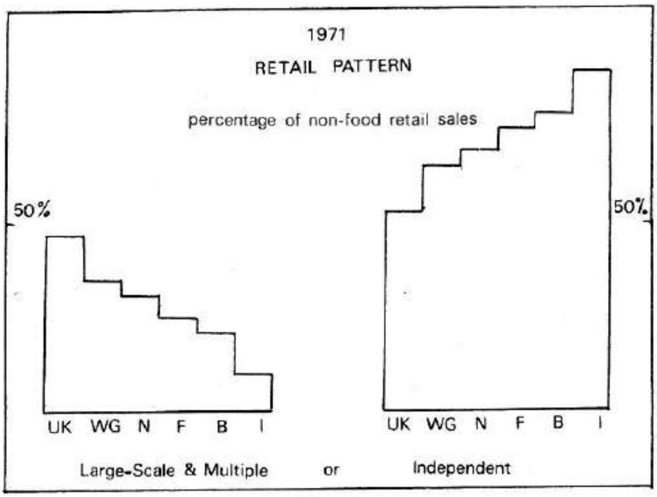

Fig. 5
The retail pattern, showing the percentage of non-food retail sales, 1971

5. CONCLUSION

The message that one has tried to convey in this paper is that, after a period of rapid and fundamental change in the European industry, a new structure is emerging. It is one that concentrates on quality and performance, with a more centralized control of all processes. It operates on a large scale and has established a strong market platform.

Despite all the prophets of doom, these changes have surely guaranteed a successful and profitably future.