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The Textile Institute

NORTH INDIA SECTION

NONWOVENS

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1992

The Textile Institute

North India Section

Published by M L Gulrajani on behalf of The Textile Institute, North India Section.
Typeset and printed at Rajkamal Electric Press, B 35/9 G T Karnal Road, Delhi-110 033.

Foreword

The production of nonwoven fabrics, like the rest of textile production, has been backed mostly by empirical knowledge. Recently, however, theoretical studies have been carried out to examine the relationship between the structure of nonwoven fabrics and their end properties. The knowledge acquired has contributed significantly to the development of new technologies and state-of-the-art equipment for the manufacture of a vast range of nonwoven textiles.

This book contains the papers being presented during the Conference. From the technical view-point, the timing of the Conference is ideal, it is taking place when the manufacturers of nonwoven goods are looking at the new methods of production to upgrade quality. The topics to be discussed at the Conference include the effect and importance of raw materials, the various types of technologies available to manufacture nonwoven fabrics, the test methods used in their evaluation and the studies on the structure of nonwoven fabrics and its influence on their properties.

I wish to express my sincere thanks to all the Speakers at the Conference and to my colleagues from the Organising Committee, in particular, Prof. Bhaskar Dutta (Conference Convenor) for his untiring efforts. I am also indebted to Prof. M.L. Gulrajani for the editorial work put in by him to publish this book.

4th December 1992 — DR. ASHWAN KAPUR

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Editorial

This Conference on NONWOVENS is the maiden international venture of the recently formed North India Section of The Textile Institute (UK). The prime aim of the North India Section is to disseminate the know-how concerning the internationally available state-of-the-art in manufacture, marketing and management of every thing related to textiles.

The Nonwovens Industry has been growing at a fairly high rate in the West and has a promising future in the Developing Countries. The technology for the manufacture of nonwoven structures has undergone a considerable advancement since the introduction of commercially successful nonwovens in the 1960s. Initially the nonwovens were produced from the staple fibres mainly by needle-punching and thermal bonding methods. Over the period production of nonwovens from thermoplastic filaments by spun-bonding and other methods such as, melt-blowing, water- and air-laying as well as spun-lacing techniques, has increased. These developments have been adequately backed by the concomitant development of production machinery for nonwovens.

There has also been a shift in the use of nonwovens. They are no longer considered as cheap disposables. The end-use has become technology and fibre specific. For instance, needle-punched nonwovens find use as filters, interlinings, house furnishings, geotextiles, automotive trim and coated fabrics. While thermal-bonded nonwovens are used in apparel linings and cover-stock for sanitary products. On the other hand spun-bonded fabrics go into cover-stock, medical textiles, furniture and carpet backing.

The nonwoven fabrics exhibit a remarkable range of structural properties i.e. strength, elongation, stiffness, bulk, permeability, moisture vapour and liquid adsorption, chemical resistance and others which can be manipulated in the various production technologies. Many academicians are engaged in measurement and prediction of these properties of the nonwovens.

The Conference covers all this and much more. This Book of Papers is the faithful reproduction of the papers submitted by the speakers. Typograhical errors are all mine. I acknowledge the help rendered by my colleague Prof. A.K. Gupta in correcting the final proofs of the book.

5th December 1992 M L GULRAJANI

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SUBHASH K. BATRA and RAHUL DHARMADHIKARY

The Nonwovens Industry was established in Europe and USA in the 1920s and 1930s, though the technology of needle punching was developed much earlier. Today North America, Western Europe and Japan are said to account for almost 90% of the production-consumption of nonwoven products. In contrast, Nonwovens Industry in the developing economies has been of recent origin and accounts for the remaining 10%.

The major TECHNOLOGY/System in use in the US are spun-bonding and melt-blowing closely followed by needle-punching, while the European industry produces nonwovens by the dry-laid, wet-laid and spun-bonding methods. Japan initially imported process technologies from US and Europe and later on developed all the newer systems and technologies.

For a country to develop a Nonwovens Industry, it is necessary for it to look at the basic ingredients that make this industry viable. Judicious mixture of the indigenous effort together with selective partnerships with global companies with established credentials might permit the country to leapfrog into the modern nonwovens technological era.

1. INTRODUCTION

The birth of Nonwovens Industry can be traced back to nature's structural engineering of plant life and other biological life forms, or to antiquities, or to modern times, depending upon one's purpose [1]. In the present context, nonwovens industry as a commercial activity was conceived of in 1920s in Europe [2] and in 1930s in USA [3], if we ignore the birth of needle-punch technology around 1890 or so. In China, Korea, Japan and other Pacific rim countries it might be dated to the beginning of *Washi* (Japanese) like structures using wet-laying of fibres derived from mulberry leaves many centuries ago. Its commercial viability can be traced to 1960s in the USA, Europe and Japan. As a result, these three regions dominate the production and use of nonwovens in the world today. In 1991, North America, Western Europe and Japan were said to account for almost 90% of the worldwide roll goods market valued at US \$ 6–7 $\times 10^9$ [4], or \$ 6–10 $\times 10^9$ [5]. John Starr estimates [5] the world roll

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In contrast, nonwovens industry in the developing economies has been rather small or is of more recent origin and therefore constitutes the remaining 10% of the global production-consumption total by dollar value or 16% by poundage. Its poundage growth rate for the 1985–1995 period is estimated to be 10% p.a. [5]. In the following pages, we examine the history of growth of the industry in the developed economies from different perspectives. The purpose of the exercise is to see what implications the developed economies' experience might have in the growth and development of the industry in the developing economies.

2. THE US NONWOVENS INDUSTRY

John Starr reports the following historical data (estimates) for the growth of the Nonwovens Industry in North America [6]. Between 1970 to 1985 the value of nonwovens shipments grew from \$$280 \times 10^6$ to \$$1{,}670 \times 10^6$, the value of converted disposable products grew from \$$859 \times 10^6$ (1971) to \$$7{,}010 \times 10^6$ the consumption of nonwovens fabrics grew from 310×10^6 (lbs) to $1{,}070 \times 10^6$ (lbs). The consumption in the US in 1991 was estimated at 1.6×10^9 lbs [5]. The corresponding growth rate estimates are reported as [5, 6]:

Value of Roll Goods	1971–1980	15.8%/yr.
	1980–1985	9.7%/yr.
Value of Converted Disposables	1971–1980	15.9%/yr.
		16.7%/yr.*
Consumption of Roll Goods	1970–1977	10.7%/yr.
	1977–1982	8.9%/yr.
	1982–1985	7.6%/yr.
	1985–1995	6.0%/yr.

*Compared to the growth rate of roll goods, this reflects increase in per unit price.

The US industry utilizes several generic technologies and systems; the systems are also often termed TECHNOLOGIES. Specific markets served by some of these are indicated below.

In 1991 [5], 33% of the US market (by poundage) was based on the melt-spun processes (Spinlay or Spun-bonded and Melt-blown). These systems are growing at a faster rate than the staple fibre based industry. In the staple fibre group, the thermal bonded fabrics have been growing at a faster rate than the resin bonded category; the former now constitute 60% of the 250–275×10^6 lbs of the "carded resin- and thermal-bonded" total. The resin bonded category market share has been declining over the last ten years, being replaced by thermal-bonded, spun-bonded and spun-laced fabrics gradually.

In 1990 [5], about 400×10^6 lbs of spun-bonded fabrics were produced; the projected growth rate of this category is in the range of 8–9% per year. The systems in this category are polymer-specific. Of the total production, 65% is polypropylene based, 20% polyester, about 15% HDPE (Tyvek®), and the remainder nylon.

Spun-bonded/Melt-blown/Spun-bonded (SMS) PP fabrics are of the order of 50 MM lbs; main end-uses are medical packs and sterile wraps [5].

The melt-blown technology products, including SMS and those co-formed with wood pulp, utilize more than 1000 MM lbs of production currently [5]. The markets served by these products include filtration applications (face masks, air conditioning materials, micron-rated bags, cartridges, coolant oil), medical/surgical fabrics, sanitary products, sorbents, wipes, battery separators, apparel insulation, protective apparel, adhesives, etc.

Air-laid pulp and High-loft pulp (Scott) products amount to about 200×10^6 lbs. The products are used in industrial/institutional wipes (45%), premoistened wipes (40%), and other sorbent and medical products. A growth rate of 6–7% is projected for this category of nonwovens [5].

Spun-laced or hydro-entangled nonwovens production currently amounts to about 100 MM lbs. About 60% of this is consumed in medical packs and gowns, followed by wipes, sponges, mattress pads, interlinings, etc. Strong growth is projected in both national and international markets [5].

The relative importance of the generic TECHNOLOGY/Systems can be seen in Table 1.1 where the poundage produced by them are given [5].

TABLE 1.1 Relative Importance of various Technologies/Systems

TECHNOLOGY/System	Production (10^6 lbs)
Thermal-bonded Staple	150
Resin-bonded Staple	100
Spun-bonded	400
Composite (SMS)	50
Melt-blown	100
Air-laid/Hi-Loft	200
Spun-laced	100
Wet-laid	100
Needle-punched	200–250

As for the future projections for this "inter-process competition", the thermally bonded products will continue to replace those made by resin bonding. Needle-punched fabrics will grow at about the industry average. Air-laid pulp nonwovens should grow at an attractive rate. Spun-bonds will grow at a rate faster than that of the industry as a whole. Spun-laced and melt-blown methods should also grow at well above the industry average but from a much smaller base. Some traditional wet-laid nonwovens are mature, but new process and product technology could lead to improved demand.

The end-use markets in the US can be categorized in a number of ways.

Starr in reference [7] uses the following broad categories, each with numerous specific applications:

Agriculture and Landscaping	Household
Automotive	Industrial Military
Geotextiles	Leisure/Travel
Clothing	Health Care
Construction	Personal Care & Hygiene
Home Furnishings	School, Office

It is useful to see the inter-relationship between nonwovens for the end-use markets and the TECHNOLOGY/Systems that produce them. For example:

* The largest thermal-bonded carded staple nonwoven market in the United States is coverstock for sanitary products.
* A sizeable portion of the apparel interlining market is served with thermal bonded fabrics.
* The largest end-use areas for resin bonded staple nonwovens are coverstock, wipes, fabric softener substrate, filters and interlinings.
* Spun-bonded polypropylene (250–275 MM lbs) fabric go into coverstock (50%), medical (10%), furniture and bedding (10%), carpet backing (7%), geotextiles (4%), agricultural apparel (19%) and other uses.
* Spun-bonded polyester (80–90 MM lbs) fabrics go into roofing (33%), automotive (20%), filtration (5%), furniture and bedding (10%), fabric softeners (10%), technical and other uses (22%).
* Flash-extruded-collected-bonded HDPE fabrics are used in protective apparel (42%), envelopes (25%), housewrap (13%), sterile packaging (8%), graphics (4%), and others (8%).
* Melt-blown (100 MM lbs) is used in filtration media, medical (SMS), sanitary products, sorbents, wipes, apparel insulation, adhesives, protective apparel, battery separators.
* Wet-laid webs are used in medical (packs, gowns and CSR wraps), food (tea bags, coffee filters, meat casings), industrial (wall coverings, battery separators, lint-free wipes, vacuum cleaner bags, interlining fabrics, filters, cigaret plug wraps, etc.)
* Needle-punched nonwovens (200–250 MM lbs) find use in automotive trim (30%), geotextiles (25%), coated fabrics (22%), home furnishings (18%), filters, interlinings, roofing, etc.

In the discussion thus far, the relationship between TECHNOLOGY/System, raw material and end-use market has been hinted at; it is a very important relationship. These three ingredients are intimately involved in determining optimal cost of the product and the profit margins available to the producer. Here we pursue the role of the raw material perspective of the US nonwovens industry a bit further. First we look at cases where the fibre extrusion forms part of the process.

Polypropylene (PP) [5]: The role of PP in spun-bonded nonwovens in the US has been alluded to already. PP spun-bonded consumption is growing world wide—from 550×10^6 lbs in 1990 to expected 800×10^6 lbs in 1996. Strong growth is expected in North, Central and South America.

HDPE [5]: Its principal use has been in the Du Pont's proprietary technology encompassing flash extrusion of a network of very fine ligaments as web, which is collected to build up the required basic weight. The collected web is then bonded, presumably thermally, to yield Tyvek®. Overseas markets for Tyvek® are expected to grow.

Polyester [5]: Its use in spun-bonded products has been mentioned previously. The future growth rate of 8–9% p.a. is projected.

Next we look at the use of the staple fibres as raw material. Table 1.2 gives a historical perspective of the staple fibre shipments (MM lbs, (% of total)) in the US [8].

TABLE 1.2

Year	Rayon	PET	Olefin	Total
1975	137 (78)	25 (14)	14 (8)	176
1980	147 (42)	167 (48)	35 (10)	349
1982	112 (36)	155 (51)	39 (13)	306
1985	114 (28)	162 (39)	136 (33)	412
1987	125 (24)	204 (39)	198 (37)	529
1988	122 (22)	244 (45)	181 (33)	547

High prices, lack of dependable supply, move toward hydrophobicity in diaper coverstock, and its non-suitability for thermal bonding have contributed to rayon's decline of market share. On the other hand, the decline in polyester's price, its dependability of supply, and its hydrophobicity and suitability for thermal bonding have contributed to its sustained healthy market share. The olefin (PP) market share has increased primarily due to low prices, good cover due to its low specific gravity, hydrophobicity and its ability to perform on thermal bonding equipment.

With the uncertainty in rayon price and supply, and the pressure for biodegradability, followed by improved processing has led to an increase in cotton usage in nonwovens. There is now (1989) 65–70 million pounds of kier bleached cotton in the US nonwovens business. Much of the cotton goes into tampons, cotton puffs and swabs. But it is finding its way into medical area, wipes, home furnishings and filtration, with development of cotton for baby diapers.

3. THE EUROPEAN NONWOVENS INDUSTRY

The 1978 roll goods production of nonwovens in Europe was reported to be about 152,000 tons [9], which is comparable to the US production in 1970. This suggests that the European Nonwovens Industry lagged behind the US industry by a few years. However, it grew dramatically during the 1980s and is continuing to grow despite the recession. Its growth to the 451,000 tons reflects a compound growth rate of 10% p.a. over the 1980–1990 decade [9].

The growth of the industry in different parts of Europe is illustrated by the data in Table 1.3 [9].

TABLE 1.3 Nonwovens Production by Countries

(1000 tons)

	1980	1982	1984	1986	1988	1989	1990
Germany	41.0	53.2	74.8	92.7	103.9	122.0	137.1
Benelux	41.4	44.5	51.5	57.3	73.1	78.3	84.6
France	28.3	29.2	34.0	42.8	52.3	56.0	60.0
Scandinavia	21.0	25.6	31.3	40.9	50.1	49.3	52.2
U.K.	33.2	34.6	38.1	36.8	41.3	45.7	49.3
Others	20.7	22.9	26.9	38.4	50.1	62.7	67.5
Total	185.6	210.0	256.6	308.9	370.8	414.0	450.7

Up to about 1986, the industry was based on three broad TECHNOLOGIES Systems: Dry-laid (a little over 50% of tonnage), wet-laid (about 15% of tonnage) and spun-bonded (the remainder). Since 1986, other systems suc as melt-blown and spun-laced have been introduced. Products from th TECHNOLOGIES have claimed about 5% of the market share, largely at the expe of dry-laid and wet-laid.

The breakdown of end-use markets, percentages based on tonnage, in Western Europe in 1990 was as follows [9].

	Per cent
Coverstock	26.3
Civil Engineering	20.7
Furniture & Bedding	8.7
Wipes	8.4
Interlinings	5.0
Medical/Surgical	4.4
Liquid Filtration	4.0
Shoe & Leather goods	3.6
Electrical & Abrasive	2.7
Automotive	2.0
Garments	1.7
Air & Gas Filtration	1.6
Agriculture	1.0
Others	10.0

4. THE JAPANESE NONWOVENS INDUSTRY

While the nonwovens industry in Japan is said to be over 30 years old [12], the production data in aggregate is available readily from 1982 onwards [10]. The nonwovens production in Japan has increased from about 92,000 tons in 1982 [10] to about 163,500 tons in 1989 [14], showing an average growth rate of 9–10% p.a. While in the early years Japan imported process technologies from US and Europe, in the most recent period it has actively participated in developing newer systems and products. Today it has all modern systems available elsewhere and some that no one else has (e.g. ultrasuede). Table 1.4 lists the more prominent ones and their relative importance by tonnage.

Reference [12] interestingly gives a Life Cycle chart of the nonwovens technologies in Japan. It might be interpreted as follows:

Germination Period	Electret Melt-blown
Growth Period	Spun-laced Carded/thermal-bonded Spun-bonded
Maturity Period	Needle-punched Wet-laid
Waning Period	Carded/Immersion Adhesion Stitch-bonded

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TABLE 1.4

TECHNOLOGY/ System	1984 (tons)	1985 (tons)	1986 (tons)	1987 (tons)	1988 (tons)	1989 (tons)	Growth (89/88) %
Dry-laid	—	—	—	—	—	45,000	12.7
Immersion Adhesion	27,116	29,674	31,111	32,830	36,932		
Needle...	38,991	41,288	43,670	47,202	53,969	56,000	8.3
Stitch-bonded	999	1,191	1,220	1,364	1,222	incl. ⇑	
Spun-bonded	19,837	22,816	25,325	29,858	34,068	41,000	29.3
Wet-laid						11,000	—
Melt-blown	400	400	860	1,080	1,350	1,500	15.4
Air-laid Pulp						6,000	13.5
Spun-laced	2,360	3,310	3,980	4,450	5,350	3,000	7.1

*1984–1988 data from reference [13]; 1989 and growth data from reference [14].

At this stage it is useful to look at the relative size of Japanese markets and their projected growth potential (Table 1.5).

TABLE 1.5

	1989 (tons/year)	
Diaper coverstock	18,000	⇒
Napkins and coverstock	3,000	⇒
Medical (gauze/gowns)	8,000	⇑⇑
Wipes	12,000	⇑⇑
Interlinings	7,500	⇒
Base cloths (carpets, leatherettes)	20,000	⇑
Agriculture, construction, civil engineering, and industrial	20,000	⇑⇑
Filters and commodities	16,000	⇑⇑
Disposables (body warmers, wrapping cloth)	10,000	⇑⇑
Others	23,500	⇑

⇑⇑ estimated future growth rate very good
⇑ estimated future growth rate good
⇒ estimated future growth rate flat

It is equally useful to look at the pattern of Japanese fibre consumption for the production of nonwovens. According to one estimate [15], of the total consumption of 121,000 tons 23% was in filament form and 77% in staple form. The filament form was further subdivided into 12% PET, 6% PP, 2% cuprammonium, 3% nylon. The staple portion was further subdivided into 24% PET, 23% PP, 19% rayon, 4% vinyon, 3% pulp, 4% others.

There are some lessons in these tables and data about the nature of the TECHNOLOGIES and their relationship to national/cultural needs and economy.

5. OTHER ASIAN AND LATIN AMERICAN COUNTRIES

Without belabouring the point, let us use selective quotes from the literature to give the perspective on other Asian and Latin American countries.

"The **Korean** industry began in 1960, originally to produce simple nonwovens for exported garments. The nonwoven roll goods production for 1989 was estimated to be 50 million pounds, valued at US $85 million. By 1990 domestic sales were US $360 million, with export markets increasing each year [15]."... "Demand for nonwovens is increasing substantially and investment is increasing at 20% per year." The annual growth rates are of the order of 12–13%. This has been partly due to the improvements in standard of living and trends toward convenience products like wipes and disposables [16].

"Dry-laid systems are most widely used in Korea. Chemical bonding and needle-punch contribute to 88% of total production. But spin-bonding, thermal-bonding and stitch-bonding were introduced in 1980's to increase productivity and now account for 8.1%, 2.7% and 0.5% respectively [16]." A substantial output uses needle-bonding technology. Indeed, Korea has developed its own needle loom manufacturing industry [17]. The leading end-use in Korea is interlinings. Additionally, Korea's shoe production has caused demand for manmade leather to rise. Other areas are filtration, geotextiles, home furnishing and consumer products. Consumption of fibres is increasing at a 7–10% annual rate. Sufficient supplies of polyester and polypropylene, the two most popular fibres, are produced domestically, but 30% of nylon usage has to be imported owing to insufficient national output and all viscose fibre used by the industry has to be imported [17].

The nonwovens industry in **Taiwan** is said to be about 30 years old. Its annual growth rate in the past decade was 10–20%, but has been slowing recently. Its 1990 production was valued at US $88 MM [19]. "Although Taiwan produces mostly dry-laid fabrics it is rapidly diversifying into other processes, with noticeable advances in melt-blown, spun-bond, thermal-bonded, air-laid and spun-lace technologies [20]. The end-use pattern in Taiwan is similar to that of Korea. According to 1985 survey, 38% was used in interlinings, while the second and third largest markets were spray-bonded high-loft for garment padding, and needle punched fabrics for shoe insole and carpet applications respectively [22]. Polypropylene is used extensively in spin-bonding and melt-blown operations. Microfibres made from conjugates of nylon and polyester are used for making synthetic leather. The spun-lace process uses rayon, polyester or cotton fibres (or blends) to make fabrics suitable for synthetic leather, surgical gowns, wipes and underwear [20].

The first **Chinese** (PRC) nonwovens factory was put into production around 1965 [22]. From 1978–1988 the average annual growth has been 30%. The 1991 production was estimated to be 70,000 tons [23]. There are now nearly 300 nonwovens enterprises scattered in 28 provinces of China. Most of the factories are small in size and some of the equipment utilized is outdated technology. More then half the factories use air-lay, needle looms, stitch-bonding, saturation-bonding and thermal-bonding equipment made indigenously. Similar indigenous equipment as well as spin-bonding equipment from Europe is also now being used.

The end-use markets in **China** include cover stock, thermal insulation, geotextiles, floor coverings, paper markers felt, etc. The industry is expected to grow to 200,000–250,000 tons level by the year 2,000, about 85–90% of it going to durable uses [24]. "The most popularly used fibre is polyester, next is viscose, polypropylene, vinyon and polyamide." "In automotives some needle-punched nonwovens made from waste fibre and molded carpets have been developed." [24]

"The **Latin American** countries are starved for real technical expertise, in both the roll goods producers and end-users area."... "Technology is still one area where the most improvements can be made. At this time many companies are involved in open exchanges of information with North American, European and Japanese firms.[25] "The needle-punching TECHNOLOGY seems to have penetrated Latin America; 160 companies are reported using this technology. The products are used as blankets, wipes, carpets, automotive trim components and paddings. While the geotextile market is a relatively new, with mountainous terrains, erosion and pollution problems, etc. geotextiles could become the single largest growth market. Synthetic leather production is on the rise, as well as the markets for apparel interlinings, shoulder pads, machine shock absorbers, decorative felts, and scouring pads. It is expected that the automotive market will grow in the future, and there should be an increase in the filtration market [25].

A few typical country cases are described below.

In **Mexico** the industry started with the establishment of Milyon, SA in 1956. Latin markets because of conservative consumption patterns rejected innovative products especially in regard to disposables. No one ever got rid of anything, not knowing when it would come in handy. Hence it took a great deal of foresight, courage and ambition to put the nonwovens project through and make these products palatable to the Latin consumer. Milyon acted as a catalyst for the establishment of more industries of the same kind in the country and the rest of the continent [25].

One of the more intriguing countries in the nonwovens industry is **Brazil**, where a number of companies are emerging to become leaders not only in South America but worldwide as well, despite the high inflation rate, foreign debt and internal political crisis during the recent decade. However, the growth of nonwovens is expected to increase in the near future as new technologies and investments in new machines replace and augment existing technologies and machines. The nonwoven disposable industry should increase due to strong growth in consumers real disposable personal income. Its TECHNOLOGY composition includes: Needle-punched 67%, spun-bonded 14.5%, thermal-bonded 2.75%, card & air-laid (spray) 9%, card resin-bond 6.0%, stitch-bonded 0.75%; felts are excluded [26].

Its markets include: Apparel, needle-punched carpets (domestic and automotive), needle-punched blankets, carpet backing, civil engineering, agricultural, electric wire insulation, printing material, papermakers felt, shoes, bags, PU and PVC substrates, fiberfill, mattress and upholstery, diapers, medical apparel, wipes, abrasives, etc.

In terms of the raw material used in **Brazil**, 14.5% is filament and 85.5% is staple. PP is used in 70% of the filament market. "In staple fibres, polyester and rayon fibres are being chased by polypropylene in the field of thermal-bonded nonwovens. In the needle-punched market, the principal fibre used is polypropylene, which contributes more than 50% to the market." [26]

Other countries in Latin America, such as: **Argentina, Chile, Colombia, Ecuador, Guatemala and Peru**, also have a budding nonwovens industry. It is expected that with the free trade agreements, the future should be bright for the Latin American nonwoven industry. "Due to an abundance of natural fibres in the Latin American region (Sisal, jute, tampico and animal hair) the production of insulator pads has been a major portion of the needle punching industry..."..."The greatest percentage of needle punched products are made from regenerated fibres, more commonly known as shoddy." [25]

According to D.K. Smith [29], "the nonwovens industry is a worldwide activity. Operations utilizing this technology exist on six of the seven continents. Only on Antarctica is there no nonwovens production, but there is certainly a lot of utilization of nonwovens on that continent. A total of 57 countries around the world boast of a nonwovens industry. Czechoslovakia has 24 nonwoven enterprises, NewZealand has a domestic nonwovens industry, Israel has several such operations and East Germany can boast of a spun-lace operation as well as a variety of other types."

The industry news bulletins are full of items such as:

"With a solid position in European and US nonwovens industries already established through its Nordlys and Polybond units, respectively Dominion Textile, Ontariö Canada has revealed plans to expand into the Asian market." It is constructing a nonwovens manufacturing facility in Ipoh, Malaysia. [Nonwovens Industry, Executive Report, July 15, '91]

German machinery manufacturer Trutzschler is planning to shift its emphasis from US and Europe towards Asia. It has already begun production of its high production card through its Trumac joint venture in Ahmedabad, India. [Nonwovens Industry, November, '91]

A joint venture between PT Risjadson Holding & Investment Co., Indonesia and Ballarpur Industries Ltd., India will be making viscose rayon grade pulp within three years. [Nonwovens Research International, April, '92]

6. GLOBALIZATION OF THE INDUSTRY

That nonwovens industry is global in its reach is no longer a question. How did it get there and what to expect next are indeed the legitimate issues for discussion. These were discussed at the 1990 INDA-tec Conference. We are going to walk you through some key presentations, and at times add some editorial comments.

Mr. Engels of Hoechst AG [27] saw the globalization of the industry in general in the context of globalization of the society. The latter is manifest in the interdependent nature of the economic structure of nations, in the ever expanding international trade, in the unprecedented mobility (voluntary or forced) of populations (labour force) across national boundaries, indeed the re-definition of some of the boundaries, the rapidity of communication (and travel), and the flow of political ideas, etc. Numerous examples can be cited in support of each of these points. The global society concept can be further seen through the emerging "global culture," which sometimes stands in sharp contrast against the traditional cultural values and symbols. This has created global markets for specific products or class of products, and even global brand names. Two major factors drive the world toward globalization: (1). The educational wave in the developed countries (significant increases over the past 30 years); (2). Communications (e.g. Int. Herald Tribune, CNN).

Another major factor involved in the globalization of the world markets is leveling of the wealth and economic (or buying) power of nations and geographic regions [27]. For example, from the early 1960s to the present the increase in combined GNP of North America, once the unchallenged wealthiest region of the world, increased nine times, while that of Europe increased sixteen times. All of the Far East increased its output by 28 times. Looked at another way, in 1988 *per capita* GNP in Japan was US $23,200, in North America US $18,600 in Europe US $13,400 in all of Far East including Japan US $2,400, and in Latin America US $1,700. The message for Japanese and Western corporate strategists is: "if you want to grow and seek greater opportunities, be in Asia and [be] well prepared!"

This leveling of wealth and economic power was accompanied by the growth of traditional industries (ship building, steel, automotive, textile and apparel) in the Pacific rim countries. They also participated in the worldwide growth of the advanced technologies such as the semi-conductor industry. While the low labour cost, in addition to political stability, was an early contributor to this growth, this advantage is disappearing.

According to another voice, Snyder [30] of Du Pont, "Globalization is the effective deployment and utilization of Worldwide resources, integrated with opportunities, to achieve competitive advantages, to achieve superior business results. "Their rationale behind this definition is: "The world is being rapidly integrated by two compelling forces: accelerating technological change and globalization of markets, customers, and competitors. These forces are causing product life cycles to shorten significantly, economies to be increasingly independent, international trade to increase at a faster rate than world GNP, and multi-domestic business strategies to be supplemented or supplanted by focused global strategies supported by integrated resource network. The key to being successful in this environment will be strengthening the management process to effectively utilize our worldwide resources..."

Thus, the globalization of the world economy has given rise to the enormous increase in multinational or global companies. There are numerous examples in energy, financial, pharmaceutical, chemical, manmade fibre, electronics and communication sectors, etc. In the textile sector, it is the nonwovens industry that leads in the growth of the global companies. Freudenberg, ICI, Hoechst, Du Pont, Dexter, Proctor and Gamble, Rhone Poulenc, Holzstoff (Fiberweb NA), Scott Nonwovens, etc. are familiar names on both sides of the Atlantic. The changes in the structure and growth of these global companies over the last few years has been dramatic indeed. Some typical news items illustrate the point.

Freudenberg has 18 operations in 11 countries. These include the US, Taiwan ... "Sodoca, one of the two French operations, is now linked through common ownership by Holzstoff (Switzerland), with fiberweb in Sweden and with former James River Nonwoven Division facilities in Pensacola and Washougal." The ... Rhone Poulenc ... polyester spun-bond is also made by a wholly owned subsidiary in Brazil and by other ventures in South Africa and Australia. "The UK based Lantor operation, has a Lantor International manufacturing associate in the Netherlands in addition to links with nonwovens operations in Spain, Australia, South Korea and even China." "Most of the disposable diaper business in UK worth around $460 million annually is dominated by Scandinavian owned but French based Peaudouce, the Italian FINAF group and Proctor & Gamble. The latter US group recently bought Arbora, a Spanish diaper manufacturer." [Global Western European Industry, Derek Ward, INDA-tec '90]

"With the recent developments in [Eastern Europe], there is a tremendous potential available in these markets. Whether the demand in these countries for consumer and industrial goods can be transformed into viable markets depends on their ability to develop industries that will bring in hard currency. Johnson & Johnson, Veratec and Proctor & Gamble have shown interest in the Eastern European countries." [Globalization, Impact of Eastern Europe, in *Nonwovens World Fact Book*. Miller Freeman 1991]

"In addition to the technical achievements of the Japanese producers, the Japanese market has benefitted from the activities of overseas producers. For example, nonwovens manufacturers in Taiwan and Korea make their spun-bond, melt-blown, and spun-lace fabrics available in Japan." ... "US and European producers are also active in Japan. Du Pont Co. which already supplies sizeable quantities of Tyvek and Sontara to this market, will manufacture Tyvek locally by 1992. International Paper, who with Rengo Paper and C. Itoh formed Rengo International Paper, to make thermal-bonded fabrics for diaper facings, has made expansion into two lines. Veratec introduced its US made spun-lace and Webril brands into Japanese market. Freudenberg has begun production of polyester spun-bond fabrics in Taiwan through a joint venture with Japan Vilene and a Taiwanese company, Far East Spinning." [14]

"Other Western companies active in Japan include: Chicopee, Kimberly Clark Corp., Scott Nonwovens, Molnlycke, Suominen Oy, Hoechst AG, BASF, United Paper Mills, Dunibila, and Merfin Hygienic." [14] "A joint venture between Amoco Fabrics and Fibres Co., Atlanta, Georgia, and Nippon Petrochemicals, Tokyo, Japan will produce and market a line of nonwoven fabrics called CLAF, which Nippon successfully marketed for 17 years." [NWM, September 21, 1990]

"The Europeanization of the Japanese nonwoven industry was further displayed by the joint venture between Holzstoff, Switzerland and Mitsui Petrochemical Industries, Tokyo, Japan. It will be a 50/50 joint venture to build a nonwoven plant and the plant would most likely use Fiberweb's new "S-tex" technology or derivative of it." [NWI, Executive Report, July 15, 91]

"One year after agreeing with AKZO on a deal to market Colback in Japan, Mitsubishi Rayon sales have reached around 500 million yen."... "Continuing success with the marketing of Colback could result in a decision to construct a Japanese production facility within next two years." [NWRI, February, 1992]

Proctor & Gamble continues its assault on the Brazilian market. It continues to ship pampers produced in the US. The majority of wet-laid nonwovens imported in Brazil are from Dexter Nonwovens, Windsor Locks, CT. [NWI, January, 1992] "A joint venture between Toga a Brazilian manufacturer and M.W. Verpackungen a German packaging company has been entered." [NWI, February '92]

Strengthening its already dominant hold on the Mexican disposable diaper market, KC is progressing with its second plant in Ramos Arizpe. KC currently holds 70% of the diaper market, P & G share is 15% and Mexican company has 15%. [NWM, February 14, 1992]

"A joint venture agreement for the marketing of polypropylene products in China has been signed by Himont, Wilmington, DE, and International Multi Petrochemical Processes, Hong Kong." German spun-bond producer, Reifenhauser, installed its second Reicofil line in Mainland China. Reifenhauser, will also be installing a third Reicofil line at Brazilian nonwovens producer Kami. The company also delivered a one metre wide melt-blown line in US, the first in the country. It already has two melt-blown lines in Taiwan, an order for one line in Czechoslovakia, and one in Italy. [NWI, November '91]

Technimont has won a contract to build a ethylene production facility in Canton, PRC. The plant will have necessary raw materials to produce various other polymers such as polypropylene and polyethylene. [NWRI, February '92] Dana Corp. of Toledo Ohio, has set up a joint venture with Tianjin, Auto filter factory, PRC, to produce automotive filters which consist of a screen formed cellulose strengthened with phenolic resin. [NWM, Jan 4, 91] "A Thai manufacturer is installing a spray bonding line built in PRC. This is the first instance of nonwovens equipment being exported by a Chinese machinery builder. [NWRI, March '92]

It is such activities that lead Jacobsen [28] to suggest even more dramatic possibilities in the next two decades. These could involve US based, European based and Asian based companies to form even larger conglomerates operating in the world economies, manufacturing and marketing not only nonwovens and converted products but also other unrelated high margin and sophisticated products. The underlying theme, I believe, would be to optimize the sourcing of raw materials, energy, labour, finance and technology to produce and sell goods and services to greatest benefit of the owners; it is also hoped that the public ownership of these companies will also become global in its distribution.

Finally, in this context, while it is true that Africa, some Eastern block countries and most of Latin America have not participated in the globalization of the world economy, it is only a matter of time. They will eventually.

Next, let us give you one multinational's, Du Pont, strategy to achieve their vision of "a truly great global company." According to Snyder [30] of Du Pont: A great global company has business leaders located in leading markets. Their responsibility is to aggressively develop *competitive advantage* with a sense of urgency and with dedication to a philosophy of continuous improvement. The company should be *obsessed* with *customers* and *markets* worldwide, and should have a strong bias toward medium/longterm *growth* and profits. It must also have an explicit global strategy for all of its major businesses. The strategy should include the aspects of marketing, research and development, manufacturing and human resource development.

Du Pont sees deployment of human resources consistent with present and future business opportunities as the key to success in globalization. The individuals involved must have the proper motivation, must represent cultural diversity and must have the ability to adapt to unfamiliar environment. The degree of globalization is determined by the market. The corporation must weigh the pursuit of its opportunities against the backdrop or its global commitment. It must strike a balance between its need for the global integration of its business and the national focus of its parts. Du Pont recognizes that their competitors will globalize because it offers the advantages of business optimization and resource integration. The principles upon which Du Pont's strategy for globalization is based may be enumerated as:

(a) The degree to which a business is globalized will be determined primarily by the market.
(b) Globalization requires strong functional capabilities to be developed in strategic markets.
(c) The primary vehicle for globalization will be worldwide business teams which will utilize our global capabilities to meet customer needs, rapidly commercialize Du Pont technologies in strategic markets, and drive bottom-line focus.
(d) Responsibility for worldwide strategy setting, resource allocation and profitability will be with a business leader who usually will be located in the leading country market.
(e) Responsibility for execution and results will rest with regional/national management.
(f) Globalization will be sufficiently flexible to permit application of Differential Business Management.
(g) Reporting systems will facilitate globalization through alignment of financial and business strategies and by providing clarity regarding regional/national contribution to the worldwide business.
(h) Most importantly, in order to be able to do all of the above, we will continuously expand the cadre of experienced managers with an understanding of and enthusiasm for management of business in a global context.

7. IMPLICATIONS FOR THE DEVELOPING COUNTRIES

At this stage one might ask: "What are the implications of globalization of the nonwovens industry for developing countries?" Or, alternatively: "How might developing countries participate in the global expansion of the nonwovens industry?"

Alas! there is no simple answer.

It does seem, however, that carding as the web forming technology is usually the first to be used by countries with an emerging nonwovens industry. This may be followed by air-lay technology. The bonding technologies in the early stages include resin-bonding, needle-punching, stitch-bonding, and thermal-bonding. These compete with each other depending on the nature of the raw material to be used and the commodity markets identified as most likely to succeed. The country's cultural approach to disposability vs. durability also plays a very important role in this decision. The introduction of more capital intensive technologies such as wet-lay, spin-laying and bonding, hydroentanglement, melt-blowing, etc. usually are later introductions after the country has gained some experience with the products in the market. The existence of a successful paper industry in the country may expedite introduction of the wet-lay technology to provide roll goods for industrial products.

At a more fundamental level, I might suggest that for a country to develop a nonwovens industry, it is necessary for it to look at the basic ingredients that make this industry viable. Without implying any order of priority, the country must have large enough market to consume the products to be manufactured. If the answer is yes, the next question may be whether the country or the geographic region has the necessary raw and accessory materials and energy resources available at an acceptable cost. The cost here will include the cost of importing, if necessary. This question may be followed by: Does the manufacturing process technology and machinery to be employed exist, at the desired level of sophistication, within the country? If it is to be imported, would it be through direct purchase in the international market, through licensing, or through a joint venture with an international company already in business successfully. If the direct purchase option is selected, it would assume the availability of technically trained and experienced manpower (peoplepower) to make it work. Many of these decisions are conditioned by the access to capital markets, the necessary managerial talent and the country's industrial infrastructure.

It is not uncommon to find developing countries wanting to go it alone and establish profitable ventures based entirely on indigenous raw material, machinery, technical know-how and human resources. Under suitable circumstances it is indeed possible. But given the rapidity with which technology is advancing in the world today, it could be an extremely, painfully slow process. Judicious mixture of the indigenous effort together with selective partnerships with global companies with established credentials might permit the country to leapfrog into the modern nonwovens technological era.

8. ACKNOWLEDGEMENTS

The authors wish to thank the organizers of this conference for the invitation to present this paper. At the same time the financial support of the National Science Foundation, the State of North Carolina and Member companies of the Nonwovens Cooperative Research Centre for the preparation of this paper is duly acknowledged. Finally, thanks are owed to Professor Thomas F. Gilmore who went through this manuscript with a fine toothed comb to improve the quality of its content and presentation.

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2

Nonwovens: An Important Segment of the Textile Scene

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Nonwoven fabrics have become an extremely important segment of the textile scene in recent years. Nonwoven fabrics are being made use of in such diverse areas as diaper liners, luggage fabrics, electrical insulators, filters and reinforcements for asphalt pavements. With the development of new types of fibres and the refinement of the manufacturing processes, the new markets for nonwovens are opening while finding efficient uses in the traditional markets, hitherto held by wovens and knitted fabrics. This paper briefly describes the various manufacturing processes and discusses some growth potential in certain markets in the future.

1. INTRODUCTION

Ordinarily whenever a reference is made to textile fabrics, it is generally in the context of woven or knitted structures. These are the two most visible and most commonly used forms of textile fabrics that an ordinary user (person) comes across. The user of a textile fabric is primarily concerned with the utility, aesthetics, and the cost of the material. The utility includes durability and performance during use, which in turn, is influenced by the ability of the structure to retain structural integrity, strength, and flexibility. These characteristics can be easily obtained by converting fibres into yarns and yarns into fabrics. This is equally true for both yarns made from staple fibres or yarns composed of continuous filaments. The process of knitting or weaving limits the use of fibres in terms of the cost of conversion of fibres into yarns, fabrics, and into made-up articles. This is obviously more than offset by the durability and the repeated use of the article.

Another utilization of fibres (both staple and continuous filament) is to convert the fibres into a sheet material through various processes used in web formation. However, the web thus formed lacks cohesion and strength; consequently, to attain strength, structural integrity, and other mechanical and physical characteristics, the web is bonded by any of a number of bonding techniques developed over the past five decades. The process of making the sheet material from discreet fibre lengths or continuous filaments, bypasses the yarn making process, thus reducing the cost of the material. It was this economy in producing sheet materials and the advances in the industrial countries that prompted the development of nonwovens. In addition, the rate of production at which the nonwovens could be produced made them quite an attractive segment of the textile production. This is obvious from Table 2.1 [1].

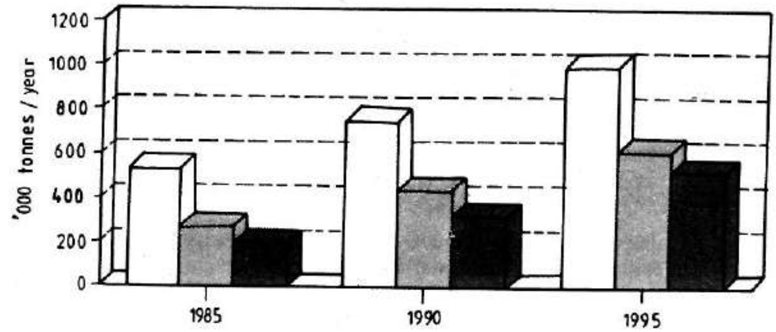
TABLE 2.1* **Comparison between Different Rates of Production in the Manufacture of Textiles and Similar Materials**

Technology	Machine	Relative Production Rate
Weaving	Automatic loom with shuttle[a]	1
	Shuttleless loom	2
Knitting and hosiery	Circular knitting machine (wide)	4
	Warp knitting loom	16
Manufacture of nonwoven bonded fabrics		
Dry method	Stitch bonding machine	38
	Fine fibre carder	120
	Coarse fibre carder	400
	Tufting machine	500
	Aerodynamic web-making machine	600
	Spin-bonding machine	200–2000
Wet method	Rotoformer	2300
Paper manufacture	Paper-making machine (high powered type)	40000–100000

[a]Average output 5 $m^2.h^{-1}$
*Reference [1]

The earlier successes in the development of bonded nonwovens, as a part of the textile industry, occurred in the 1950s and by the 1960s the success of nonwovens in such end-uses as linings, filtration, disposable diapers, wipes, sanitary and medical applications, etc. was well established. Because of the nature of the products and the connotation of disposability attached to the early nonwovens, the developments could not penetrate into more traditional areas of applications such as apparel. Consequently, the early growth of the nonwovens was limited due to the characteristics of the products, and the availability limited the number of bonding technologies. Once the understanding that the wovens and knits were hard to replace with this new technology in the 1960s came, it was only a question of time that new end-uses of these materials produced with newer technologies were developed. In the process, the newer nonwovens (such as stitch bonded, spun-bonded and the like) found their uses in such areas as the furniture industry where wovens and knits were traditionally used.

The development of nonwovens over the past five decades has brought the total production in 1991 to 3.5 million pounds world-wide, as shown in Fig. 2.1 [2]. Out of this, North America accounts for nearly 50% of the total world-wide production, while Western Europe, Japan, and the rest of the world account for 29%, 10%, and 11%, respectively. In the earlier years, the



	1985	1990	1995	
North America	535	750	1000	6% / Year
Europe	270	440	615	7% / Year
Other	200	325	525	10%/Year

Average Groth 1985–1995 – 8% / Year

North America Europe Other

Fig. 2.1 World outlook-nonwoven fabrics
Source: John R. Starr, Inc. estimates [2]

growth of nonwoven fabrics in the US was almost 10% per year, while the current growth is around 6%. On the other hand, the nonwovens market in the rest of the world has been growing at a steady rate of 10% per year. The nonwovens markets in Western Europe and Japan are shown in Figs. 2.2 and 2.3, respectively [3, 4].

2. CLASSIFICATION AND END-USE APPLICATIONS

The end-use applications of nonwovens have been the driving factors in the development of materials and new technologies; the requirements of the desired properties for an end-use application determine the type of fibre, the method of production, and the bonding employed. For example, for filtration application in the medical field where the most important requirement is the removal of bacteria (with a size of ~ 1 micron), the nonwoven material made from microfibres that will perform the best is the one made by the melt-blown process; the fibre should be preferably the one that is made from thermoplastic polymer. Or for example, when the characteristics of super absorbency in the nonwovens is required, it should be made from a highly hydrophilic type of a fibre and converted by either the carding or air laying process to produce a highly bulky structure.

The types of fibres used in the nonwoven industry are all the different types of fibres that are used in the traditional textile industry with the exception of pulp. Pulp and short fibres cut from all types of textile fibres, of the order of up to ~ 6 mm length, are used in the making of nonwovens by the paper making (wet laid) process. Practically all types of natural, regenerated, and synthetic fibres are used in the making of nonwovens. The bulk of the nonwovens all over the world are made from staple fibres. The second large category is the manufacture of nonwovens by spun-bonding

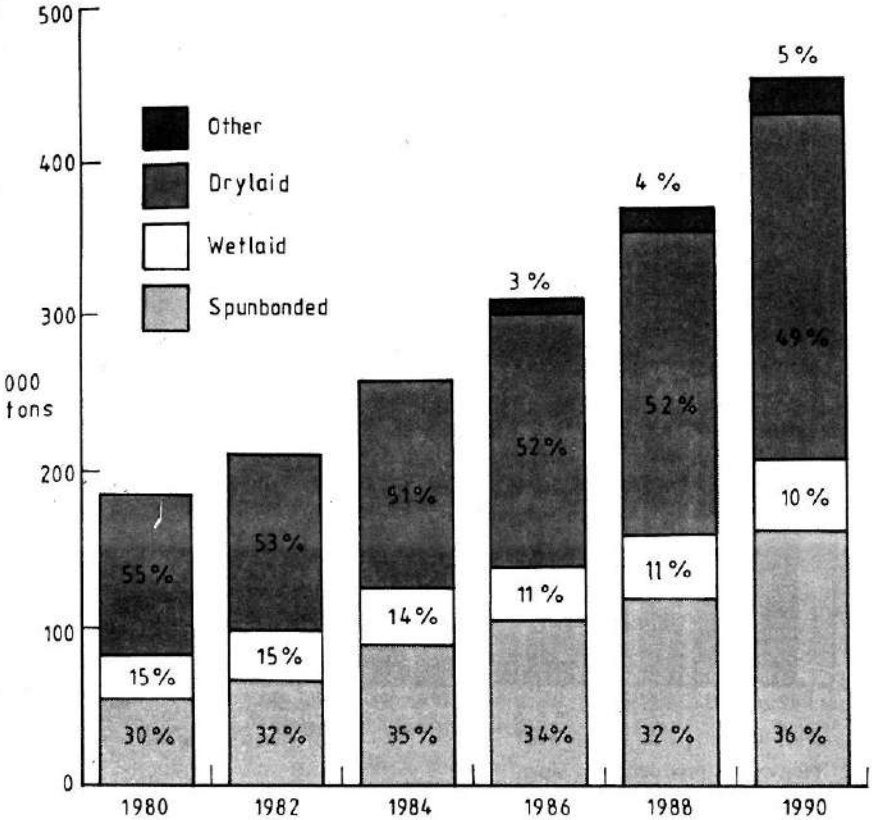


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Fig. 2.2 Nonwoven production in Western Europe by manufacturing process
Source: EDANA [3]

and melt-blown processes (polymer melt through extrusion) where continuous filaments are converted into a web. The next category comprises the conversion of pulp and fibroids into nonwoven sheets by the wet laying (paper making) process.

3. METHODS OF MANUFACTURING

The end-use application is strongly influenced by the type of fibre, method of bonding, and finally the finishing (coating, laminating, printing and impregnation, etc.) process employed. The process of manufacturing and the classification of nonwoven fabrics is shown in Table 2.2.

The selection of the type of fibre will depend on the end-use application, e.g. does the application require moisture and water pick-up, or protection from hazards or rot resistance, or filtration of liquids and hazardous gases. Besides the commodity fibres, such as cotton, jute, coir, polyester, polypropylene, rayon, and other specialty fibres, e.g. polyphenylene, bisulfide (Ryton), Novoloid (Kynol), PBI, ceramic, glass, carbon, and PANOX are available in the market to meet special requirements.

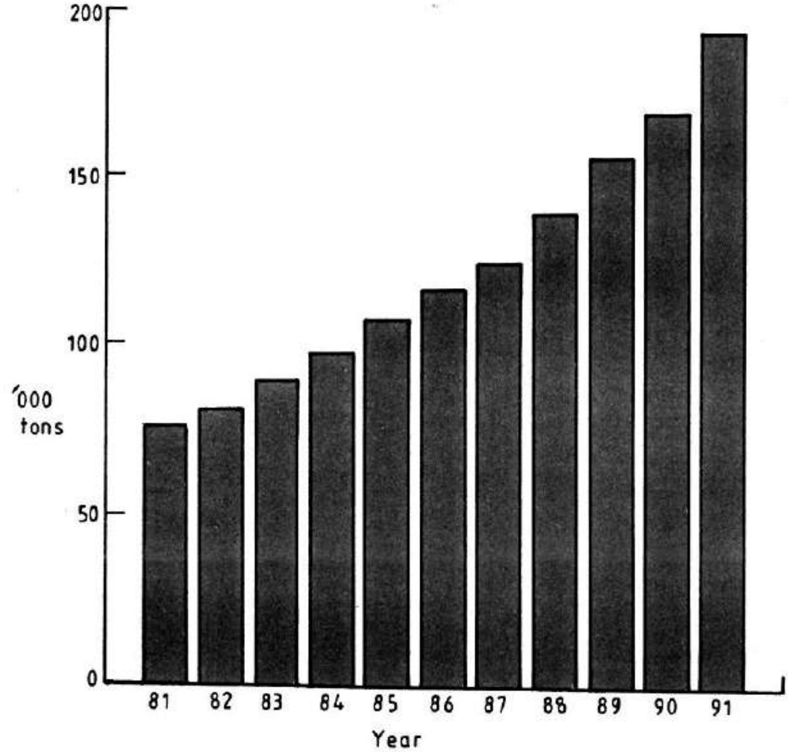


Fig. 2.3* Nonwoven production in Japan
*Reference [4]

Carding, including garnetting, is perhaps the most commonly used process for converting fibres into webs; the carded web—made by the cotton system. But the fastest growing process is the fabrication of end-use products by the combination of reinforcement of two or more components to form a composite nonwoven structure. As Drelich [5] points out that the composites should..."not be confused with layered structures." The composites may be made by combining a nonwoven with another component by any of the four different methods:

(a) by reinforcement of a web with a scrim or netting bonded by latex,
(b) by thermally bonding (heat and pressure) two or more nonwoven substrates,
(c) by entangling (and bonding by needles including: thermal, sonic, or hydroentaglement) fibres within a web, and
(d) by stitching or knitting through heavy webs or slivers by the stitch bonding process.

Drelich [5] has given the kinds of composite structures that may be categorized by this term as shown in Table 2.3.

Drelich [5] has also given a classification of nonwoven fabrics which takes

TABLE 2.2

Nonwoven Process of Manufacture

Fibres
Fibrids
Filaments
Film
⇓
Web Making Process
⇓
Web Bonding Process
⇓
Finishing
(coating, crimping, laminating, impregnating, shrinking, corrugating and texturing)

Web Making Process

DRY PROCESS:	A. Carding (i) Parallel-laid (ii) Cross-laid B. Garnetting C. Air-laid
WET PROCESS:	Wet Laid (paper making)
POLYMER EXTRUSION:	Flash Frozen-high-density-polyethylene Melt Extrusion-spun-bonded — net — film — stretch, fibrillate, etc. Melt Blown—blow the extruding polymer with blast of hot air SMS-Spun-bond/Melt-blown/Spun-bond

Web Bonding

CHEMICAL:	Chemical binder such as latex or rubbers, resins, PVC, PVA, self-cross linking acrylases, solvents, gas (e.g. HCl for nylon), SBM, neoprene, etc.-applied as powders, emulsions, saturation, films, foams, printing, spraying, etc.
MECHANICAL:	Needle Punching Hydroentanglement Stitch-bonding
THERMAL BONDING:	Agents: powders, fibres, polymer melt, homopolymer, bicomponent, films, nets —heat process: Calender Embossing Hot air (through air) Radiant Heat (or convection ovens) Sonic bonding
COMPOSITES:	

TABLE 2.3 Composites*: Reinforcements and Single Layer Structures

* Paper reinforced by nylon scrim
* Staple-fibre web reinforced by plastic netting
* Staple-fibre web reinforced by spun-bonded web
* Stitch-bonding
* Polyester/wood-pulp operating room fabrics
* Thermal embossed composites such as spun-bonded/melt-blown/spun-bonded

*From Drelich [5].

all the four basic aspects of the nonwoven making processes. This is shown in Table 2.4.

TABLE 2.4*

	Fibres	Web	Binder
Card and bind	Rayon, Polyester	Card	Latex
Thermal-bonded	Rayon, Polyester, Polypropylene, Wood Pulp	Dry Formed Wet Formed, Spun-bonded, Melt-blown	Low melting fibres, powders, bicomponent fibres
Hydroentangled (Spunlace)	Rayon, Cotton Polyester, Wood Pulp	Card. Wet Formed Air Formed, Composite	None; latex (in small amounts)
Needle-punched	Any	Any	Latex
Stitch-through-bonded	Any	Any	None; strength from yarns in structure
Spun-bonded	Polypropylene, Polyester, Nylon	Spun-bonded	Low melting binder fibres
Melt-blown	Polypropylene, Polyethylene, Polyester, Nylon	Melt-blown	Thermal activation
Wet-formed	Wood Pulp, Short-Cut Rayon, Short-Cut Polyester; may include Long Fibres	Wet-formed	Latex, polyvinyl, alcohol, thermal binders
Air-laid-pulp	Wood Pulp, Short or Long Synthetic Fibres	Air-dispersed	Latex, spray and/or embossed
Composites	Any —In variety of combinations—	Any	Any

* Drelich [5]

Further classification of nonwoven fabrics may be made into two groups, e.g. durables and disposables. The examples of the disposable type nonwovens include disposable diapers, sanitary napkins, filters, packaging, medical and surgical supplies. The primary considerations in their use are absorbency and liquid repellency. The semi-durable nonwovens include wiping cloth, pillow covers, and other nonwovens that have to be laundered a few times. In most end-use applications disposable nonwovens have replaced knits, paper or light weight nonwovens.

Durable nonwoven fabrics on the other hand include such materials as interlining and interfacing, automobile interiors, trunk liners, and hood insulators, substrates for vinyl coated upholstery, luggage, furniture, furnishings (mattress covers, under spring covers, draperies, etc.), carpet backing (primary and secondary), blankets, floppy disc covers, wall coverings, garment insulation, fibre-fill (pillows, sleeping bags, etc.), roofing tiles, architectural fabrics, suede-like composite structures, and geotextiles (civil engineering applications).

Table 2.5 [6] shows a partial list of various end-uses of nonwoven fabrics.

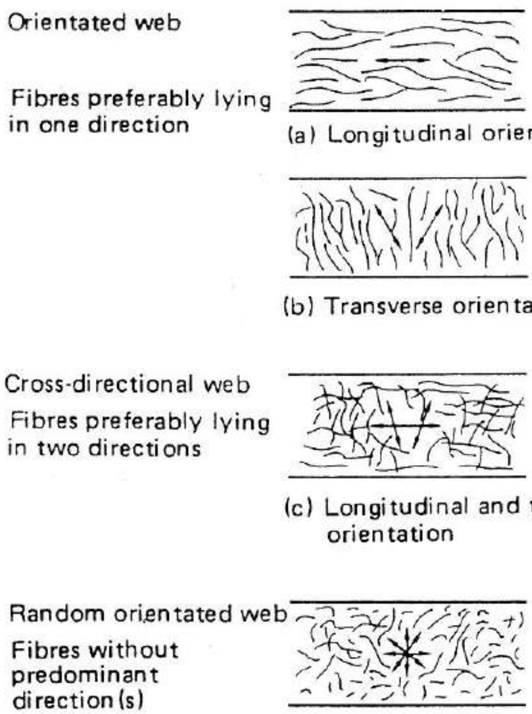
TABLE 2.5 Nonwovens—End-use Applications

1. Abrasive pads, sheets
2. Acoustic ceiling
3. Agricultural covering, seed strips
4. Apparel: industrial, laboratory, cleanroom
5. Apparel: medical, surgical
6. Apparel: outerwear, sportswear, swimwear
7. Aprons
8. Art canvas
9. Automotive headliners, interior trim
10. Upholstery, vinyl roofs, filters
11. Bags: vacuum cleaners, laundry, garment
12. Bandages
13. Battery separators
14. Bedding sheets
15. Pillowcases
16. Bibs: baby, dental, cosmetic, restaurant, saloon
17. Blankets, quilts, quilt covers, bed-spreads
18. Mattress covers
19. Book covers
20. Bra, shoulder pads
21. Caps/wraps: cosmetic, examination
22. Carpet backing/underlayments
23. Casket liners/shrouds
24. Cheese wraps
25. Civil engineering fabrics
26. Coated fabric backings
27. Cubicle privacy curtains
28. Drapes, drapeliners cover stock, facing
29. Drapery, drapery liners
30. Dressing medical
31. Electrical insulation
32. Envelopes, tags, labels
33. Fiberglass boats
34. Filters: air, gas, dust
35. Filters, food
36. Filters, liquid, nonfood
37. Filters, medical
38. Floppy disc liners
39. Geotextiles
40. Gloves/glove liners
41. Headrest covers
42. Impregnated wipes: baby, cosmetic,
43. polishing, dusting
44. Incontinence diapers
45. Incontinence pads
46. Insulation: heat, sound
47. Interlinings/interfacings
48. Ironing board pads
49. Lamp shades
50. Laundry softener sheets
51. Maps, signs, posters
52. Mats: bath, place, door
53. Mattress ticking
54. Medical/surgical: drapes, gowns, packs, masks
55. Shoe covers, caps, slippers
56. Oil absorbents
57. Orthopedic cast padding and covers
58. Overwraps sterile
59. Packaging sterile
60. Packing wraps
61. Pads absorbent
62. Pads scouring
63. Roofing
64. Sanitary napkins
65. Shoe linings, innersoles
66. Sleepwear
67. Synthetic leather
68. Table cloths
69. Tampons
70. Tapes, ribbons
71. Tea, coffee bags
72. Tents, trampolines
73. Towelettes, impregnated
74. Towels, wash clothes
75. Underpads
76. Underwear
77. Upholstery backing, scrims
78. Wall coverings
79. Window shades
80. Wipes—baby medical
81. dusting
82. household
83. industrial
84. Personal, cosmetics

4. WEB MAKING PROCESSES

4.1 Production Technologies: Carding

Krĉma [7] and Lunenschloss and Albrecht [1] have thoroughly discussed the carding technology for producing nonwoven webs. There are numerous other publications, reports, and literature published by the machinery manufacturers describing the equipment and the capabilities of the machinery in producing a desired web. The traditional cards used in the cotton textile industry, though suitable for making webs, have a number of limitations such as fibre orientation, web weight, and productivity. Some of the newer cards do achieve production rates of 50–75 kg/h on a web weight of 7–10 g/m^2. The woollen cards, which are much larger in width than the regular cotton cards, have production rates 5–7 times as high. However, these cards also suffer from preferential fibre orientation. The consequence of such an orientation is that webs usually have longitudinal to transverse strength ratio of 5 : 1 to 15 : 1. In some applications this may not pose any problems; however, in most semi-durable and durable applications it is necessary to achieve strength and elongation, which is practically equal in all possible directions. The latter can only be achieved if the fibres are randomly distributed in the web. Different types of orientations are shown in Fig. 2.4. The geometric anisotropy can be overcome by cross-lapping layers of carded webs. Cross-lapping has two



(a) Longitudinal orientation

(b) Transverse orientation

(c) Longitudinal and transverse orientation

(d) Not orientated

major purposes. First, is to achieve a desired fabric weight, which may vary up to several hundred grams per square meter, and secondly, to achieve random orientation. A modern garnett-modified woollen card and a cross-lapper is shown in Fig. 2.5. Sometimes fibre orientation is not a major concern, but the higher fabric weight is a prerequisite, in which case, webs from

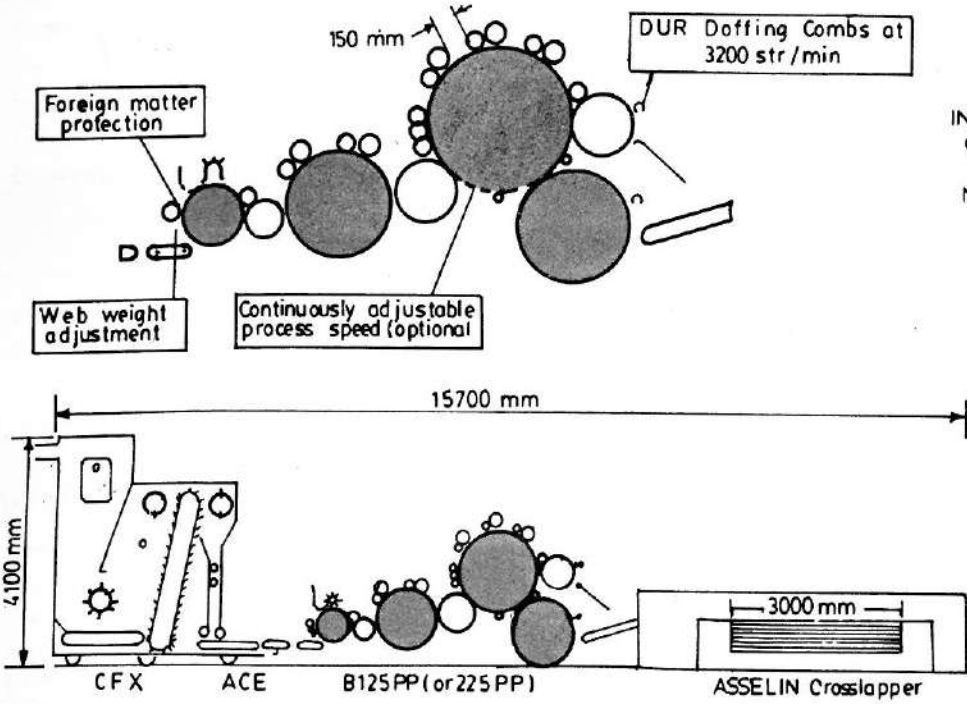


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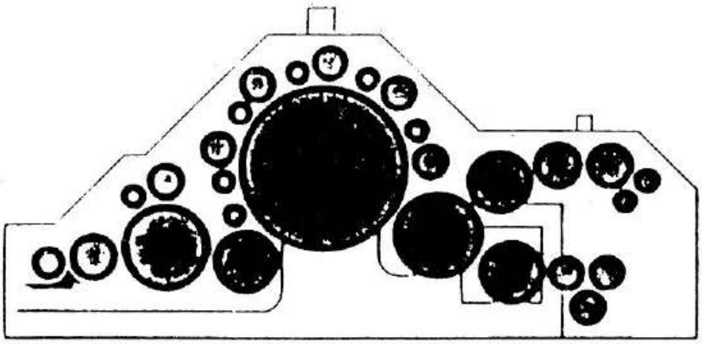
Fig. 2.5 Thibeau nonwoven card type CA6

several cards or web forming machines, as they are now called, are layered in a parallel fashion. Web folders or straight plaiters may be used with cotton cards to produce materials such as surgical waddings and with wool and garnetts to produce paddings and cushion fillers.

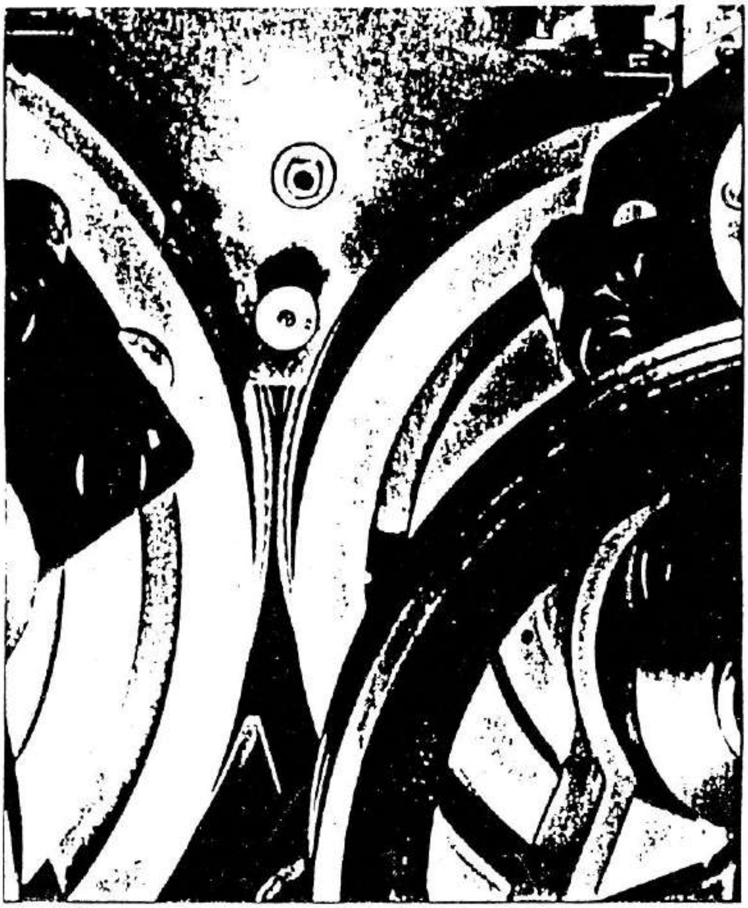
Random fibre orientation in the web is achieved by incorporating randomizing rolls in the card. The random rolls are generally located between the doffing roll and the main cylinder. The configuration, diameter and the position of random roll(s) differs with the garnett manufacturers. In one system (Fig. 2.6) the random roll is arranged between the main cylinder and the doffer. The random roll is run in the direction opposite to the main cylinder; this action combined with the scrambling of the wire clothing, leads to random orientation of the fibres in the web. By varying the speed and the position, fibre orientation varying from highly parallel to highly randomized may be obtained. By using additional scrambler rolls, fibre orientation ratios can be as low as 1.5 : 1 (machine direction to cross direction). The number of card elements will depend on the type of fibre, length, fineness of fibre, and the productivity of the system.

According to Lunenschloss and Albrecht [1] these elements are:

* single or double card with or without a pre-card
* combination of several cards to make a set
* single or double draw-off
* with or without web device, and



Card concept of the nonwoven random card with scrambler rolls above and roll take-off below.



Reorientation of the fibre material in the cross direction and in the third dimension takes place at the point of contact: Main cylinder/ random roll.

Fig. 2.6 Random card concept

* diameter of the cylinder and consequently the number of workers and strippers

The productivity of a card will depend on the web weight to be produced, working width of the card, the delivery speed, and the efficiency, which may be written as follows:

$$P = \frac{M_w \cdot V_L \times W \cdot 60}{10^3} \times E \text{ kg/h}$$

where P = production rate, kg/h
M_w = web weight, g/m^2
V_L = delivery speed of the doffer, m/min^2
W = card width, m
E = efficiency

4.2 Web Spreading and Web Drafting

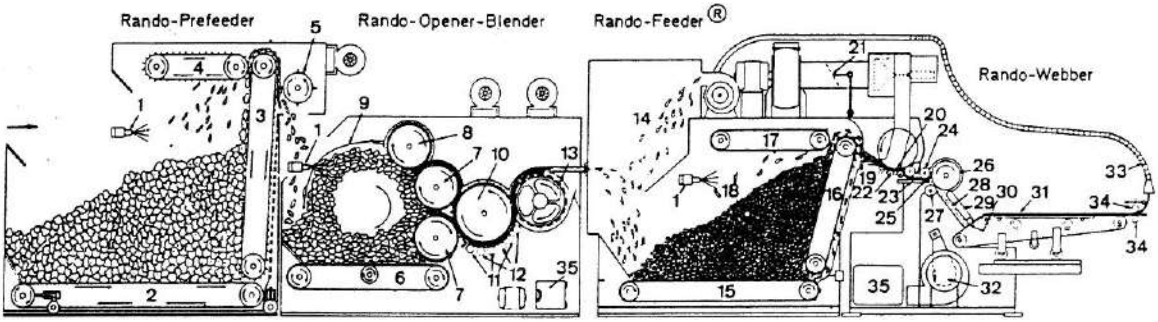
Sometimes it is necessary to vary the fibre orientation, web width, and web regularity when producing light weight nonwovens such as disc liners or diaper liners. In this case, the card web is subjected to controlled stretching or drafting after the web is delivered from the card. This does not alter the productivity but allows the achievement of controlled orientation. The increased web width spreading is accomplished by using modules of bowed rolls of increasing widths, each successive pair of rolls operating at a relatively higher speed. The operation alters the fibre orientation both in the machine and the cross direction. Width increases of 50–250% are not uncommon in some operations.

A typical carding garnetting line for making nonwoven fabrics may have openers, blenders, carding unit, cross-lapper, stretcher and a bonding system. On these systems fibres of 2 to 15 cm (and 1 to 15 denier in fineness) may be processed.

4.3 Aerodynamic Web Formation

The aerodynamic web forming system evolved from the earlier random matt forming machines primarily used for processing hair and mineral fibres. In the processing of hair, the fibres were stripped from the licker-in and were allowed to fall under gravity on a collecting surface. Obviously, this was a slow process and did not produce a uniform compact web. The earlier system of air-laying was developed by the Rando Machine Company, where the opened and blended fibres are fed into a licker-in type opening roll and the fibres are doffed by an air stream created by vacuum drawn through a porous belt or a condenser as shown in Fig. 2.7. The consequence of this arrangement is the randomization of fibre orientation in the matt, as well as the web weight and the thickness that can be made without layering, as is the case in carding. The matt produced by this method (web weight varying from approximately 10 g/m^2 to 2500 g/m^2) may be produced at speeds of up to

12 m/min. In recent years a number of other machines, for example, the Fehrer K-21 (a card/air former) system, has been introduced by the Fehrer Machine Company. The equipment is designed to produce randomly oriented three dimensional web structures from a carded or a crosslaid feed matt. Fehrer also has a Fehrer K-12 Card (single cylinder), where the web is doffed by an air stream thus producing a randomly oriented web. The Fehrer K-21 system can operate at production speeds of 50–150 m/min. The aforementioned systems can process fibres of length up to 10 cm long. For



1. Antistatic spray system
2. Feed table
3. Elevator lattice
4. Stripper
5. Stripping off roller
6. Feed table
7. Opening rollers
8. Stripper comb
9. Guide plate
10. Main opener
11. Worker
12. Worker
13. Doffer
14. Fibre delivery
15. Feed table
16. Elevator lattice
17. Stripper
18. Fibre mass control system
19. Air conduit
20. Perforated cylinder
21. Suction control system
22. Conveyor rollers
23. Feed trough
24. Feed roller
25. Troughed lip
26. Opener
27. Guide roller
28. Air conduit (venturi)
29. Guide plate
30. Condenser
31. Delivery belt
32. Fan
33. Return of selvedge waste
34. Selvedge cutter
35. Waste collector

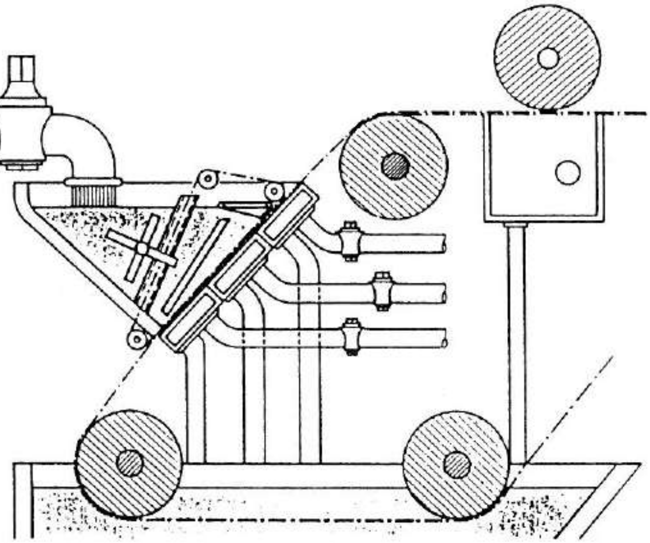
Fig. 2.7 Rando web method of the Rando Machine Corp—Airlaid

very short fibres, (wood/pulp-2 mm) and fibres up to 10 mm a variety of other air forming systems such as Rando, Dan-Webforming and the M&J System are available.

An airlaid nonwoven fabric manufacturing line will have an opening, blending, feeder, web former, and bonding equipment. Most of the lines are equipped with instrumentation to control web weight, web uniformity, and web thickness.

4.4 Wet-laid Nonwovens

The paper making process is perhaps one of the fastest processes to make a fibrous sheet material. It involves, (i) the preparation of a slurry of fibres in a liquid, usually water, (ii) filtering the suspension on a moving screen to make a continuous web, and (iii) drying and bonding of the sheet. The only drawback is the maximum fibre length that can be used in this process. Beyond a fibre length of 30 mm the fibres tend to agglomerate thus producing an uneven dispersion. For the purpose of making wet-laid nonwovens, the 'wet web machine' is a modified version of the paper making equipment. The two most commonly used machines are based on the inclined wire design of Hydroformer machine and cylinder type rotary former of the Sandy Hill Machine Company, as shown in Fig. 2.8. The nonwovens made by this process



Web formation from restrained back fibre suspension (USA Patent no. 11394 (1948)).

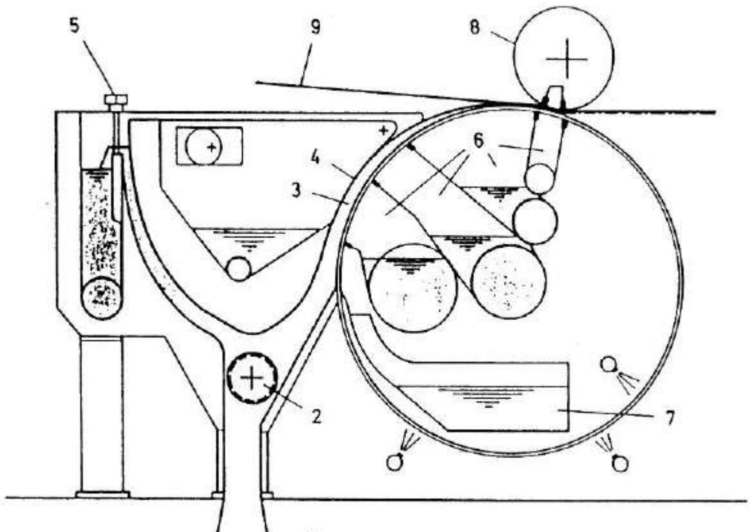


Diagram of a rotary former (Rotoformer: Sandy Hill). (1)

1. Distributor
2. Dispersing roller
3. Web forming sieve
4. Adjustable front wall
5. Adjustable over-flow
6. Suction box
7. Screen water collecting bath
8. Suction or draw-off roller
9. Deliver belt

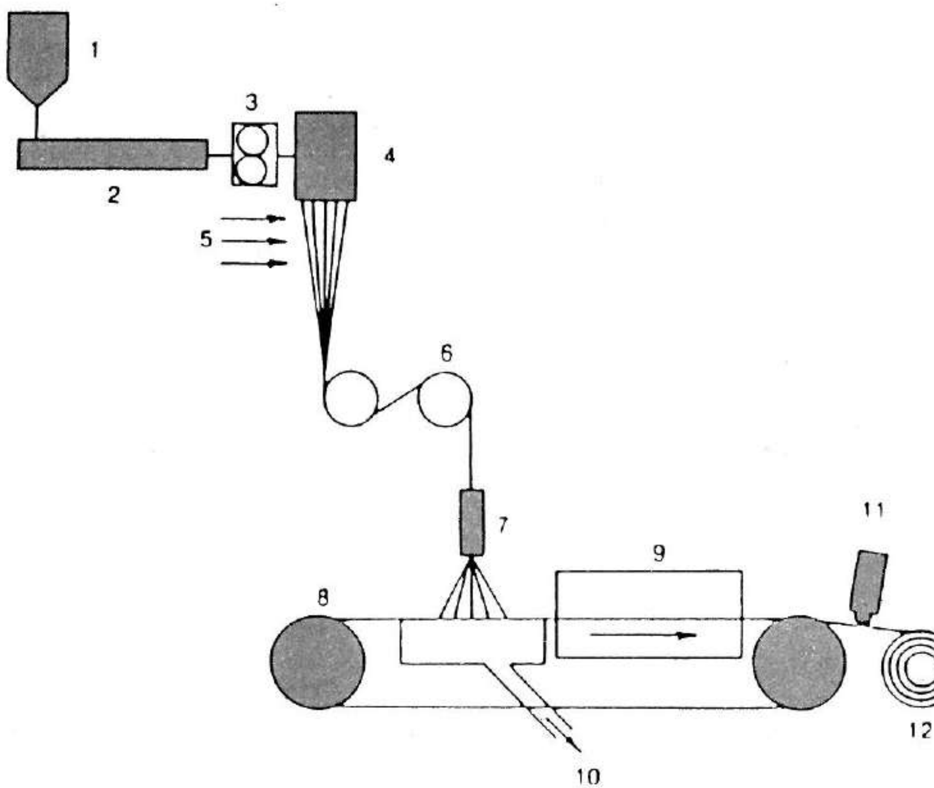
Fig. 2.8 Wet-laid systems

are used for a variety of end-uses, e.g. filter papers, water-proofing sheets, tea bags, table cloths, face cloths, surgical clothing, battery separator, shoe uppers, insulation, gaskets (seals) and interlinings to name a few.

The wet-laid nonwoven line requires a very large investment, perhaps as much as ten times the cost of a carding line, but the productivity is very high. Small installations are relatively less economical.

4.5 Spun-bonded and Melt-blown

The spun-bonding and melt-blowing processes of manufacturing nonwoven have been the fastest growing systems for the past fifteen years, each showing a growth rate of 10-15% per year. Ever since the commercial production of polyester (Reemay®), polypropylene (Typar®) and polyethylene (Tyvek®) spun-bonds by du Pont, in the early sixties, numerous companies have entered the production of spun-bonded fabrics. The spun-bonding process avoids the process of first converting melt-spun filaments into staple and then carding and bonding them to form fabrics. The process is shown in Fig. 2.9, where



1. Feed Hopper
2. Extruder
3. Gear Pump
4. Spinneret
5. Cooling Air
6. Draw Roll
7. Air Gun
8. Porous Belt
9. Bonding Oven
10. Vacuum Exhaust
11. Fabric Inspection
12. Wind Up

Fig. 2.9 Typical spunding line

the polymer is extruded through a spinneret and sometimes is drawn by rollers, crimped, and then passed through an air gun (aspirator jet) before being spread on a conveyor belt. To keep the filaments on the conveyor belt a vacuum is pulled through the porous belt. The web thus formed can then be bonded either thermally, by needle punching, by application of latex, or by any other desired system. Sometimes two streams of extruded filaments, one that has a lower melting point than the other, are mixed to achieve thermal bonding. The most commonly used polymers are the thermoplastic type such a polyesters, polypropylene and polyamides.

Tyvek®, which is a trademark of du Pont, is produced by exploding the polymer (polyethylene) that is dissolved in a solvent and flash freezing the fibrillated polymer on a collecting screen. The process produces a fabric with very fine fibres and the fabrics are bonded by heat. The fabric thus produced is primarily used in protective clothing, packaging, labelling and filtration.

The spun-bonded fabrics are used in a variety of applications, but the bulk of the fabrics are used in diaper linings, civil engineering (geotextiles), and carpet backing applications. Other major uses include: furniture, filtration, bedding, roofing, apparel, medical, packaging, agriculture, coating substrate, electronics, and interlinings. The most commonly used polymer is polypropylene.

The melt-blown process (Fig. 2.10) is a variation of the spun-bonding process. Here the highly fluid (very low viscosity) polymer as it comes out of a die (slit die with holes, 25–30 holes per inch) is carried away by hot air (temperature of blowing air is same as the die temperature) thus attenuating the filaments as they solidify. The solidified filaments are collected on a surface to form a web. The filaments are extremely fine (varying in fineness

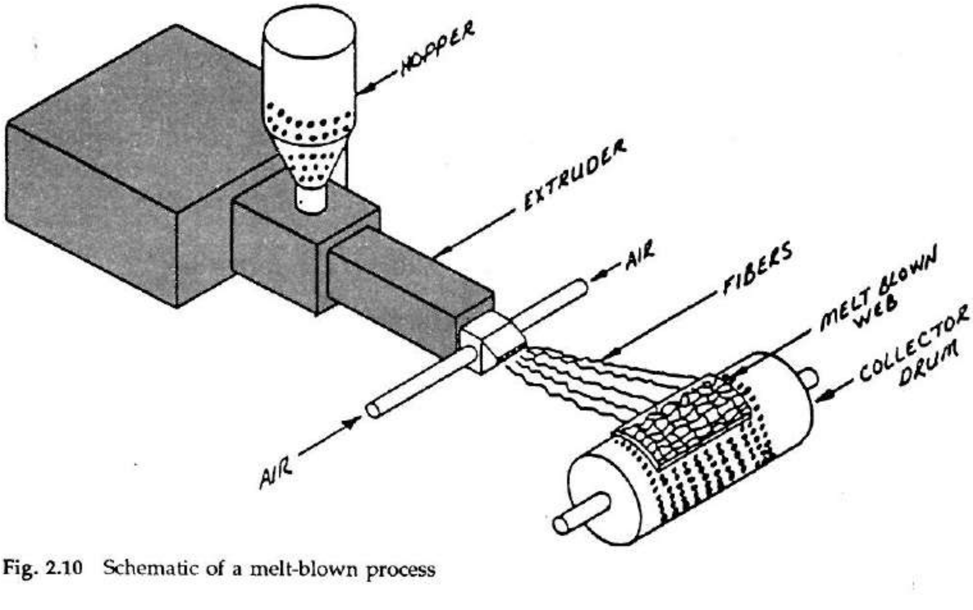


Fig. 2.10 Schematic of a melt-blown process

from 1 micron to 10 microns) and the matt thus formed lacks strength. It is therefore combined with other types of nonwovens, to attain structural integrity and strength in the end product. Because of the fineness of the filament, the fabric has extremely good filtration and insulation characteristics. It also has very large surface area and has the ability to retain large quantities of fluids such as oil. The melt-blown fabrics are used in surgical masks, dust and particle filters, thermal insulation, and cleaning up of oil spills.

A new system of making a composite of spun-bond/melt-blown/spun-bond has been developed and is gaining wide-spread use.

4.6 Bonding

Nonwoven webs, whether made from staple fibre by the dry process or from filaments, lack structural integrity. The only exception is paper made from wood pulp, where hydrogen bonding holds the fibres together. Consequently, the fibres have to be held together either by entangling them or by incorporating a bonding agent such as a resin, solvent, or a polymer melt. Besides the characteristics of the fibre (length, fineness, crimp, fibre surface, cross-sectional shape, etc.), the method of web making, the bonding type has a great influence on the mechanical (strength, elongation, recovery from deformation, stiffness, tear, etc.) and the physical properties (handle, drape, abrasion, softness, bulk, surface characteristics, etc.) of the product. There have been a number of developments in the technology of bonding. All these technologies, singly and in combination, have given versatile tools in the hands of industry to tailor-make a product to meet the end-use requirements. These bonding techniques and the various end-uses of the products made by the process are discussed in the following sections.

4.7 Chemical Bonding

As the name implies, the bonding between fibres is accomplished by adding chemical substances, either in a latex, plastic dispersion, polymer emulsion, or a solvent. Most commonly used bonding agents are in polymer dispersions (emulsion in winter). Some of the polymers can be in the powder and paste forms.

The types of polymers that are used in dispersion forms are:

- synthetic rubbers, such as butadiene polymers
- acrylic acid polymers, such as acrylates, and
- vinyl polymers and copolymers (vinyl chloride, vinyl acetate, vinyl ethers and vinyl esters)

Other materials include polyurethanes and silicon compounds.

The chemical and physical properties of the polymer dispersions, such as particle size, pH, solid content, viscosity, and the degree of cross-linking have a significant influence on the mechanical and physical properties of fabrics. Carded or garnetted resin-bonded fabrics form the largest single group of nonwoven fabrics produced in the world.

The resin in the emulsion form may be applied by any of the following application techniques:

* saturation bonding
* spray bonding
* print bonding
* foam bonding
* knife-over-roll coating

One of the greatest advantages the resin binders have over other binder types is the cost. They are inexpensive and because of the various methods by which they can be applied, nonwovens with very wide range of properties can be produced. However, they are being challenged by the thermal bonding process, due to a number of considerations. The most important of these are, (i) no aqueous discharge, (ii) no atmospheric emissions, (iii) less energy use, (iv) higher production rates, and (v) better physical characteristics.

The resin-bonded nonwovens are on the decline. The largest end-use areas for the resin-bonded-staple-fibre nonwovens are cover stock, interlinings, wipers, and fabric softener substrates. Most of these are being slowly replaced by the thermally bonded nonwovens.

4.8 Thermal Bonding

Thermal bonding, as the name implies, is accomplished by the use of heat. It is used in conjunction with adhesives that melt, such as thermoplastic polymers. In recent years the development of different types of bonding polymers and the precision bonding equipment has placed this technology in the forefront of binder technologies. The thermal bonding agent may be incorporated in the web (made from any type of fibre either in the powder or fibre form, or it may be applied in the melt form. The amount of the binder may be varied to produce a variety of physical characteristics. Sometimes a web made from a thermoplastic fibre may be bonded by the application of heat and pressure without any additional binder. Heat sensitive fibres (usually made from polymer that melts at a lower temperature than the bulk of the base fibres may be blended with the base fibres in quantities ranging from 5–50% during carding, air-laying, or spun-bonding process. The web then may be passed through hot columnars (smooth or one smooth and the other engraved for print bonding), hot air oven, infrared heater, or an ultrasonic machine to activate the binder. Thermal bonding techniques can be used to bond fibres other than thermoplastic such as rayon blended with polypropylene or any other binder fibre given in Table 2.6. Polypropylene is effective when used in 100% form but sometimes bi-component fibres of polypropylene core/polyethylene sheath have been used.

Hot air bonding (Fig. 2.11) is used for producing high loft fabrics, but to achieve higher strength in these types of fabrics, the amount of binder fibre has to be relatively high. The high amount of thermally sensitive low melting

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TABLE 2.6 Fibre Types and Methods Developed for Thermal Bonding

POLYMERIC FIBRES

* Polyester Copolymers: PET, PCT and Modified PCT Crystalline and Non-crystalline; Binder Fibres (Melt at Low Temperature-Blended with Matrix Fibres); Self Bonding Melting Point in Mid-range
* Polypropylene and Modified Polypropylene
* Polyethylene
* Nylon Copolymers
* Bicomponent; Homo and Heterogenous Polymers

CORE: SKIN

PP-PET; PE-PET; Nylon 66-Nylon 6;
PP-PE; PET-PET-PET-PET copolymer
(In Fibre, Powders and Melt forms)

BONDING PROCESS

Melting (Binder)/Non-Melting(Matrix) Fibre Blends

* Heat without Pressure (Through Air or Oven)
* Calender (Heat with Pressure)
* Embossing Roll (Heat with Discreet Pressure Points)

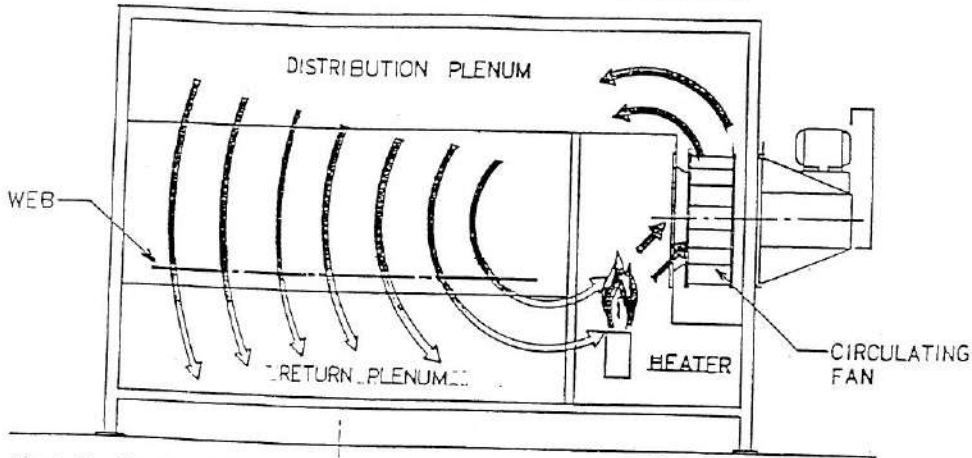

Fig. 2.11 Thru-circulation conveyor oven cross-section

fibres makes the fabric stiff and have low extensibility. On the other hand, print bonding, either by hot columnar rolls or by the ultrasonic technique (Figs. 2.12a and 2.12b) produces a fabric that has high loft and flexibility but is relatively weak. The bond created by the raised portion in the engraved roll, has a morphology that is different from the base fibre. In addition, the interface at the bond and the web develop high crystallinity, and consequently, brittleness that produces a web with lower elongation.

In thermal bonding, fibres are used most commonly, but the use of granules and powders is becoming increasingly important. A product made from wood pulp is bonded by incorporating olefin-based granules in the pulp and then

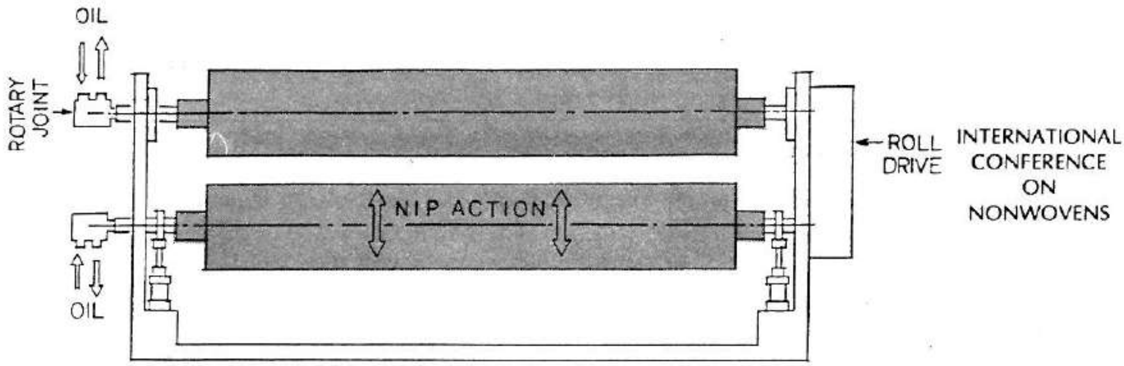

Fig. 2.12 (a) Two roll calender

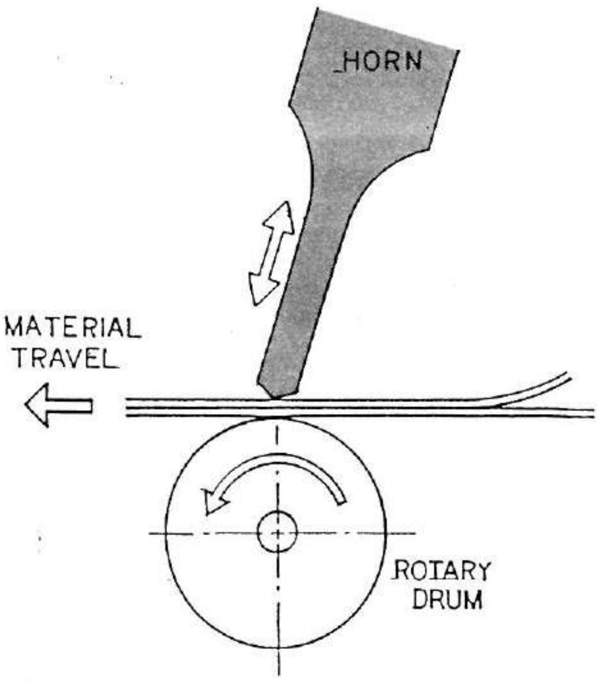

Fig. 2.12 (b) Ultrasonic bonding

heating the web under pressure to produce a bonded synthetic wood. Powders made from low melting polyesters are also being used in the industry.

The use of bicomponent-thermoplastic fibres has also been increasing lately. These fibres can be of the sheath/core or side-by-side type polymer. The outer sheath polymer has a lower melting point, while the inner core polymer has a high melting point. Fabrics made from 100% bicomponent fibres may be bonded through air bonding in the absence of pressure or may be bonded by the embossing or ultrasonic bonding technique. Fabric made in this manner are soft and lofty and can be highly bonded which makes them tough and firm. Table 2.7 lists the techniques of bonding thermally bonded fabrics.

TABLE 2.7* **Thermobonded Nonwovens**

Type of Web Forming	Weight Range	Application	Bonding Method
Carded or aerodynamic	Light-weight webs (disposables) 18–25 g/m^2	Cover stock, medical and sanitary webs	Calender, combination air flow principle/ calender, air flow principle (bicomponent fibres and blends)
Spun-bonded	Light-weight webs (disposables) 18–25 g/m^2	Cover stock, medical and sanitary webs	Calender
Carded or aerodynamic	25–150 g/m^2	Interlinings	Calender, straight-through air-flow treatment
Carded or aerodynamic	100–1000 g/m^2	Filtration webs, high-loft webs or needled webs	Straight-through air-flow treatment
Carded or aerodynamic and spun-bonded	80–400 g/m^2	Geotextiles	Straight-through air-flow treatment, special stretching frame with air jetting
Spun-bonded	150–200 g/m^2	Carpet backing	Straight-through air-flow treatment
Carded or aerodynamic	80–2000 g/m^2	Industrial textiles, coating substrates, protective material +insulating material, decorative webs, nonwoven covers (furniture industry), webs for upholstery industry, nonwoven wall coverings	Straight-through air-flow treatment
Carded or aerodynamic	80–2000 g/m^2	Padding material fibre fill webs	Straight-through air-flow treatment
Carded or aerodynamic	100–250 g/m^2	Wiping cloths	Straight-through air-flow treatment
Carded or aerodynamic	80–3000 g/m^2	Waste-fibre webs for various applications	Straight-through air-flow treatment
Carded or aerodynamic	300–800 g/m^2	Needle-punched carpets	Straight-through air-flow treatment
Carded or aerodynamic	150–350 g/m^2	Roofing felts	Heat-setting with straight-through air-flow treatment
Web forming machine	20–200 g/m^2	Light-weight webs, decorative webs, tea bag paper	Straight-through air-flow treatment
Dry-laid paper	25–150 g/m^2	Wiping cloths, technical products, medical and sanitary webs	Straight-through air-flow treatment

*Reference [11]

Diaper cover stock made from polypropylene, thermally-bonded-carded-web forms the largest use in this category. Other end-uses include feminine hygiene products and adult incontinence pads.

One of the most important developments has been the use of thermally sensitive polymeric nonwovens in moldable products to create a final shape, e.g. trunk liners, face masks, and headliners. Most of these products utilize composites of nonwovens with other nonwovens or other types of textiles.

4.9 Mechanical Bonding

There are basically two major technologies that can be categorized under this heading. These are: (i) Needle punching, and (ii) Hydroentanglement. Even though needle punching and hydroentanglement (making of felts from wool and hand-made paper) are old technologies, it is only recently that these two technologies have really caught the imagination of manufacturers and users. The refinement of these technologies has been in response to the stiff and tacky products produced by the resin bonding system, which dominated the earlier developments in the nonwoven field.

Needle punching technology, where a batt of fibres is subjected to the action of barbed needles penetrating through the thickness of the web, the barbs carry bundles of fibres which retain their entanglement in the web when the needles are withdrawn as shown in Fig. 2.13.

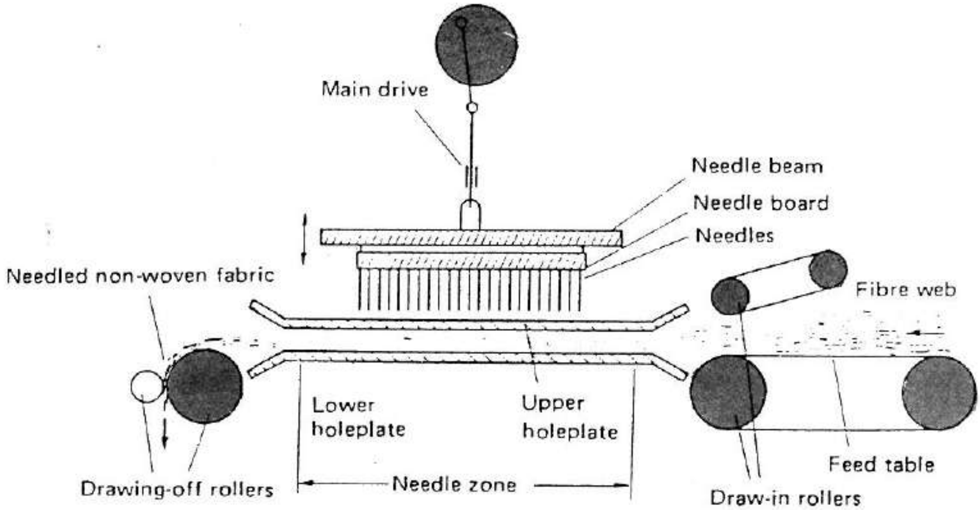

Fig. 2.13 Diagrammatic illustration of needling

The basic operations of the needle punching have not changed; however, there have been tremendous improvements in the mechanical design of the loom and the needles [8]. The speeds of the loom have increased to nearly 2500 strokes per minute at linear production speeds of 1–10 m/min. The needle design has allowed the processing of high modulus, high tenacity fibres such as ceramic, carbon, aramids, and glass without causing undue damage. The structuring capabilities of the needling machines has allowed the nonwoven manufacturers to enter the floor covering market successfully. Needle punched fabrics, where the porosity, fibre characteristics, and chemical nature of the layers can by controlled through the thickness of the fabric, have become increasingly important in the filtration industry. Other areas include needle punched batts for the composite industry and the wall covering end-use application. Needle-punched fabrics are also used as substrates for coating. Scrim-bonded-needled fabrics are an important segment of the needle punched fabric market. Blankets and other durable nonwovens are usually made by this technology.

An important consideration in the use of needle-punched fabrics is their flexibility with relatively sufficient strength and high elongation. They can also be produced with a good control on the porosity and permeability of the structures. A large quantity of geotextiles made from spun-bonded fabrics are needle punched, which imparts structural integrity and at the same time allowing the fabric to be permeable to liquids. Other end-uses include the shoe uppers and inners, padding, insulation, roofing tiles, interlining, furniture, abrasive and polishing pads, glove linings, lubricating and diaper pads, noise absorbent and office partition panels.

4.10 Hydroentangled Fabrics

The 'Spunlace' technology developed by du Pont, where a nonwoven web is impinged by very fine jets of water at high pressure, up to 250 bars, thereby whirling the fibres that results in their entanglement. Because the only bonding that is achieved between the fibres is due to the entanglement of the fibres, the fabric thus produced is highly flexible and has a supple hand. Precursor webs, made by either carding, wet laying, spun-bonding, whether from one type or blends of fibres including wood pulp, may be used. One system employed commercially is shown in Fig. 2.14.

Spunlaced fabrics are alternately called water-jet-entangled, hydroentangled or hydraulically-needled nonwovens [9]. The spunlace or hydroentanglement process involves the following elements:

* Fibre
* Web forming
* Water jets
* Needling substrate
* Water system
* Drying
* Finishing

Fibre

The choice of fibre will have a great effect on the productivity, amount of entanglement, and final product characteristics. In general, fibres with low bending modulus entangle more easily than fibres with high bending modulus. Thus, cotton and rayon entangle with much less energy input than does

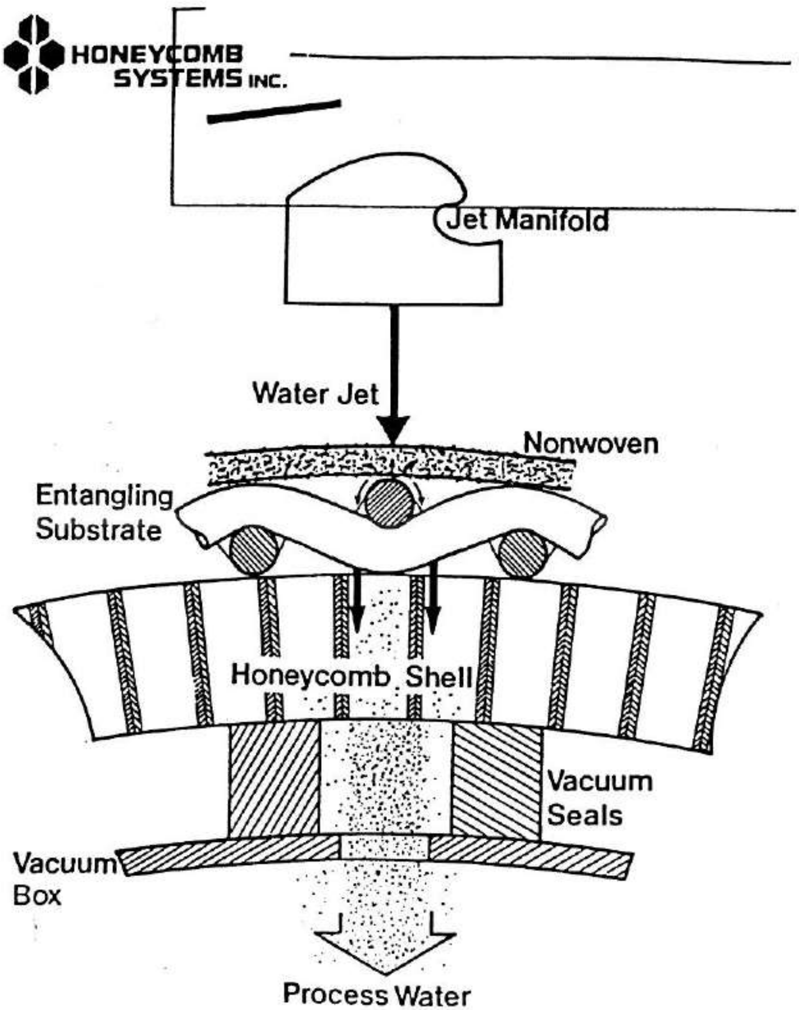

Fig. 2.14 Honeycomb process

polyester. Since the fibre cross-section affects bending modulus, fibres of the same polymer type with a ribbon cross-section entangle more easily than trilobal fibres. The temperature of the high pressure water is generally kept as high as possible because warm water reduces bending modulus and increases entanglement. Bending modulus also decreases as the filament size (denier) is decreased.

The number of tie points or entangled areas is directly proportional to the number of fibre ends present in the web; therefore, short fibres will produce more tie points than long fibres. However, fabric strength is also directly proportional to fibre length, and a balance between fibre ends for more tie points and fibre length for increased fabric strength is necessary. For polyester, a fibre length of slightly less than 1 inch (1.8 to 2.4 cm) seems to be the best.

Wood pulp fibres are short and create many tie points but are not long enough to provide fabric strength.

Web Forming

Both dry and wet laid systems are employed to prepare precursor webs for spunlace processes. When cards are used to prepare the web, the final product has much higher machine direction strength than cross direction strength. These nonisotropic products are acceptable for some of the spunlace market; however, when balanced MD/CD properties are required, they are not acceptable. The two major producers, Chicopee and du Pont, have developed proprietary high speed air-lay systems that produce isotropic webs. These products have MD/CD ratios of as low as 1.2 to 1.5 as produced on the spunlace machine. More recently, wet-laid processes have been used to prepare the webs. These systems have the capability of producing very uniform webs with balanced MD/CD properties.

Water Jets

The objective of the high pressure water system is to create fine, high velocity columnar streams of water. Small holes are placed in a jet strip in one or two rows with a density of 10 to 20 per cm. The holes range in diameter from 0.08 mm to 0.25 mm but usually are either 0.12 or 0.18 mm. The holes are highly finished to smooth surfaces and produce columnar jet streams. Small imperfections in a hole will cause the jet stream to break up and be less efficient. The jets are placed as close to the web as possible to assure that the jet streams do not break up and dissipate their energy. The usual jet to substrate or screen distance is 2 inches (50 mm) or less. Special care must be taken in designing the manifold or water distributing system to assure that each hole is supplied with adequate water with minimum turbulence.

Each jet strip is placed perpendicular to the direction of web travel with as many as ten strips in series making up an entanglement station. Water pressure is increased step-wise from the first to the last jets. Occasionally, the last jet will have lower pressure to provide for improved surface integrity. Two types of substrate configurations are used in spunlace production: a travelling screen or belt and a rotating drum fitted with a perforated cover. Under some conditions, the drum entangling units give higher entangling efficiency, better machine efficiency, and longer life than belt units. Vacuum is applied underneath the needling substrate to remove water. If sufficient water is not removed, the excess absorbs some of the energy provided by the water jets and reduces entangling efficiency. Entangling can be achieved with a single needling station, or multiple stations can be employed. Also, a fabric may be needled on only one side, or both sides may be needled.

Needling Substrate

Needling substrates play an important role in hydraulic entanglement. In addition to holding the web in place, substrates are designed to increase needling efficiency and to create either non-patterned or patterned products.

Joining the belt, screen, or drum sleeve together in the right length is a particularly complicated process. Substrates can be constructed to produce virtually any design desired. However, with the moving belt or screen systems, patterns are limited by the physical constraints of that system. A drum sleeve is much more versatile because very coarse screens and metal plates can be used as substrates.

Water System

The high pressure water system requires a large amount of water that has a nearly neutral pH, contains almost no particulate matter, is low in metallic ions such as Ca, is at a prescribed temperature, and contains no bacteria or other organic materials. Because of the large amounts used, water must be filtered and reused. This requires a complicated and efficient water filtration system. Depending on the raw materials, a combination of the following filtration processes are employed: air/water separators, bag filters, settling ponds or clarifiers, precoat-filters, cartridge filters, and deionization units. In addition, at some point, bacteria and other organic organisms must be eliminated. Centrifugal pumps have been installed on virtually all of the large commercial installations. Reciprocating pumps are often used in small laboratory or prototype units. For a typical high pressure system, pressure at the pump is usually maintained at approximately 150 bar. At the needling station, this pressure is reduced for individual jets where pressures range from 15 to 150 bar.

Drying

Thorough air and drum drying are used in spunlace operations. For 100% fibre products, the fabric is not affected by the drying method. For wood pulp/polyester products, thorough air drying will produce a softer, loftier product than drum drying.

Finishing

Although most nonwovens are considered finished when they are rolled up at the end of the production line, many receive some other chemical or physical treatment to provide special characteristics. Some of these treatments can be applied during production, while other must be applied in separate finishing operations. Examples of finishing treatments are as follows:

- Flame retardant
- Rewet agents
- Hydrophobic agents
- Coloration
- Printing
- Antistat agents
- Bonding
- Stretching

Spunlace vs. Card and Bind Nonwovens

Strengths:
* Soft
* Strong
* High absorbent, instant wetting
* Low linting
* Wash durable
* Great pattern flexibility
* Chemically pure
* Fabric like

4.11 Stitch-bonded Nonwovens

The technology of production of nonwoven fabrics based on web stitching with fibre strands taken from the web to be reinforced is called stitch-bonding. Stitch-bonding technique may be described by the two basic concepts of the Arachne and Malimo stitch-bonding machines, where either fibre web base or yarn base are used. Figure 2.15 shows the principles of the two stitch-bonding systems [10].

The Arachne version was built mainly for delivering cross-lapped, loose

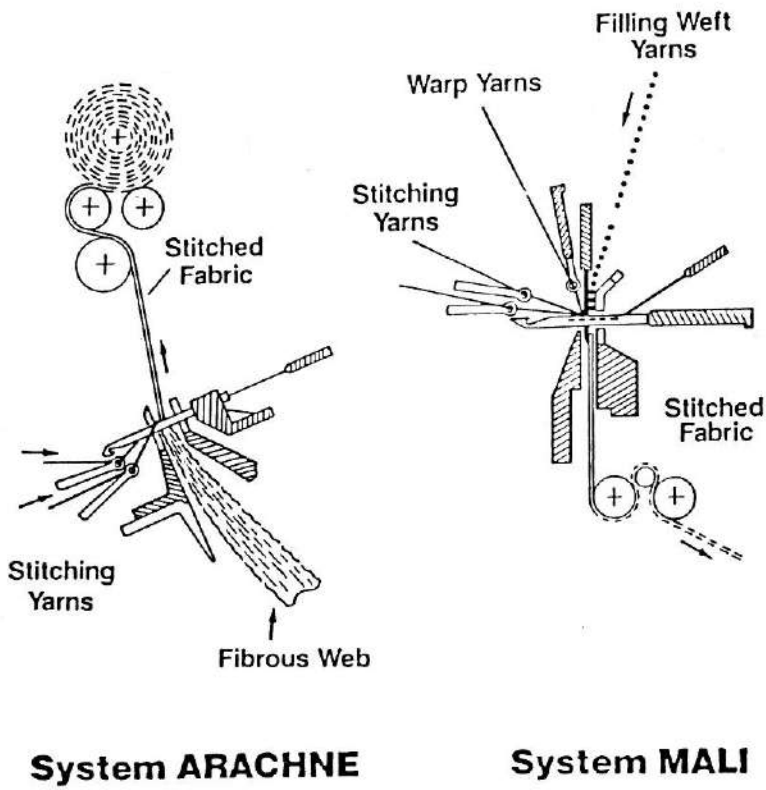

Fig. 2.15 Stitch-bonded fabric forming elements

fibre web into the stitching area. The basic concept of the position of needles and take-off system was designed accordingly to bring the fibres on the supporting aprons to close proximity of the needle penetrating area. The first functional model was equipped with two lapping bars for future exploration of the advantages of a two-bar knit structure which is much more versatile for parallel development, structural patterns and better control of the required properties of fabric.

The Arachne stitching needle was derived from a high speed tricot knitting machine, FNF, and provides a pointed head for penetration through the fibrous web. It is a compound needle with a closed hollow shank inside of which the closing wire slides in exact coordinated movement to overlap the hook when the yarn inserted into the hook is pulled through the layer of fibres and converted into the stitch loop.

The Malimo version begins in the arrangement shown except for the second lapping bar which was added into this version sometime in 1973. The original concept was built for feeding and filling weft yarns by way of chain with carrier hooks to the stitching area. Stitching needles are arranged in a horizontal plane with the open side of the hooks facing up and the take-off system under the machine. The single bar lapping movement was derived from the sewing machine drive, e.g., a two-way crank. The Malimo machine uses needles with open groove and knee profile closing wires sliding in the open needle groove. In addition, the basic shape of needle point is different.

The stitch-bonding functional stroke of stitching needles occurs in one revolution of the needle bar drive system which makes one stitch forming cycle. Each stitch cycle consists of the following phases:

Penetration :	A needle passing through the subjected layers of material to their maximum penetration position.
Lapping :	The stitching yarns are inserted onto the open needle hook.
Closing :	Laid-in yarn is closed inside the needle hook by latch just before and during the return stroke of needles through the stitched base layers.
Knocking-over :	Pulling the yarn through the old, previously formed loop which is sliding on the needle shank between the knock-over comb and back side of stitched layers.
Take-off:	Formation of new loop, row of stitches, by pulling the stitched section of fabric out of the needles penetrating line for a distance which determines the stitch length (stitch density).

The stitch-bonding process uses standard types of elementary warp-knitting lapping structures. This can be used as a single bar structure with one lapping bar or in mutual combinations with the use of two bars.

5. MARKETS AND END-USES

Nonwovens are being used in numerous end-use applications. A partial list of end-uses is given in Table 2.5 [6]. Some remarkable aspects of the nonwoven structures are the varieties and the range of structural properties, i.e., strength, elongation, stiffness, bulk, permeability, moisture, vapour and liquid absorption, chemical resistance and others which can be achieved by manipulation in various manufacturing processes. Consequently, nonwoven fabrics have established themselves in certain end-uses, such as in baby diapers, feminine hygiene products, and other disposable materials (these account for nearly 60% of the North American market), apparels, garments, home furnishings, geotextiles, interlinings/interfacings, wipes/cleaning, building and construction. However, there are other areas such as filtration, electrical/electronic, gaskets/seals, various industrial abrasives, substrates, automotives, roofing, battery separators, food packaging and agricultural end-uses, where the growth in the next few years is supposed to keep up a healthy rate of 6–8% annually. The reason for such optimism is the availability of newer types of fibres, optimization of the emerging processes such as hydroentanglement, spun-bond/melt-blown/spun-bond, and the needs of the specific industries which have made the nonwovens extremely useful materials. The following is a brief description of the areas where the nonwovens will find their expanded use in the near future.

5.1 Filtration

This is an extremely important segment for the application of nonwoven materials. Filtration can be divided into two main categories: (a) wet, and (b) dry. Besides geometric integrity, the basic properties required in filter fabrics are permeability, particle retention, and capacity.

Nonwoven fabrics used in wet filtration include those made by both the paper making process and the dry process. Tea bags and coffee filters and coolant filters form the two largest segments in this area. Other significant markets include; milk and dairy product filters, edible oil, drinking water, paper-maker felts, support and drainage fabrics, industrial cartridges, automotive air, oil, and fuel filters, and microfibre membrane filters. Some of these markets were served by woven fabrics, others are relatively newer end-uses.

In dry filtration end-uses, the major applications are in the area of large particulate filtration; dust filtration in power plants, foundries, cement, flour, and industrial; as face masks in the work place, such as coal-fired boilers, incinerators, clean rooms; filters for removing toxic materials, smoke, intake filters for internal combustion engines, air compressor filters, pharmaceutical industry and as bags in industrial and household vacuum cleaners.

One development that has enhanced the filtration efficiencies of fabrics is the treatment of fibres, especially the melt-blown by electrostatic charge, the fibres thus charged are called 'electrets.'

Both needle-punched and spun-bonded fabrics have found extensive uses in dry, as well as, in wet filtration. The structure of the fabrics can be engineered to provide suitable permeability.

The filtration end-use market for nonwovens amounted to $ 250 million in 1991 and is supposed to increase to $ 300 million by the year 1995.

5.2 Nonwovens in the Electrical Industry

Nonwoven fabrics have been used in the electrical and the electronic industry as high temperature insulation materials. These fabrics have been made by the wet laying techniques. However, the development of laminates and composites from combinations of different types of nonwovens and melt-blown fabrics in combination with other strengthening components, offer an attractive alternative. Polyester fibre mats have been used in the production of solid cast coils and vacuum pressure impregnated coils. High temperature nonwoven composites are being used in dry transformers. In some electrical applications, (e.g. an electrical appliance) nonwovens are used as a flame barrier or heat barrier. Other end-uses include motor slot insulators, buss fuses, substrates for printed circuit boards or electrical grade tapes (fibres such as glass, Nomex and polyester are used in such applications).

Cable wrapping tapes for binding, separation, water blocking, heat barriers or partial conductors made from nonwoven fabrics have been used in the industry. Besides these applications, the nonwoven fabric wrapping tapes may be used as diffusion barriers and protectors from environmental and electrical degradation. Because of the high flexibility, non-frying, non-creasing, and highly porous nature of the nonwoven tapes, they are preferred over inexpensive woven or paper tapes and plastic films. The use of nonwoven fabrics has prompted the development of water-swellable tapes for use in protecting the telecommunication cables from water damage. This is accomplished by coating and bonding the water-swellable powder in-between two layers of nonwoven tapes. The swellable coating blocks the water from reaching the cable.

The nonwoven fabrics for use in cable wrappings are generally made from synthetic fibres that are non-biodegradable, non-hygroscopic, non-wicking, anti-mildew, rot-resistant, have high thermal resistance and possess good ageing characteristics. For such applications, the candidate materials generally used are polyester and polyacrylonitrile fibres, and the bonding agents are usually polyacrylates. There is a tremendous scope in further development of nonwoven cable wrappings primarily due to the stringent standard requirements in the cable construction and cable life cycle.

5.3 Battery Separators

Battery separators as insulators in lead acid automotive batteries are traditionally made from PVC or resin-impregnated cellulosic and glass fibre mats. However, a newer development has been the use of an envelope made from microporous PE and synthetic fibrous material. In recombinant batteries (a special class), an absorbent glass fibre mat is used. The function of the separators is to provide electrical insulation between each cell and as a mechanical spacer holding the plates in position to retain the active mass in contact with the grid. Consequently, the separator should be porous, wettable to allow the acid and ionic flow (permeable), and must be resistant to acid and oxidative degradation. In addition, it should be strong enough to withstand the rough handling and vibrations during the life cycle of the batteries. The new improved separators made from thinner webs and low weight have allowed the design flexibility in developing batteries for newer car models. This development has allowed automation, and the use of enveloping separators will further help in the automation of battery plants in the manufacturing of batteries around the world.

5.4 Automotive Industry

Nonwovens have found extensive use in the automotive industry over the past two decades, and it is still continuing to grow. Nonwovens have replaced some traditional textiles; and, in some cases, new end-uses have been found where there were none before. Nonwovens are currently being used as primary and secondary carpet backings for floor and trim fabric for the passenger compartments and trunks, in seat construction, and as sound insulation pads under the hood and carpets. They are being used as structural reinforcements for headliners, interior door panel reinforcement, hood liners, and as exterior body panel reinforcements. There is a further scope for growth as the demands for low cost, high performance, lower weight constructions become inevitable.

5.5 Roofing Fabric

The built-up roofing material is traditionally made from alternating layers of cardboard-like-paper products as reinforcement, and coal tar or asphalt used as a water-proofing material. Since the early development, roofing materials have gone through a number of changes, vis-a-vis, the use of asbestos and organic plied systems (with disastrous results). However, the glass-fibre mat and the polyester-spun-bonded fabrics have proven quite successful, providing lighter weight roof decks and the ability to withstand mechanical and thermal stresses. Freudenberg holds numerous patents on high-performance-built-up, high-performance-roof-membrane constructions made from polyester-spun-bonded fabrics that do not require pre-saturation with asphalt, which was the case with earlier reinforcement. Sometimes the polyester or fibreglass nonwoven fabric reinforcement is saturated and then coated with a modified polymer asphalt to form a roll-roofing membrane. Such materials may be heat welded in place with an open torch, or mopped in place with hot asphalt to form strong yet flexible roofing. The pliability elastomeric-roof membrane derives its properties from a combination of the characteristics of the modified bitumen and polyester fibre (nonwoven) reinforcement. In the North American market, polyester spun-bonded fabrics accounted for 60 million square yards in 1990.

5.6 Agricultural Applications

Until recently, the carrots, potatoes, sweet corn, and lettuce growers have been using either perforated or non-perforated clear plastic films for protecting their crops. However, since 1983–84 thermally bonded light-weight polypropylene-spun-bonded fabrics, have been used, which provide strength, but are also translucent, allowing sunlight to pass through. They provide high permeability to light and water; consequently, can be used for early cropping and extended cropping without sacrificing quality. Because of the light weight (coupled with strength), the spun-bonded fabrics do not impede plant growth and do not cause damage to the plant due to abrasion, as is usually the case with polyethylene films. Fabric weights of 15–20 g/m^2 to 250 g/m^2 are commonly used in agriculture and horticulture.

5.7 Health Care Products

The health care industry has been one of the greatest beneficiaries of the innovations in the development of nonwoven fabrics over the past two decades. In the medical-surgical area, the use of disposable isolation and barrier gowns, isolation and splash resistant masks, sterilization wraps, shoe covers, towels, wash-cloth, drapes and other materials is commonplace. The next challenge to the industry will be to provide fabrics and garments to the end-user which will meet the day-to-day needs for protection for health-care workers, as dictated by Health and Safety agencies. This is especially true in the case of hazards against the HIV virus. There is a tremendous scope for growth in uses of nonwovens in protective clothing and sterilization products.

6. CONCLUSION

The foregoing is a brief description of the various processes used in the manufacture of nonwoven fabrics. It is obvious that the process of manufacture determines the functional, the end-use application, and the performance of the fabrics. Fibres, i.e. the polymer type, in the making of nonwovens for a specific end-use cannot be ignored.

There is a tremendous growth potential in spite of the inroads made by nonwovens (in some areas as high as 15–20% growth rate of some nonwoven products) in the 90's. Nonwovens have been slowly replacing wovens and knits in some cases, and in others, creating new markets that have mushroomed to the extent that the total value of nonwovens amounts to nearly $17 billion around the world.

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3

Cotton: The Most Important Fibre in the World How it is Best Used in Nonwovens

DUNCAN RHODES

The world statistics on the consumption of various fibres shows that cotton accounts for more than 46% of all textile fibres used. The properties of cotton that make it outstanding across the whole textile spectrum are exactly those which make it particularly suitable for nonwovens, such as absorbency, vapour permeability, handle, wicking, crimp retention, biodegradability, low electrostatic build up, good cover and opacity.

The paper brings out the strong points of cotton and its suitability for the manufacturing of nonwoven fabrics.

1. WHY COTTON

To start with a totally uncontroversial statement is often difficult. However, when talking about cotton it is fortunately very easy.

COTTON IS THE MOST IMPORTANT TEXTILE FIBRE IN THE WORLD

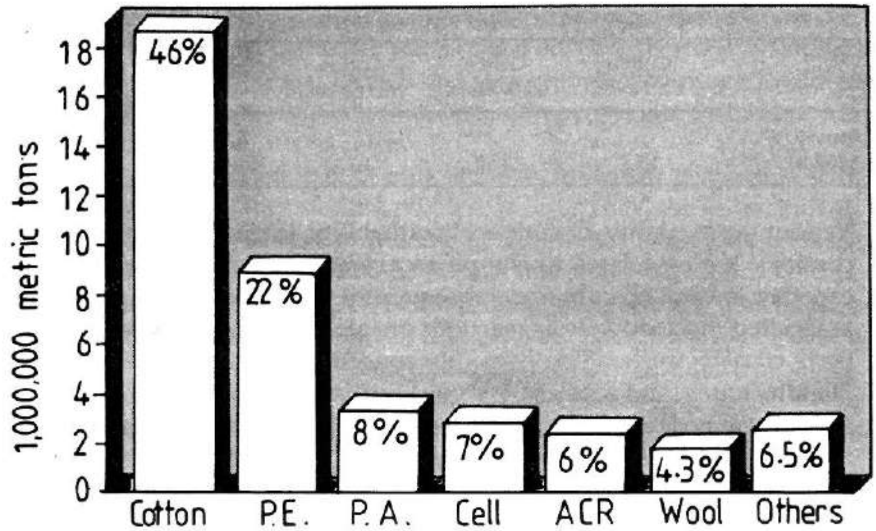
If we examine data published by Textile Organon we see cotton was 46% of all textile fibres used in 1990 (see Fig. 3.1).

Thus consumer preference for and acceptance of cotton, can clearly be seen from these dramatic statistics.

1.1 Cotton as a World Leader

Cotton is important to the world economy because of the sheer scale of its growth and manufacture as can be seen in Table 3.1.

* In some 80 countries, employing some 200 million people, (and deliberately excluding China from this figure), cotton is grown harvested and converted.
* Cotton has been and will continue to be invaluable in the economies of underdeveloped countries.



INTERNATIONAL CONFERENCE ON NONWOVENS

Fig. 3.1

TABLE 3.1

Year	1984	1985	1986	1987	1988	1989	1990
Cotton consumption in 1,000 metric tons	15528	16619	17181	18243	18484	18733	18714
Annual % increase	3.3	7.0	3.4	6.7	1.4	1.4	0.1
Average annual increase:	3.4%						

* ✶ As an annually renewable non-perishable cash crop it can transform the lifestyle of complete regions.
* ✶ As a natural fibre it does not diminish world energy sources in its production.
* ✶ By-products from fibre production in the form of cotton seed account for more than 10% of the worlds edible oil sources.

1.2 Cotton cannot be Matched

The properties of cotton that make it outstanding across the whole textile spectrum are exactly those which make it particularly suitable for nonwovens.

A textile fibre is not likely to survive on the basis of a single property, except in specific applications where that one property is all-important. Thus, a well-balanced set of physical and chemical properties broaden the range of a fibre's potential end-uses and longterm commercial viability.

Cotton has achieved its dominance for exactly this reason. Its properties are broad-based in the range of advantages over other fibres. The most important properties of cotton are described below:

* ✶ Absorbency of liquids, which is not only related to surface chemistry, of fibres, but also considerably influenced by the gross and fine morphology of fibres. Table 3.2 illustrates the comparative absorbency of cotton, standard rayon, and wood-pulp.

TABLE 3.2

	Cotton no Finish	Cotton 0.2% Finish	Cotton Mercerized	Standard Rayon	Wood-pulp
Absorbency g/g ASTM 1117-80	25.7	27.0	31.1	20.5	18.2

* Vapour permeability or comfort breathability, is clearly related to user comfort. It also relates to the physical make-up of the fibre and its capacity to both absorb, and subsequently release, water vapour. The associated thermodynamic reactions are also important in maintaining body comfort in changing humidity conditions.
* Handle, touch, and softness, (properties that cannot be assessed in any one test method) are influenced not only by the stress/strain and flexural rigidity properties of the fibre (both dry and wet) but also by the extremely fine fibrillar surface structure. This property, together with absorption capacity, is also responsible for the ability of the cotton fibre to wipe dry.
* Wipe dry and wicking: the cotton fibre is unsurpassed in this ability. These are the same properties that apply in apparel comfort, when body fluids are moved away from the body before the skin begins to feel damp or wet.
* Good cover and opacity result from the fine fibrillar surface structure and the resultant actual surface area deduced from fibre diameter, and is the result of the outer layers of fibrils, which overlay one another.
* Strength: the stress/strain curves indicated in Fig. 3.2 show that cotton

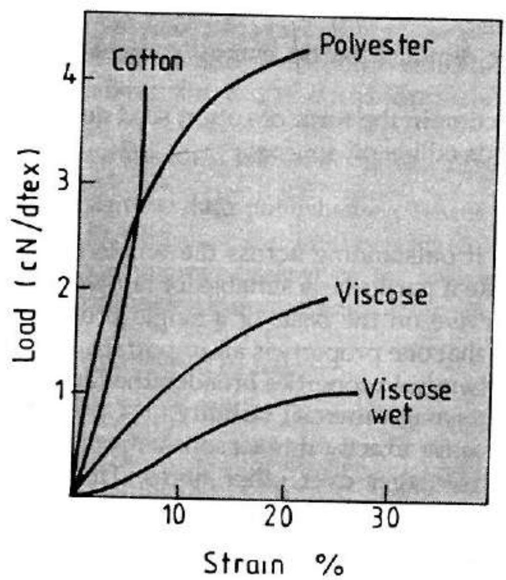


Fig. 3.2

is very similar to standard polyester and stronger than standard viscose in the dry state. In the wet state, cotton not only increases in strength but also retains a pleasant touch and softness when compared with viscose.

* Wet bulk and crimp retention are both properties that result from the high wet modulus of cotton.
* Density is related to both bulk and opacity/cover properties. Although the density of the cellulose polymer is 1.54 g/cm^3, the actual bulk density of dry cotton fibre is only 1.268 g/cm^3. In the wet, fully swollen state, the density drops to 0.85 g/cm^3. In this state, the total non-fibre void volume represents 44.8% of the total swollen volume. The implications of absorption and water holding capacity are obvious.
* Biodegradability allows cotton to be used in disposable products with complete confidence.
* Sterilisable by heat (with less discoloration than viscose), by ethylene oxide, or by gamma radiation.
* Low electrostatic build-up propensity: this property is becoming increasingly important in regard to safety aspects in medical applications, and cotton thus requires no special after-treatment and remains unaffected by repeated washing.
* Chemical structure: the amorphous regions of cotton can be penetrated by special finishes in aqueous medium, and their reactivity with the hydroxyl groups of the cellulose chain enables the application of treatments such as antimicrobial finishes.

1.3 Why the Consumer Demands Cotton

From 5,000 BC to present day space technology, cotton has continuously been the preferred user friendly fibre. The track record of this marketing achievement in being *No. 1 for 7,000 years* cannot be ignored.

It reflects the customers satisfaction with, or rather insistence on cotton in all areas where comfort, handle and reliability are important.

Applications where skin contact is important such as underwear, bed linen and towels have for centuries chosen cotton as unsurpassable. Newer areas of application, such as wet wipes and make-up removal pads are equally sensitive to consumer demand in favour of cotton.

In a recent US consumer survey of personal care products the user was asked:

(i) *What did they think the product was made of?*
They were given four options to select from;
Rayon
Cotton
Polyester
Polypropylene

(ii) *What they preferred the product to be made of?*

Except for swabs, puffs or balls, most women do not know what the products they used were made of (see Fig. 3.3). Few feminine hygiene products, wet and baby wipes contain cotton. Today, disposable diapers rarely contain cotton. Yet, among those who thought they knew, cotton was most frequently mentioned as the content for each category. This suggests the desire for these products to be made of cotton.

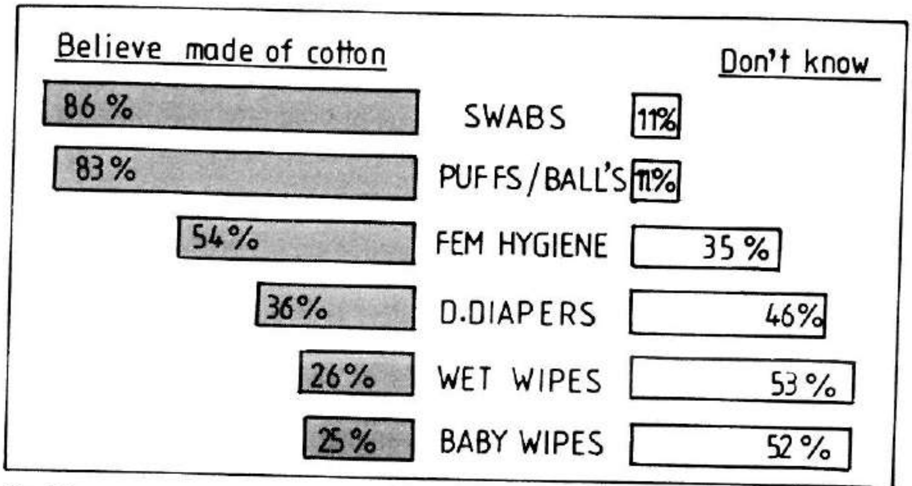


Fig. 3.3

The belief that these personal care products were made from any of the other materials was low.

Cotton is preferred overwhelmingly for each personal care product. Cotton is the dominant choice for cosmetic puffs or balls, and for swabs, with 8 out of 10 selecting cotton for these products (see Fig. 3.4). Preference is so strong for cotton than for other products that the next leading material was selected by only 5% of the women surveyed.

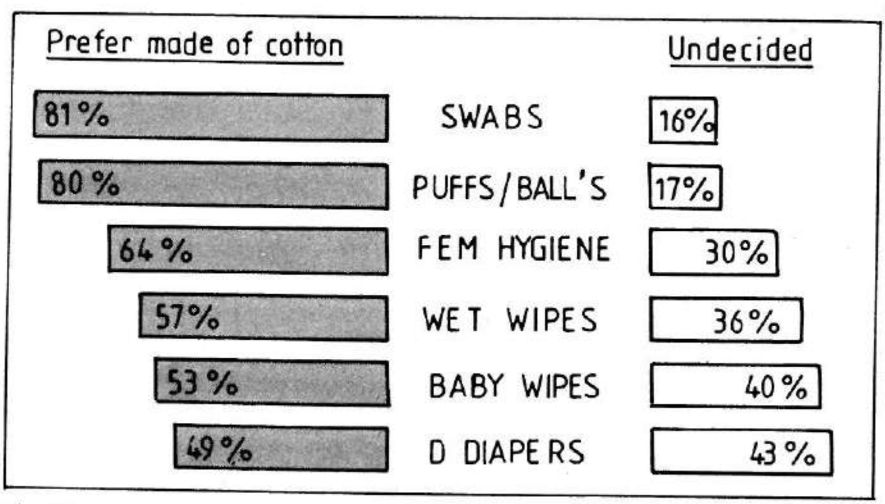


Fig. 3.4

The public prefers cotton because the consumer is comfortable with its softness, absorbency, naturalness, and purity.

These preferences for cotton are increasingly demanded by the consumer. Furthermore, the consumers increasing awareness of the environmental issues begs such questions as:

- How much total energy goes to produce the fibre?
- What harmful effluents, liquids or gases, result from the production of the fibre?
- What is the replacement cycle of the cotton plant, (which, in some cases, is harvested twice a year) compared with timber?
- How can the product be disposed of, is it biodegradable?

2. WHAT COTTON

Cotton fibres are an excellent example of how easily processable natural fibres have been and still are since they were first used.

The natural waxes and fats which act as lubricants are uniquely suitable for the carding and spinning of grey fibre. However, to enable the nonwovens manufacturer to process cotton by his preferred short process route it is first necessary to remove the waxes and fats by scouring the fibre and then the pectins to optimise whiteness by bleaching with hydrogen peroxide.

The conventional kiering operation wherein the cotton is boiled in sodium hydroxide under pressure to remove the waxes and fats, followed by the bleaching cycle in hydrogen peroxide results in considerable mechanical agitation of the fibre, which in turn results in fibre twisting and entanglement.

LUXICOT®, is the trademark for continuously bleached cotton as processed and supplied by Edward Hall Limited.

This system of fibre cleaning and bleaching results in a fibre which is outstanding in openess, good whiteness, uniformity of treatment, and uniformity of lubricant added back to the fibre.

It should be noted that in undoing the natural conditions of the 'grey' fibre as provided by nature, bleaching results in a fibre which is virtually unprocessable because of its high fibre to fibre frictional properties. Thus the selection of the correct type and uniform application of the right amount of lubricant to ensure satisfactory processing by the nonwovens manufacturer are critical. Furthermore the type and amount of lubricant can also be fundamental in respect of the fibre's ultimate end-use. Thus, not only is it essential to select the right lubricant be it for say carding, air-laying, etc. but also the system of bonding, be it hydro-entanglement or thermal-bonding is very relevant to that selection. In the same way the lubricant chosen for a lofty resilient product would be entirely different from that selected for a dense compact product wherein high fibre cohesion would be important.

Typical examples of differing friction curves which are effected by changes of lubricant type illustrate (Fig. 3.5) how product suitability for differing end uses can be engineered into the fibre.

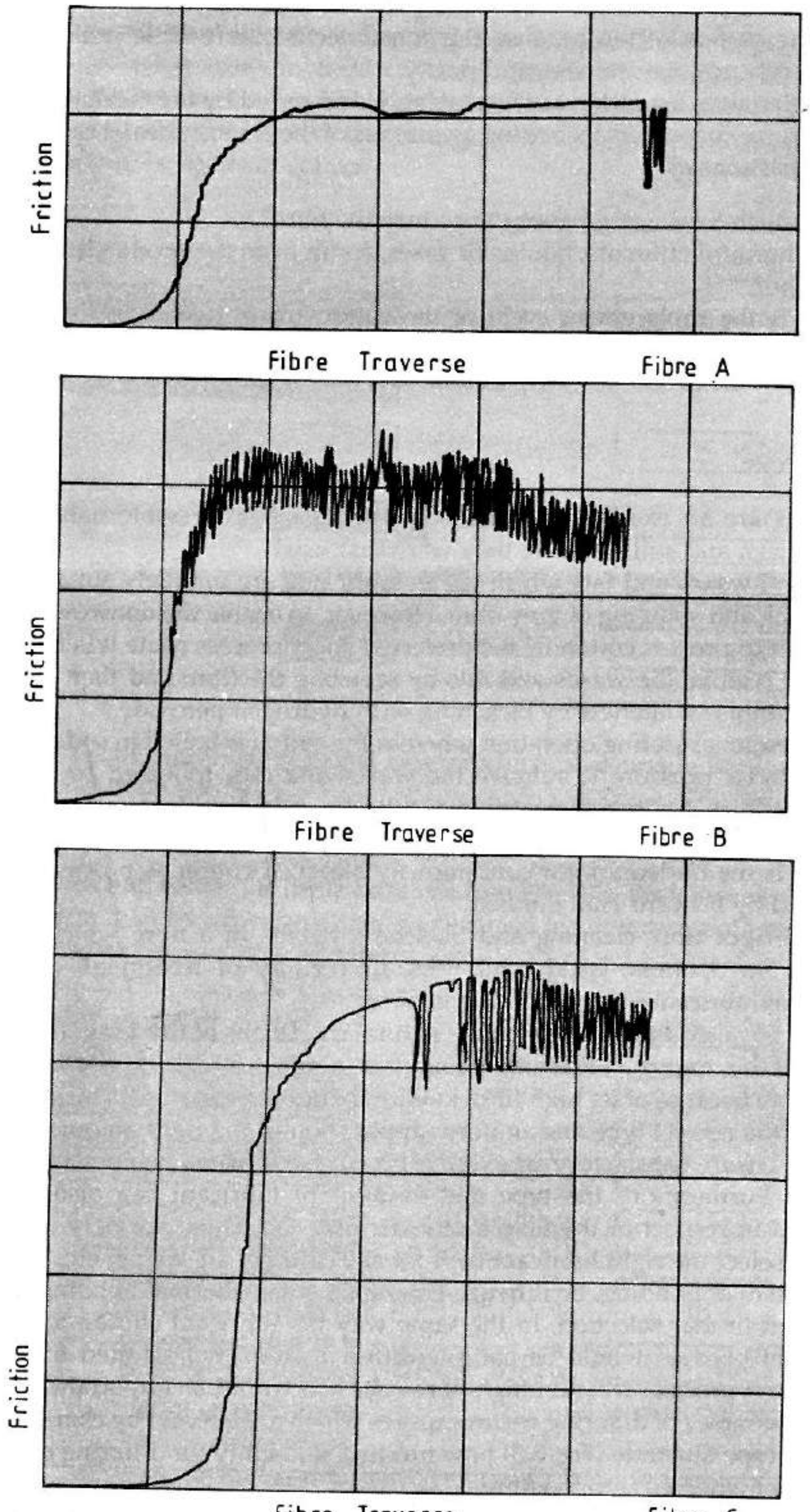

Friction
Fibre Traverse
Fibre A
Friction
Fibre Traverse
Fibre B
Friction
Fibre Traverse
Fibre C

Fig. 3.5

Because cotton is a natural fibre, of course, it is of variable staple length and this property together with fibre diameter, is routinely and accurately measured to enable blend selection using the Uster AFIS instrument which is proving itself invaluable in short fibre % determination (Fig. 3.6).

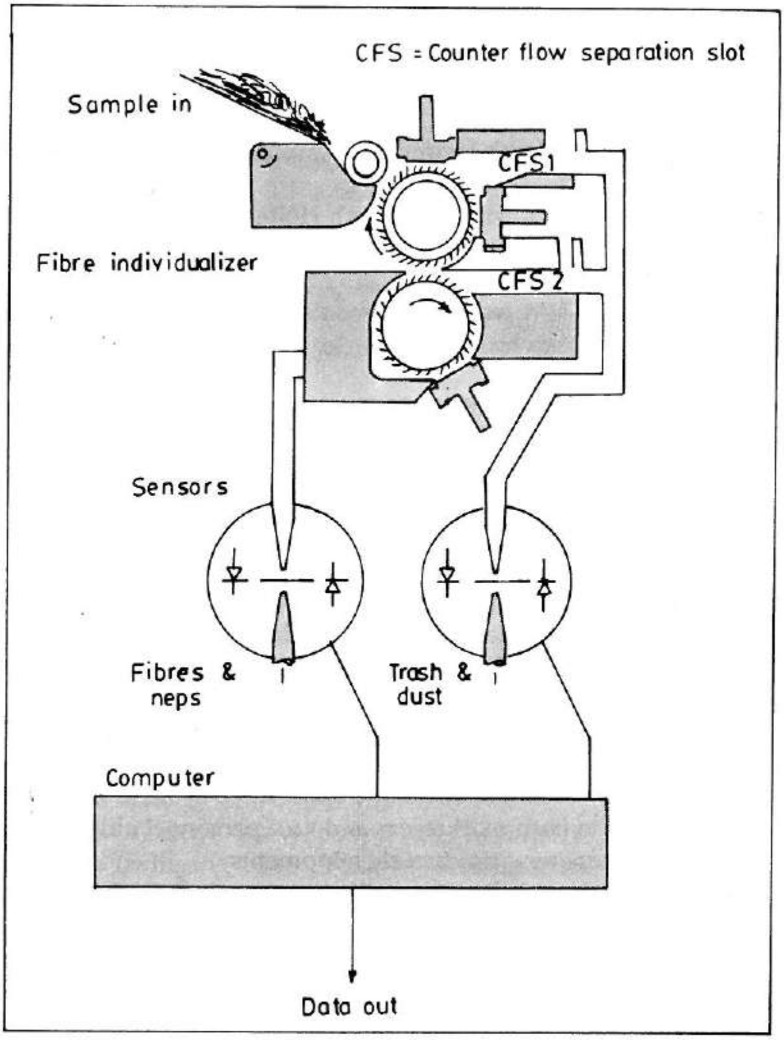


Fig. 3.6

Control can thus be effected, not only of purchased raw materials and production control of cleaning/opening machines, but also the delivered bleached final products to the customer.

This information together with all the routine testing which accompanies the supply of medical/surgical grade fibres should clearly show the importance which has to be attached to quality and reliability in the cotton fibres LUXICOT® which we supply.

The types of cotton fibre used in nonwovens manufacture vary from virgin raw cotton with an average staple length of say 22 mm, to comber noils of say 12mm average and even to first cut linters of say 9–10 mm average length.

The system of nonwoven manufacture and the end-use of the final fabric largely dictate the choice of fibre to be used.

3. HOW COTTON

Alongside the development of LUXICOT®, Edward Hall have simultaneously evaluated both specific carding/web forming systems and different bonding systems.

To this end fabrics have been made on Hergeth Hollingsworth F.O.R., and Spinnbau nonwoven cards to produce webs of varying blends for thermal bonding on Kuster and Ramisch calenders.

Similarly fabrics using air-laid webs have been made on Curlator Rando Fehrer K21, and Spinnbau Turbolofter to produce webs for spun-lacing on Perfojet machinery.

In the web weight range of 20–100 gsm excellent web quality and very high degrees of isotropy in the final product can be achieved. It is certainly our opinion that in spun-laced products the future, in terms of product range versatility and product quality, are very much dependent upon high class air laid web forming systems.

The results of this work have further reinforced our knowledge and expertise of the inter-relationship of LUXICOT® cotton fibre, its lubricant, the processing conditions in both web forming and bonding, and finally the final product properties and suitability for end-use applications.

In this way Edward Hall feel well placed to assist and short circuit development programmes for customers who wish to consider the use of cotton in their nonwoven product range. The ability to handle and test fabrics made using LUXICOT® via both thermal-bond and spun-laced systems has been found to be of great value to both marketeers and R&D personnel alike in the early stages of our customers new product developments.

We are confident of our ability to engineer LUXICOT® to suit both processability and the required final product properties, and so help nonwoven manufacturers who are often reluctant to process cotton on equipment which may not have been originally designed for the specific task of handling bleached cotton.

The main criteria for handling any fibre is the ability to open the fibre easily from the state as received in bale and to have the correct moisture level both in the fibre and in the processing area.

Since LUXICOT® is not only presented virtually completely open it is very easy to handle in bale breaking and blending operations, thereby ensuring optimum web forming conditions in carding/air-laying.

Specific points which should be remembered are:

IN THERMAL-BONDED PRODUCTS CONTAINING COTTON

(i) For fabrics in the range of say 20–70 gsm to achieve calendar bonded products of adequate strength the thermal-bond portion of the blend should be at least 65% of the total fibre content and is more commonly 70% thermoplastic fibre and 30% cotton.

Under these conditions the need for very good fibre presentation to blending and very good blending of the opened fibres is an essential element.

(ii) In through-bonded products of course the cotton proportion of the blend can be increased to as high as 90% along with 10% thermoplastic fibre. The final loft and strength properties are the dictating criteria in blend selection.

IN SPUN-LACED/HYDRO-ENTANGLED PRODUCTS

Cotton has, as has been seen, a unique surface structure. For this reason cotton is an ideal fibre to enable very good inter-fibre locking and cohesion to take place. Thus for even relatively low energies very strong fabrics can result.

The fibre finish is physically removed by the high energy of entanglement and thus the final properties and desired handle of the ultimate nonwoven will dictate what type and level of finish should be re-applied to the fabric, if any.

Because of the length and length variability of cotton fibre one note of caution should be added. This relates to the filtration of the circulating water used for the entanglement. In terms of ease of water handling/filtration the list polyester, viscose, cotton, pulp indicates the order of increasing difficulty of filtration.

The importance of original design specification together with the manufacturer of spun-lace equipment, be it Perfojet or Honeycomb system as regards full range of intended fibres and fabric types is fundamental.

However, since many people are commercially producing spun-laced products including pulp it can be seen that the problem is certainly not insurmountable.

AFTER-TREATMENT OF FABRICS

The receptivity of cotton nonwovens to finishes of all types allows for printing, water repellancy, flame retardancy, fungicides, and bactericides, etc. to be added to the fabric prior to, or immediately after drying, before fabric conversion.

4. CONCLUSIONS

- Cotton is not the most important fibre in the world without good reason.
- The ability to exploit this stature is being recognised by marketeers who are alive to the consumer perceptions of using a cotton branding mark.

- Technology via the availability of LUXICOT® now allows the manufacturer to provide nonwoven fabrics for the marketeer to enhance both added value in sales and at the same time what we all seek, added profitability.

Edward Hall Limited
ENGLAND

4

Thermobonding Nonwovens: Methods and Application Possibilities

M. SEGLIAS

The aim of the first part of this presentation is to demonstrate the suitability of various thermobondable polymeric feedstocks with an engraved calender, for interlinings, cover stock and other substrate applications.

The second part addresses to the solvent-free bonding of nonwovens with the thermofusion-system by using fusible fibres.

It has been shown why some feedstocks are eminently suited for certain end-uses and why others fail.

1. FEEDSTOCK

1.1 Feedstock Selection and Analytical Determination

Following the principle why look far afield when the best is immediately at hand, feedstock sourcing was concentrated within the EMS company. A list of the feedstocks investigated is given in Table 4.1.

TABLE 4.1 Product Coding Key

Source	Type	Code
Grilene	EP 403	TB PES
Grilene	EP 413	TB CoPES 1
Grilene	EP 412	TB CoPES 2
Competitor		TB CoPES 3
Grilon	M 25	TB PA6
Grilene	EP 410	PES 1
Grilene	F 3	PES 2
Grilon	MC-1	PA 6 siliconized
Competitor	Biko K/M (bicomponent core/sheath)	PP/PE

Two interesting competitors' products have, nevertheless, been included in the study as well. The coding key of the product description contains five special thermobond fibres, three mixed-component fibres and a bicomponent fibre.

1.2 Performance and Analysis of Experiments

The longitudinally oriented nonwovens were produced at the EMS-Chemie AG, AWT-TF+K technical centre under a well-defined trial program utilizing specified processing conditions. In order to adapt to the most frequently used interlining, cover stock and substrate end products, a nonwoven weight of 25 g/m^2 was selected. The upper calender roll selected is engraved in a rhombic-shaped standard pattern offering a 19% contact area.

In order to keep the research effort within reasonable limits, the research team relied upon many years of practical experience for the selection of the thermobonding temperatures and calender roll pressures. The selected line speed during manufacture of all nonwovens was 40 m/min. The products produced are typical for the type of machinery used.

First, however, let's take an interesting look at the processing of four different feedstocks. The working window in Fig. 4.1.

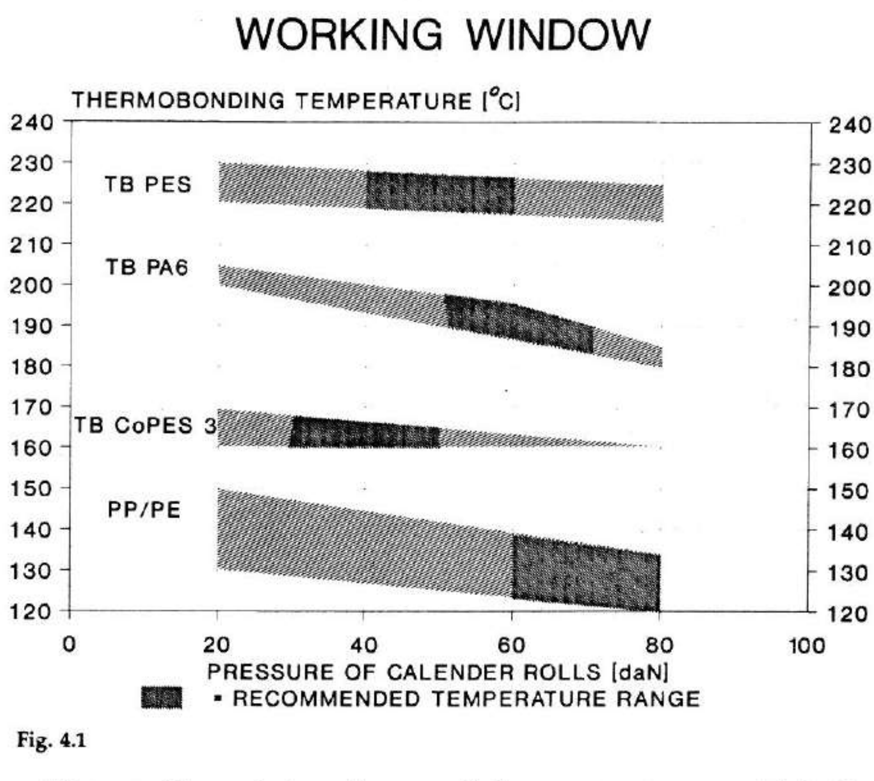


Fig. 4.1

The working window is one of the most controversial indices in thermobonding. The behaviour of four typical thermobondable feedstocks is demonstrated as a function of temperature. The areas plotted indicate the possible working window for each feedstock with regard to temperature setting and linear pressure of the calender rolls. The recommended working window is indicated by the dark shaded areas.

As practical experience is available for all nine feedstocks selected, a decision with respect to processing in pure form as well as in mixtures had to be made.

By processing in a pure form the different fibre types show the expected performance regarding breaking length and elongation-at-break, as shown in Figs. 4.2 and 4.3.

With a blend of 60% GRILON M 25 the performance regarding breaking length

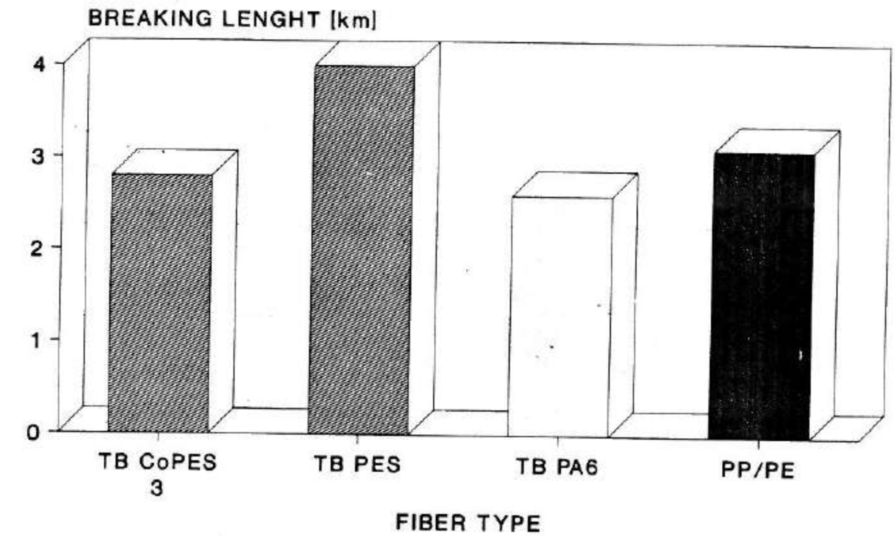


Fig. 4.2 Breaking length of nonwoven in machine direction (pure fibre)

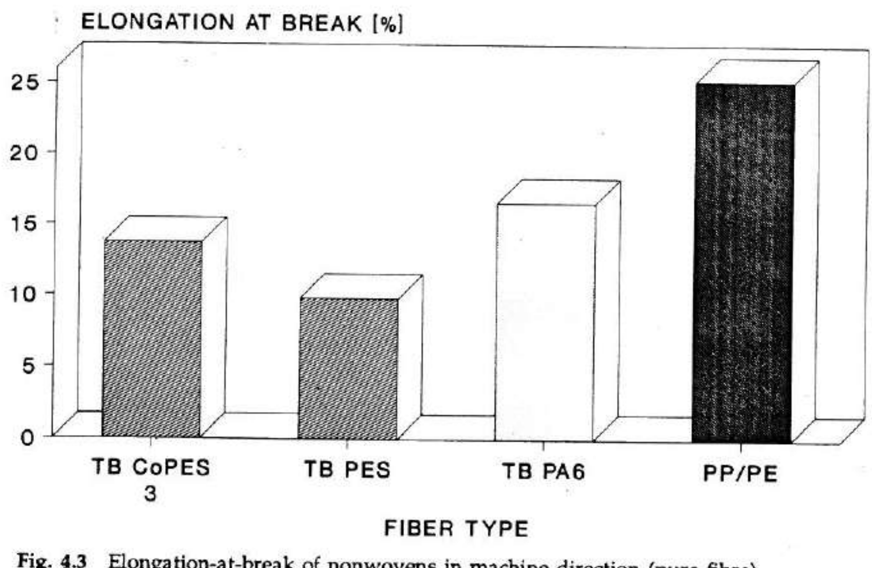


Fig. 4.3 Elongation-at-break of nonwovens in machine direction (pure fibre)

and elongation-at-break are more balanced as can be seen in Figs. 4.4 and 4.5. However, the strength properties are higher with 100% use of pure fibres. The reason is, because the temperature setting of the calender rolls must be adjusted to the polymer type present in the mixture exhibiting the lower fusing range.

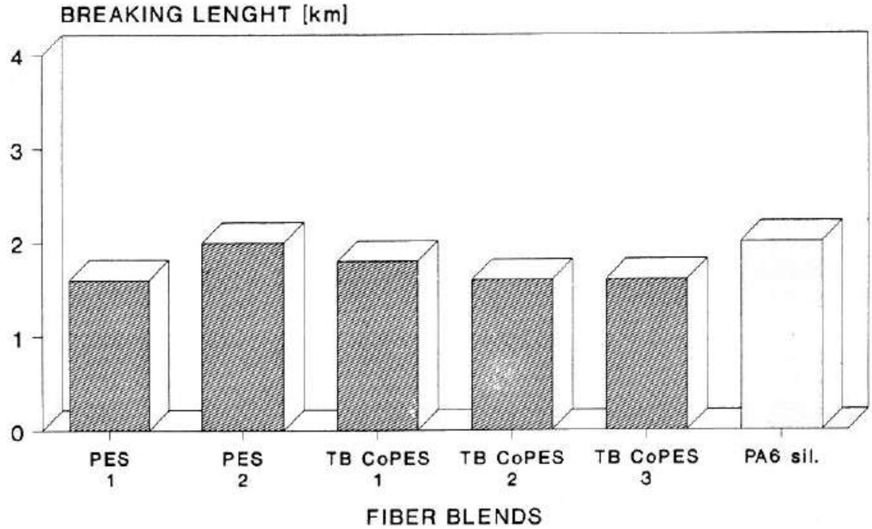


Fig. 4.4 Breaking length of nonwovens in machine direction blends of 60% TB PA6/40%...

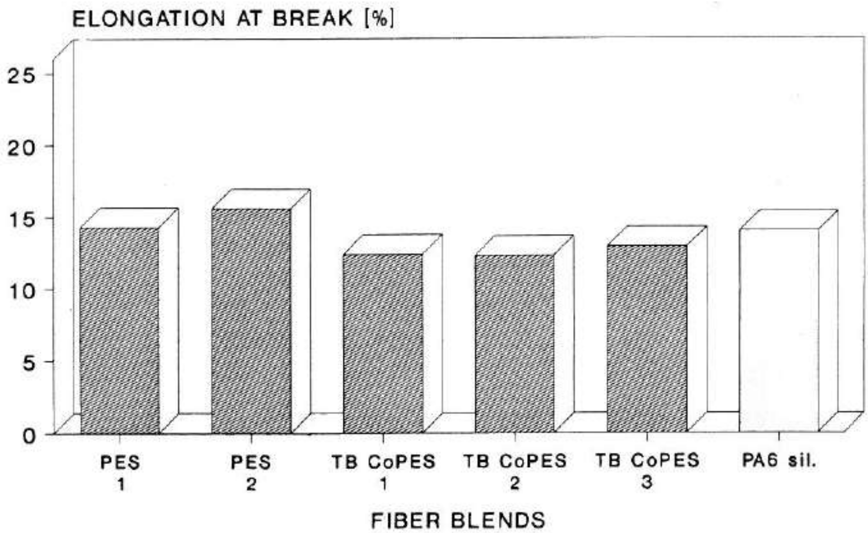


Fig. 4.5 Elongation-at-break of nonwovens in machine direction blends of 60% TB PA6/40%...

The thermal shrinkage at 120°C, 140°C and 160°C for the same four straight and six blended thermobonded nonwovens is very selective (Fig. 4.6). The highly modified CoPES 3 and the PP/PE bicomponent fibre possess shrinkage too high for use in interlining applications.

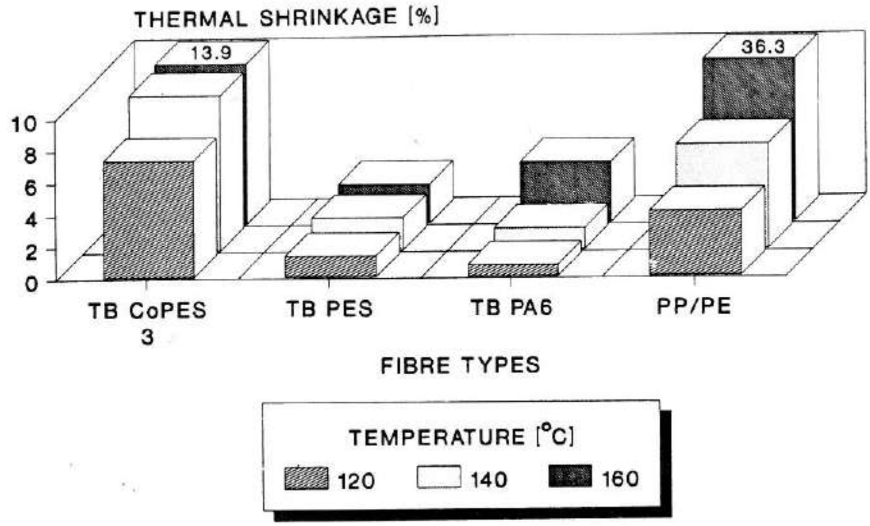


Fig. 4.6 Thermal shrinkage of nonwovens pure fibres DIN 53 866 (15 minutes exposure)

In the blended versions tested, the thermal shrinkage could be reduced mainly through the low shrinkage of the PA 6 fibre as reported in Fig. 4.7.

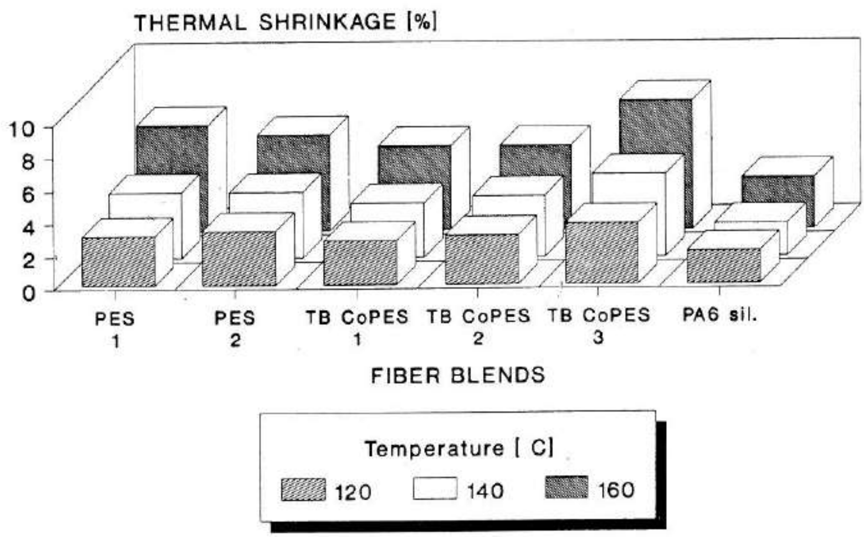


Fig. 4.7 Thermal shrinkage of nonwovens blends of 60% TB PA6/40% ... DIN 53 866 (15 seconds exposure)

Researchers active in the development of interlining materials will find confirmation of the above when conducting practical tests.

Figure 4.7 further demonstrates that the incorporation of a siliconized PA 6 fibre into PA 6 does not increase the thermal shrinkage of the blend, because the siliconized fibre undergoes exactly the same thermal treatment during the fibre production as the regular PA 6 grade. One of the most important criterion by the qualification of a nonwovens for interlinings is the judgement of the softness. The softness should not only be checked on the uncoated nonwovens, it should also to be checked on the coated nonwovens.

Our nonwovens have been coated by the rotary screen paste printing technique in our AWT TF+K technical centre with copolyamide GRILTEX 11 and copolyester GRILTEX 8. The distribution of adhesives is shown in Fig. 4.8.

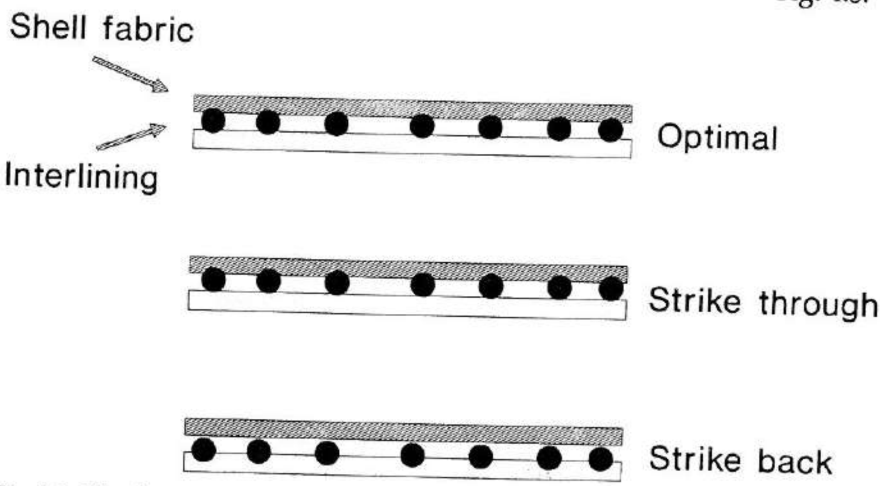


Fig. 4.8 Distribution of adhesives

Often the soft-hand and the softness of the interlining is checked by a subjective judgment of skilled labourers. To be able to recieve measurable values for this performance we decided to work as recommended by EDANA (European Nonwovens Association with the method (ERT 50.2–80)

The nonwoven strip, cut to 2.5 cm width and 20 cm length, is placed into the measuring device, topped with a metal ruler, then pushed along the support base until the test strip drops onto the level of the 41.5° mark, and the bending length is recorded as shown in Fig. 4.9.

The bending length, along with the area weight of the tested nonwoven, is then substituted into the formula shown below to calculate the Bending Resistance Index *G*.

$$G = \frac{\text{Bending length (cm)}^3 \times \text{Area weight}}{1000}$$

$$G = \frac{(\text{m})^3 \times (\text{g/m}^2) = (\text{mg} \times \text{m})}{1000}$$

The result of this simple test is impressive and confirms what is referred to as either soft-hand or stiff interlining in a day to day operation.

This test further confirms that the blend of 60% GRILON TB PA 6 and 40% GRILON siliconized MC-1 PA 6 offers an unsurpassed nonwoven material. The bending resistance of these nonwoven materials is shown in Fig. 4.10. On the other hand, as soon as TB CoPES 3 or PES 1 is blended with TB PA 6, the stiffness of the

INTERNATIONAL CONFERENCE ON NONWOVENS

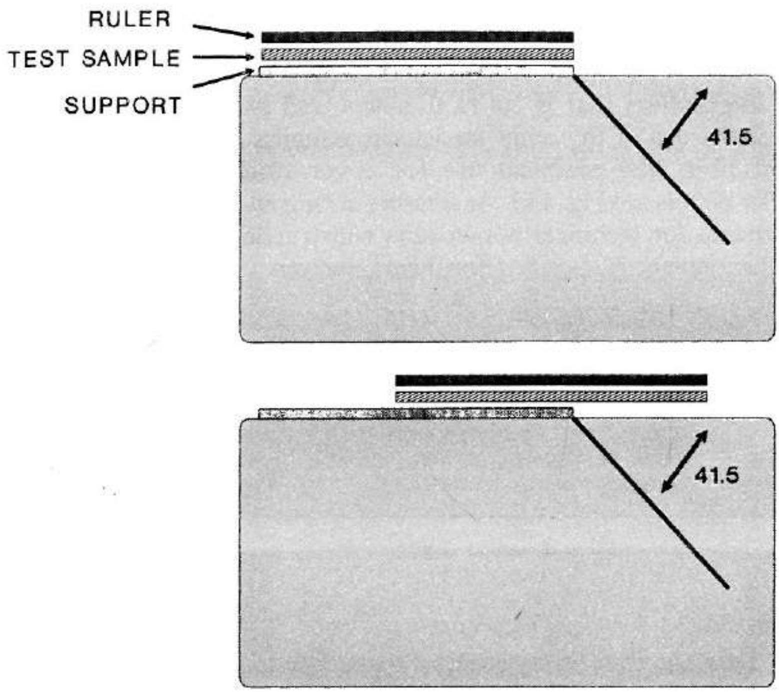


Fig. 4.9 Determination of bending resistance

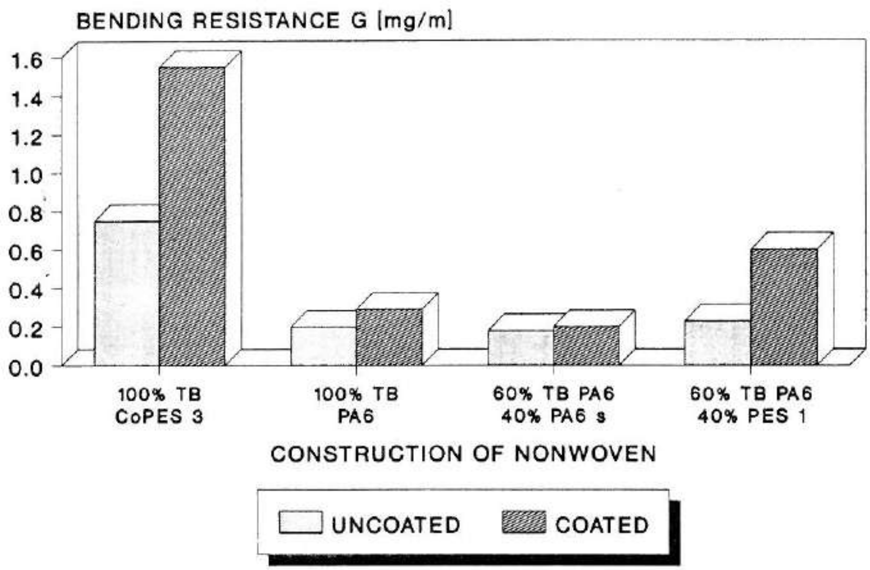


Fig. 4.10 Bending resistance of coated and uncoated nonwovens

nonwoven fabric increases. An influence of softness by using coated CoPA or CoPES nonwovens could not be found.

1.3 Summary

After discussion of the four major feedstocks suitable for the manufacture of nonwovens interlinings that is (TB PA 6, siliconized PA 6, PES 1 and PES 2), assessment of the use of the other feedstocks remains. In the case of PP/PE bicomponent fibre, the practical use for cover stock applications was confirmed. For details see Fig. 4.11. As a rather strong and stiff fibre, the TB PES is mostly suitable for technical nonwovens constructions, especially when high thermal resistance is specified for the nonwoven.

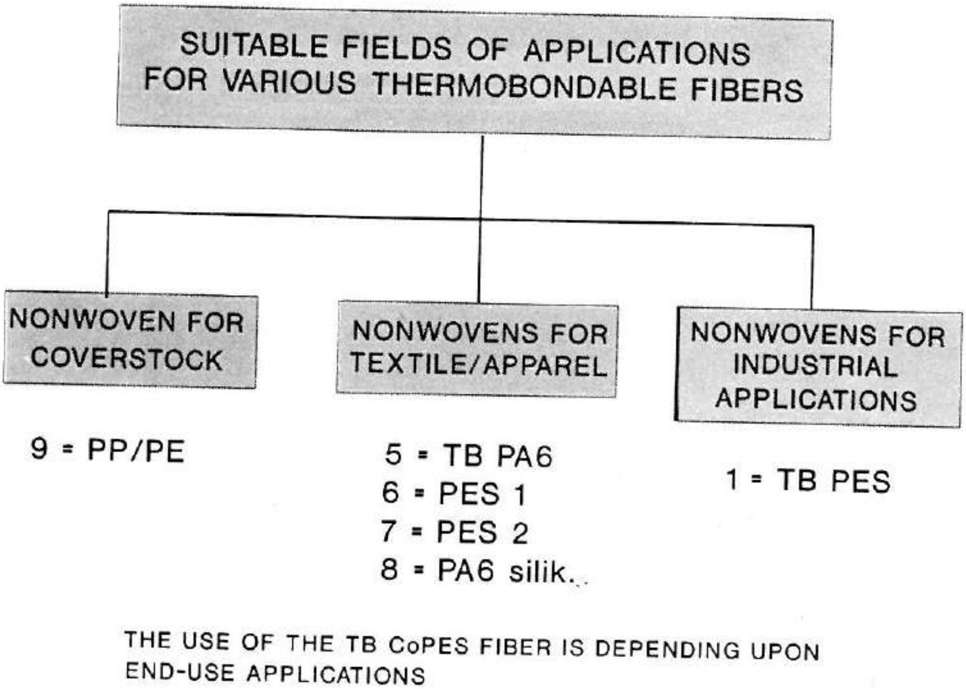


Fig. 4.11

In conclusion, the presentation of a technical application model as described above for thermobondable nonwovens is never complete. Such dynamically expanding technology leaves room for many improvements and innovations. The need is already obvious for development and manufacture of a thermobondable CoPES feedstock with improved thermobondable characteristics.

2. THERMOFUSION BY MEANS OF FUSIBLE FIBRES

Besides the thermobond technique with an engraved calender, there exists the thermobond technique by thermofusion with fusible fibres. By this technique the so called fusible fibres are mixed together with the support fibres, (normally PES fibres). The processing is possible on conventional nonwovens equipment without any problems.

The fusible fibres that have to be melted assume the function as a binding agent as shown in Fig. 4.12. Due to this process the fusible fibre looses its fibre form and the melt collects in preference at the interfibre contact points of non-melting support fibres and binds these together (see Fig. 4.13). Cooling causes the molten components to solidify and provide the nonwoven with a secure bond.

unbonded nonwovens:

31 times enlarged

carrier fibre white/bonding fibre dark black

65 times enlarged

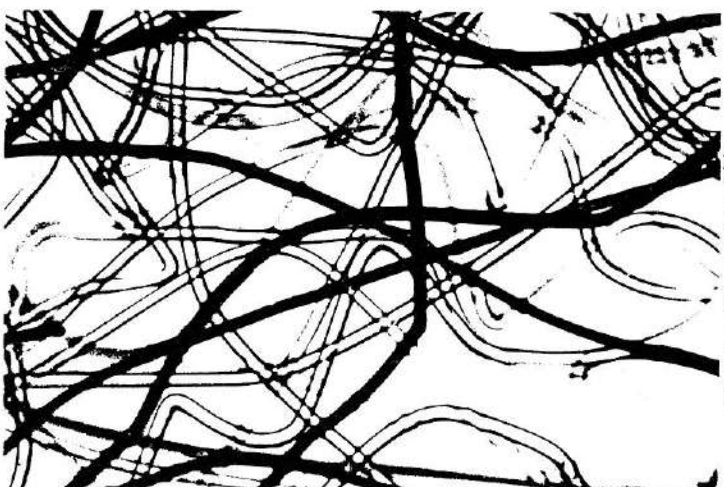


Fig. 4.12 Grilene CoPES, type K 170

bonded nonwovens:

31 times enlarged

carrier fibre white/bonding fibre dark black

65 times enlarged

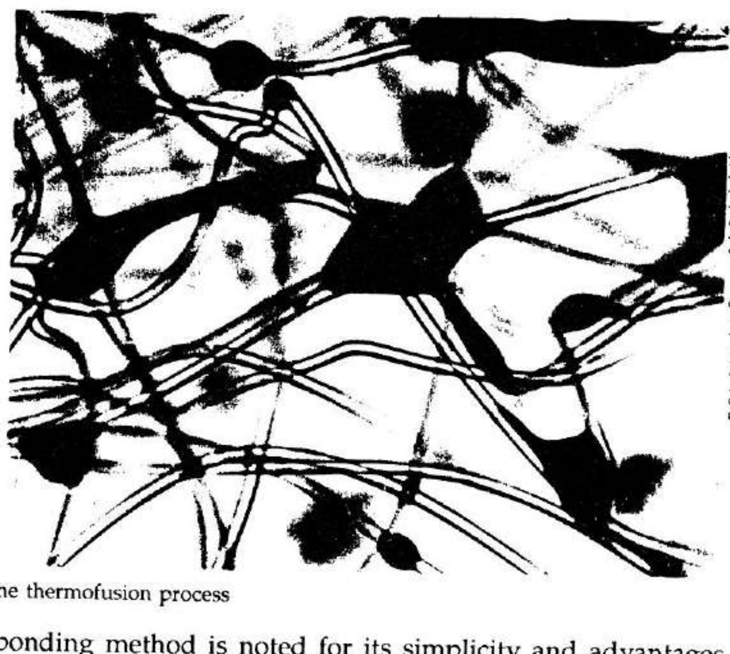


Fig. 4.13 After the thermofusion process

The thermobonding method is noted for its simplicity and advantages, that is:

* ✶ no exhaust air problems
* ✶ no solvent vapours or other gases are released
* ✶ lower capital expenditure cost
* ✶ simpler plants

The melting process can be done directly after the nonwoven is produced or at a later time. If the thermofusion is done later, it will be necessary to pre-needle the web to give it sufficient strength for easy handling.

The convection dryer is the most suitable equipment for this purpose. The conventional circulating-air dryer is inadequate for efficient thermobonding. Perforated drum units and band dryers with controllable forced-air flow specifically for thermofusion have been developed. These machines heat the web within seconds and allow high out-put manufacture of soft, high-bulk products. Optimal strength is achieved when support fibres and fusible fibres are of the same polymeric feedstock. That means that the best results will be achieved when for both fibre types polyamide and polyester, respective co-polyamide and copolyester fusible fibres are used. Proven fusible fibres known for good handling by thermofusion of polyamide nonwovens is the fusible fibre GRILON K 140 and for polyester the GRILENE K 170.

Type	Melting piont	Count (dtex/mm)
GRILON CoPA K 140	140°C	4.2/51
GRILENE CoPES K 170	170°C	5.5/60

2.1 Difference between Thermobond and Thermofusion Processes

With the thermobond processing method on an embossing calender only flat nonwovens can be produced as shown. Because the two parameters pressure and temperature are necessary to get a good strength of the end-products.

Applications are therefore,

* interlinings for the garment industry
* cover stocks
* substrate applications

With the thermofusion processing method it can be used with or without pressure. By this means the volume of the nonwovens can be adapted to the requirements of the end-product. Applications are therefore,

* upholstery industry
* filtration
* interlinings

EMS-Chemie AG
SWITZERLAND

5

Adhesive Binders for Nonwoven Fabrics

A.K. Mukherjee, R.K. Mohanty, N. Sriram and P. Barar

Nonwoven fabrics are finding increasing use because of the variety, ease of manufacture, low cost and unlimited application areas. Besides, for the various type of fibres notably, nylon, polyester, carbon, acrylic and polypropylene the adhesive for bonding is a major ingradient in the nonwoven fabric.

The role of adhesive is not only limited to serve as a binder, it may also provide, depending upon the nature and type of the adhesives, flexibility, flame resistance, chemical resistance and several other desired characteristics in fabric.

In general rubber based adhesives mostly in the form of latex and acrylics have traditionally acted as workhorse in such adhesive applications. They can be both thermoplastic or thermosetting as per requirement. Most notable adhesives are based on natural rubber, nitrile rubber, styrene butadiene rubber (SBR).

On the other hand an acrylic based adhesive will have acrylic or methacrylic acid together with an acrylate as a copolymer as the polymeric binder in the adhesives. In fact the greatest advantage of acrylic based adhesive is, it can be either thermoset or thermoplast. Glass transition temperature (Tg) can also be varied with ease over a wide range which is an added advantage in the case of acrylic adhesives.

Other types of polymers have been used as binder with profit for developing specific properties in nonwoven fabrics. Such products include ethylene-vinyl acetate copolymers, vinyl chloride-vinyl acetate copolymers, phenol formaldehyde resins and the like. More recently special epoxy based resins, poly-urethanes have also been used for developing specific products. Starch based biodegradable adhesives have been used for super-absorbent nonwoven fabrics. Phenolic bonded carbon fibre based nonwovens can meet demanding application characteristics. This paper reviews the present day knowledge in the area.

1. INTRODUCTION

Nonwoven fabrics are textile structures where the bonding of fibres have been achieved by interlocking the fibres by using a mechanical method and/ or chemical adhesive [1]. The attraction of nonwoven fabric manufacture is not only due to their ease of manufacturing, variety in products and wide-range of products, but also due to use of suitable polymeric adhesives, which contributes in its development of versatility of properties. The role of adhesive is to provide binding of the fibres and also, depending upon adhesive nature, to impart specific and desirable properties such as resistance to deformation, better retention of mechanical properties, resistance to laundering and solvent treatments, resistance to fire and weather. These are only some of the examples.

The choice and characteristics of an adhesive is also dependent upon the nature of fibre used for making the finished products [2–4]. Besides, the process of manufacture is also important in deciding the type of adhesive to be used.

2. FIBRES

The choice of fibres in the manufacture of nonwovens is markedly dependent on intended application of the fabric such as strength characteristics, abrasion resistance, resistance to water, chemicals, weather and light. For such demanding requirements usually manmade fibres such as polyester (PET), polyamides (nylon 6, 66), poly-vinyl chloride or its copolymers, polypropylene (PP) and poly-vinyl alcohol are prominent in this regard. However, polyester fibres have been most successful in this regard.

High performance fibres including glass, carbon, ceramic and metallic fibres are gaining importance in making adhesive bonded nonwoven fabrics for meeting demanding engineering and industrial applications.

Though the fibres referred above fall in the class of thermoplastic fibres, binders can be both thermoset and thermoplast. However, irrespective of this, a binder must be compatible with the fibre by having natural affinity to the fibre. This demands a close similarity in the polarity of the two materials, i.e. fibre and binder. Once this basic adhesive characteristic is fulfilled, thus ensuring strong bond between the fibre and the binder, one can look for other desirable adhesive characteristics depending upon the requirements.

3. REQUIREMENT OF AN ADHESIVE

In fibre bonding, adhesives are usually polymeric in nature and for optimum performance the adhesive-fibre combination should have most of these characteristics [5]:

POLARITY

The adhesive and fibre should be of similar polarity. Thus, polar water soluble animal glue will stick to cellulose as both are highly polar. But rubber adhesive will not adhere to cellulose.

SURFACE TENSION

The adhesive must be capable of wetting the fibre, thus reducing the surface energy between the adhesive and fibre. This essentially means lowering the contact angle between the two surfaces. The effect of wetting has been discussed elsewhere [5a].

SURFACE PROPERTIES OF FIBRES

The fibre characteristics, especially physical surface properties are also determinant of magnitude of adhesive bonding strength. The three most important variables are, (i) primary fibre roughness, (ii) fibre cross-section, and (iii) multifibre substrate geometry and porosity.

(i) *Primary Fibre Roughness*

With the increase in the roughness of the fibre the adhesive bond strength increases. However, the wetting of the fibre by the adhesive is of great importance as good wetting increases the adhesion [6, 7].

(ii) *Fibre Cross-section*

Generally fibres are of circular cross-section. However, crenellated cross-section increases the surface area and as a consequence adhesion increases. However, this is to be weighed against increased stiffness of the nonwoven product.

(iii) *Multifibre Substrate Geometry and Porosity*

It is known that substrate geometry and total porosity affect adhesion characteristics substantially. Thus adhesion characteristics using a rubber adhesive of a tightly woven nylon monofilament fabric, a loosely woven fabric made from continuous multifilament nylon yarn and a fabric woven from spun cotton staple when compared; the results as measured by special force showed that the loosely woven fabrics show 10–20% higher adhesion characteristics. On the other hand, that of cotton duck fabric was much higher than that of both the nylon fabrics. This may be ascribed to the penetration of single filament ends of the spun yarn bundles into the adhesive [8, 9]. Similar results have been obtained using tyre cords [6, 10, 11].

GLASS TRANSITION TEMPERATURE (Tg)

One of the most important factor for adhesive binder in nonwoven is Tg. Hardness and flexibility of the polymer at normal temperature is dependent on the Tg of the binder. Tg of the binder is adjusted as per the requirement of the finished fabrics by copolymerisation of different monomers. Figure 5.1 illustrates the effect of transition temperature of a series of acrylic binders on strength properties of rayon nonwoven web. As hardness of the binder increases, tear strength and elongation decrease and tensile and bursting strength increase [la]. Increase in the Tg of the binder leads to increase in the Dynamic Thrust Moduli (DTM) of the nonwoven fabric as shown in Fig. 5.2 [4]. It can be seen from the figure, the increase in crosslinking density in the adhesive during binding results in increased dynamic thrust modulus which is maintained over a wide temperature range [4].

The effect of binder hardness on DTM with Tg has been shown in Fig. 5.3 [4]. With increasing glass transition temperature beyond 40°C in the acrylic binder DTM shows a remarkable exponential fall. However as the hardness of the binder increases the DTM remains static upto as high as + 40°C. Similarly DTM of a nonwoven fabric bonded with a softer (lower Tg) acrylic binder is

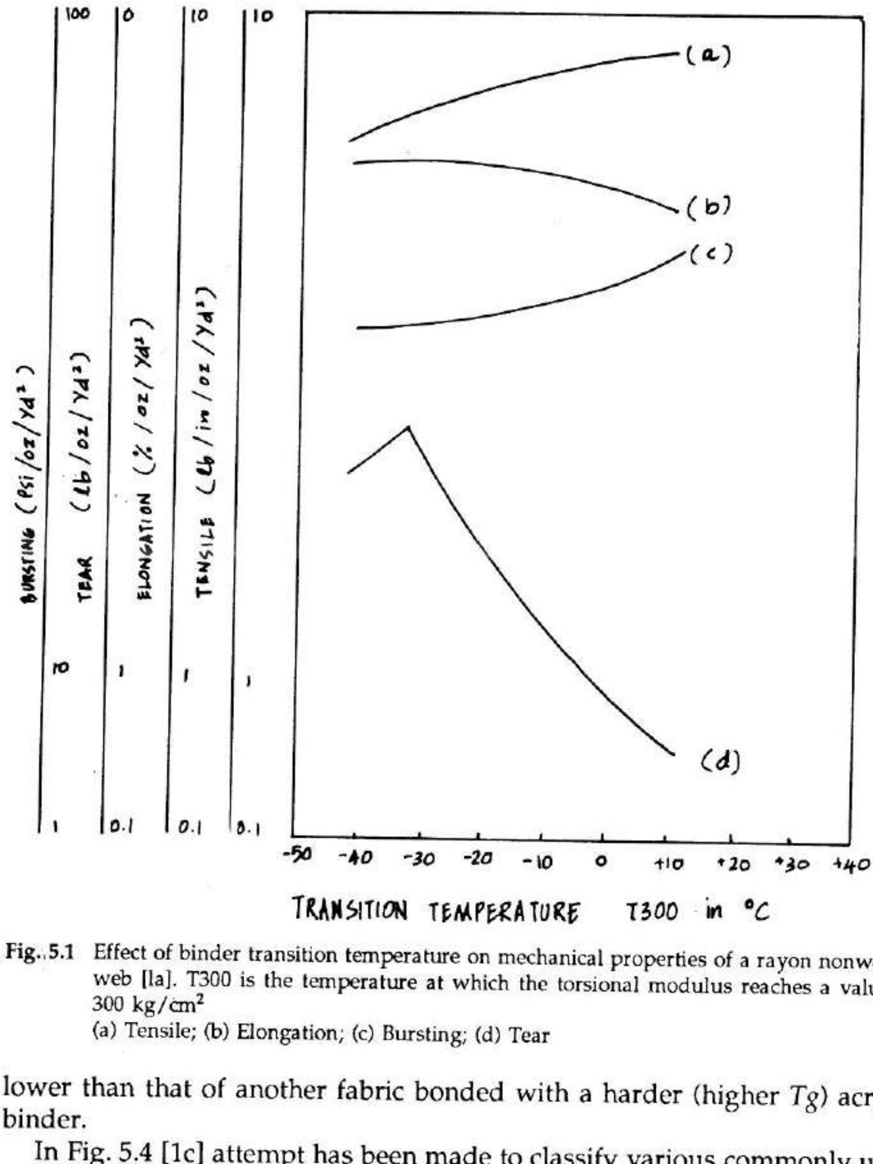


Fig. 5.1 Effect of binder transition temperature on mechanical properties of a rayon nonwoven web [la]. T300 is the temperature at which the torsional modulus reaches a value of 300 kg/cm^2

(a) Tensile; (b) Elongation; (c) Bursting; (d) Tear

lower than that of another fabric bonded with a harder (higher *Tg*) acrylic binder.

In Fig. 5.4 [1c] attempt has been made to classify various commonly used polymeric binders for making nonwovens as per increase in *Tg*. Among the acrylates, increasing chain length of the monomer leads to a decrease in *Tg* resulting in increased flexibility of the bond. Increase in flexibility can be achieved beyond that of acrylates by using diene polymers (rubbers). On the other hand flexibility gets drastically reduced by the incorporation of aromatic moiety such as in styrene base adhesives. Vinyl chloride yields a horny and brittle polymer whereas polyvinyl acetate is highly flexible. Suitable copolymers prepared from them can then have wide range of flexibility within the two extremes [1c].

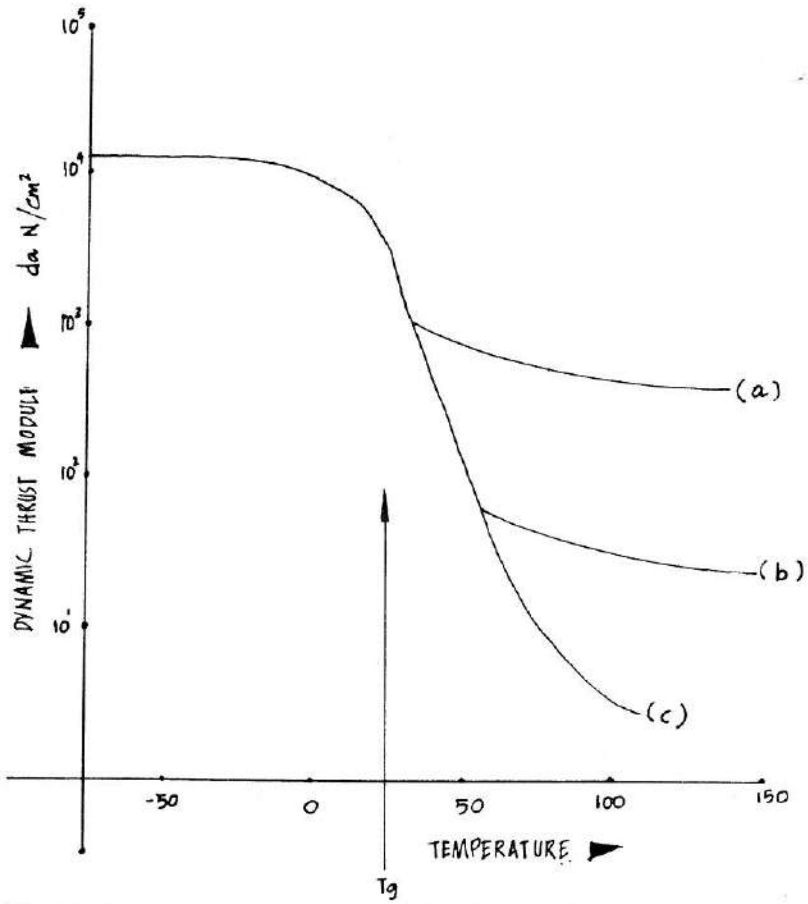


Fig. 5.2 Dynamic thrust modulus for bonding films as a function of crosslinking and temperature, elastic films exhibit a horizontal curve for temperatures above brittle point, *Tg* [4].
(a) Strongly crosslinked; (b) Weakly crosslinked; (c) No crosslinking

FORMULATION AND FORM

Depending upon the nature of application, a suitable formulation is to be made. The primary ingredients are the binder (i.e., polymer) and a vehicle (solvent). Several other ingredients might be present depending upon the nature of application. Such optional additives include fillers, heat sensitizers, optical brighteners, plasticising agents, pigments, thickners, UV absorbers, antirust agents, stabilizer to prevent thermal decomposition, antimicrobial additives, antistatic and hydrophobia inducing additives. Sometimes, thermosensitive additives such as oxalkyl amine, polyether, ethylene oxide addition compounds are used. The additives are added depending upon the requirement of finished nonwoven fabrics [4].

After the formulation is arrived at, the adhesive is prepared in a particular form as demanded by the application technique. The adhesive may be in a form of latex, emulsion, or colloidal dispersion.

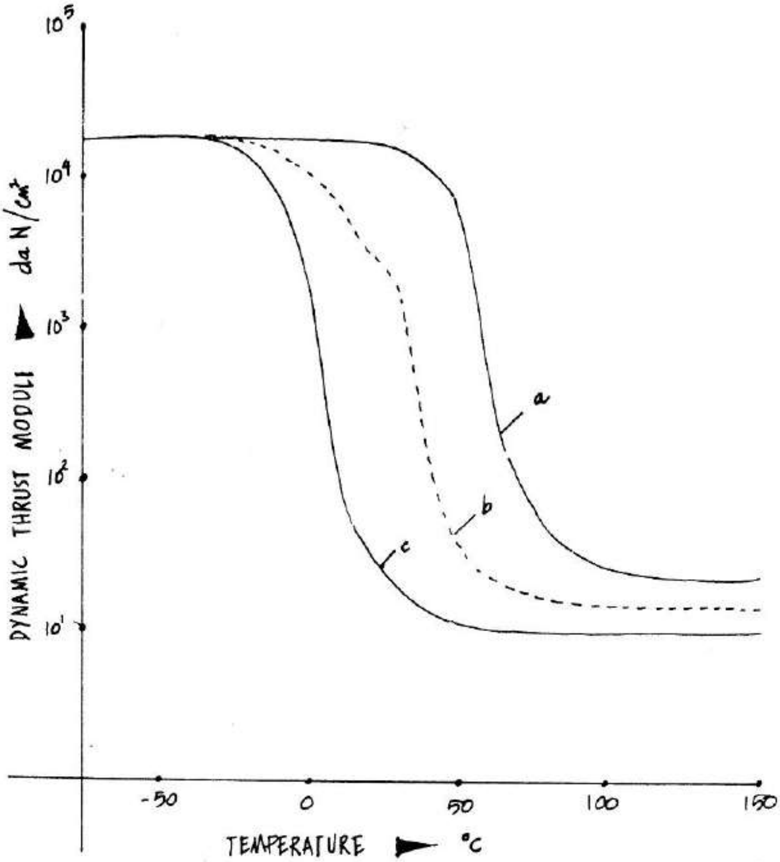


Fig. 5.3 Dynamic thrust module of bonding films as a function of hardness and temperature. Dynamic thrust module increases at constant temperature as hardness increases [4] (a) Maximum hardness; (b) Intermediate hardness; (c) Minimum hardness

The following factors are determinants of the final adhesive characteristics [4, 5].

* *Ionogenity:* Binder may be anionic or non-ionic depending upon the requirement.
* *Solid Content:* In most cases it is adjusted between 50 ± 15%. It can be adjusted as per the requirement of adhesives.
* *Particle Size:* The variation in particle size determines the properties of the product and its use. Hence, the factor should be considered during formulating the binder.
* *pH Value:* This is adjusted usually between 2 and 10 depending upon the requirement of the fabric.
* *Viscosity:* Viscosity of the binder is an important factor, usually varies between 50 and 50000 Pa.s.

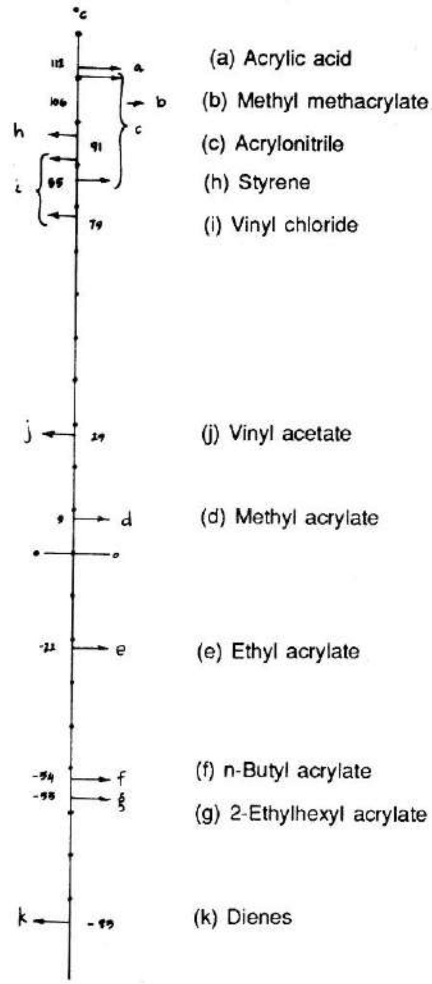


Fig. 5.4 Approximate glass transition temperatures for a range of homopolymers [1c]

4. TYPES OF ADHESIVES

Adhesives used as binders for nonwoven can be classified as thermoset or thermoplastic. Thermoset adhesives are available in soluble and flexible form, but after application and subsequent processing under heat, they undergo a chemical reaction (cross-linking or curing) aided or unaided by catalysts. This process transforms the binder into an infusible and insoluble state, providing necessary bonding. High performance nonwovens use thermoset polymers.

On the other hand, thermoplastic adhesives come in the soluble and fusible form and can be applied on the fibres in the usual manner. They solidify as the solvent evaporates, or melt during heating and spread over the fibres on cooling they solidify and provide the bonding. However, they remain soluble and fusible and can be removed from the nonwoven product, if necessary.

This process of solution and fusion is thus reversible in the case of thermoplastic adhesives in contrast to thermoset adhesives.

Therefore, due to the nature of the adhesive, thermoplastic binder has a tendency to loose bonding characteristics with increased temperature and so nonwoven fabric made using it looses bonding strength and as a consequence mechanical properties also, at elevated temperature. In the case of thermosets, however, no such negative dependence of performance characteristics with increasing temperature is visible.

In the thermoset category the most notable adhesives used for nonwoven fabric are natural and synthetic rubber-based adhesives, phenol formaldehyde resins, urea and melamine formaldehyde-based resins, epoxies and asphalts. On the other hand, the variety of thermoplast category is much more. This group includes adhesives based on acrylics, acrylonitrile based resins, polyvinyl acetate, polyvinyl chlorides and copolymers of vinyl acetate and vinyl chloride, and polyurethanes. Acrylics provide a very wide choice of adhesive characteristics and, therefore, provide widest variety of binders.

5. CLASSIFICATION OF BINDERS

5.1 Acrylic

Acrylic polymers are the most widely used for bonding nonwoven webs. The glass transition temperature (Tg) of the acrylic polymer is a key factor in designing the adhesive [2]. Usually acrylates that have more than four carbon atoms in the ester alkyl group yield polymer with a low Tg. Low Tg has been correlated with high degree of tackiness in acrylic polymers [12, 13]. A typical binder consists of a copolymer of butyl or 2-ethylhexyl acrylate with vinyl acetate, and N-methylol monomers for crosslinking in emulsion form. These polymers have exceptional resistance to UV light, heat, ozone yellowing, chemicals, water, stiffening, drycleaning, etc. They impart a soft hand to the fabric.

In some systems reactive monomers are incorporated into the polymer chain and serve as crosslinking sites. These monomers frequently contain amide, substituted amide, or carboxyl groups and the cross-linking reaction can be catalysed in acid conditions using para toluene sulfonic acid catalysts, oxalic acid and citric acid. The solvent resistance, flexibility and water resistance of the binders can be modified by the choice of monomers [12] (depending on Tg values). Some properties of acrylic esters with increasing alkyl chain length are presented in Table 5.1 [1c].

5.2 Vinyl Polymers

Besides acrylates, various other vinyl monomers are also used as binders in the manufacture of nonwoven fabrics.

The polymers of this category are mostly vinyl chloride and its copolymers with vinyl acetate. Various other combinations are also used.

TABLE 5.1 Properties of Acrylic Esters with Increasing Alkyl Chain Length [1C]

Acrylic Ester	Polymer Properties		
	Flexibility	Solvent Resistance	Water Resistance
Methyl acrylate	Stiffest	Highest	Lowest
Ethyl acrylate	↓	↓	↓
Isobutyl acrylate			
n-Butyl acrylate			
2-Ethyl-hexyl acrylate	Softest	Lowest	Highest

The characteristics [4, 14] of such binders are:

(1) They remain thermoplastic over a wide temperature range.
(2) Polymers made from single monomer (homo polymer) provide brittle but high strength film. They are useful as dispersion as well as in a brittle powder form. The second type can be conveniently handled as a hot-melt adhesive and is becoming popular.
(3) To reduce brittleness of homopolymers it is common to use an external plasticizer, alternatively a copolymer (polymer made from two or more monomers) where the comonomer acts as an internal plasticizer. Such modified adhesives are of reduced hardness, and provide a soft hand to the fabric. However, in the case of external plasticizer there is a danger of sweating out especially during drycleaning operation. Example of external plasticizers are diallyl phthalate or organophosphates.
(4) This group of binders are of low cost, possessing good water, alkali and flame resistance. They have wide applications in nonwoven industries.

VINYL ACETATE POLYMERS

Vinyl acetate based binders are somewhat stiffer than the acrylics and do not have good washing and drycleaning resistance.

However, due to low price, good film forming ability, good colour and heat sealability they are in use, but polyvinyl acetate cannot be used as adhesive requiring service at extreme temperature [2, 4, 14]. The homopolymer produces a hard film which has a *Tg* of 30°C. In nonwovens, various copolymers of vinyl acetates and softer comonomers, such as acrylates are in use. Most binders are: vinyl acetate-acrylic ester copolymers [1], vinyl acetate-ethylene copolymers and vinyl acetate-ethylene copolymer latexes [2, 3, 4].

Other special type of vinyl acetate copolymers used are vinyl acetate-natural rubber, ethylene-vinyl acetate copolymer modified with 40% SBR [54], vinyl acetate-ethylene copolymers, and vinyl acetate-ethylene copolymer latexes [2, 3, 4].

The glass transition temperature can be varied over a wide range as shown below [1b].

Polymer	—	PVA > 80 : 20 (VA-DBM) > 50 : 50 (VA–EA)
Tg°C	—	30 > 10 > 0
Polymer	—	80 : 20 (VA–E) > 50 : 50 (VA–BA) > 20 : 80 (VA-BA)
Tg°C	—	– 5 > – 20 > – 40

PVA—Polyvinyl Acetate; DBM—Dibutyl Maleate ;
EA—Ethyl Acrylate; E—Ethylene; BA—Butyl Acrylate

VINYL CHLORIDE POLYMERS

Vinyl chloride derived binders give relatively stiff nonwoven fabrics (Tg 80°C. They impart good colour fastness, binding strength, improved abrasion resistance, toughness, flame retardance, resistance to oil, water and many chemicals. PVC latexes offer as solvent free adhesive materials for nonwoven fabrics. Unlike vinyl acetate polymer, they are not film forming and even when they are plasticized, temperature of 150°C is required to obtain fusion. The fusion temperatures can be reduced by copolymerisation with monomers, such as the acrylates. Hence, self-cross-linking PVC acrylic copolymers are available as bonding adhesives for nonwoven [1, 3, 13, 15]. For those comonomer levels that give a better balance of overall properties, plasticizers such as phthalates or phosphate esters are generally incorporated as well. Phosphate ester plasticization has the advantage of maintaining the self extinguishing properties of the vinyl chloride copolymers. Vinyl chloride polymers are particularly responsive to the radiofrequency heating and this has led to the use of high loft (spray bonded) nonwoven fabrics in application such as padding in car door trims [4]. Vinyl latexes may also be bonded with other latexes in order to obtain specific properties.

Vinyl chloride copolymer latex blended with an acrylonitrile butadiene copolymer produces a latex that behaves similar to a plasticized latex. It acts as non-migrating, nonextractable plasticizer with enhanced oil and grease resistance [1, 2, 3, 13, 15]. Other vinyl chloride copolymers are in use, e.g. ethylene-vinyl chloride copolymer emulsion, ethylene-vinyl ester-vinyl chloride copolymer, acrylic acid-2-ethylhexyl acrylate, vinyl chloride-vinylidine chloride copolymers. The decrease in Tg of vinyl chloride polymers due to copolymerization has been shown in Table 5.2 [1b].

POLYVINYL ALCOHOL

It may act as a bonding agent for nonwovens [2, 3]. Since it imparts greater stiffness to the fabric, its use have been restricted. Polyvinyl alcohol is mostly used when solvent resistance is a prime requirement. Polyvinyl alcohol copolymers are used in glass fibre materials and to prebond wet processed fabric.

5.3 BUTADIENE COPOLYMERS AND SIMILAR TYPE BINDERS

Copolymers of butadiene fall in the category of elastomeric binders. With increasing butadiene content extensibility of adhesive film increases [4]. This can be reduced by using other monomers such as acrylonitrile or styrene [4,

TABLE 5.2 Glass Transition Temperatures of Vinyl Chloride Copolymers [1b]

Polymer	Tg°C
Polyvinyl chloride	80
75 : 25 Vinyl chloride-Vinyl acetate	65
80 : 20 Vinyl chloride-Ethyl acrylate	55
80 : 20 Vinyl chloride-Ethylene	25
40 : 60 Vinyl chloride-Vinylidine chloride	10
40 : 60 Vinyl chloride 2-Ethylhexyl acrylate	– 30

16]. This class of binders includes butadiene copolymers, the most extensively used being butadiene-acrylonitrile copolymer (NBR), butadiene styrene copolymer (SBR), as well as polychloroprene and natural latex.

Butadiene Styrene Copolymer (SBR)

SBR are generally considered to have moderate binding properties, latices give high surface strength. They are almost colourless to yellow, have fair resistance to washing and drycleaning and have moderate stability to heat and light after suitable formulation. They are mainly used in nonwoven bonded fabrics meant for technical use, for disposal materials, in the carpet field and paper coating. Drycleaning resistance is achieved using carboxylated styrene-butadiene latices.

Butadiene Acrylonitrile Copolymer (NBR)

NBR latices are elastomeric and give the nonwoven fabric a resilient hand. They have high resistance to washing and drycleaning and moderate stability to heat and light with proper stabilisation. Because of poor colour fastness, they are used mostly in such applications where there is no exposure to light. Such adhesives possess good resistance to oils and chemicals. They improve wear resistance of fabrics and provide good ozone resistance when blended with small amount of PVC. [2, 3].

Polychloroprene

This is also an elastomeric material and compares favourably in mechanical properties with natural rubber. However, it can crystallise leading to stiffness and hardening of the bond. Its resistance to chemicals and exceptional antidegradation characteristics are superior to butadiene-based copolymers. However, because of dark colour and high cost, binder of this category is used mainly for bonding insole substrate and glass fibre based fabrics [5].

Natural Latex

Out of all types of elastomer-based adhesives natural rubber latex is the most versatile. Unfortunately, being a natural material variation in consistency and quality as well as price are a problem and, therefore, synthetic latices have replaced natural latex to a large extent but the soft feel of the fabric and high elasticity of the bonds remain unchallenged.

5.4 Polyurethane

Polyurethanes are a special category of binders and their property can be varied widely during preparation. They are available in the form of solution in an organic solvent like dimethyl formamide (DMF) or in aqueous dispersions. The organo solvent based adhesive has the problem of high toxicity of the solvent and tendency of binder coagulation during impregnation of the web. Such problems are avoided by using aqueous dispersions. But because of the sensitivity of dispersion (electrolyte affects the dispersion stability adversely), they have to be handled carefully.

Polyurethane based binders are of outstanding characteristics [4, 17]. They are capable of providing high elastic film with soft handle. They have outstanding stability to weathering conditions and heat. Their resistance to organic solvents is satisfactory. Polyurethanes are used to produce high quality nonwoven fabrics.

Besides, other polymeric binders that are popular in nonwoven industries include phenolics, aminos, and epoxies.

5.5 Phenolic

Phenol-formaldehyde adhesives are available in two forms. They are classified as resol-based and novolac based resins. Both type of adhesives are used for the nonwoven fabric industries depending on the properties require. Resol-based resins have excellent curing properties and low content of solvent extractables after curing. Bond strength to the fibre is high. Novolak based adhesives usually requires a crosslinking agent, such as hexamethylene tetramine. Fibre bond strength is good producing mats with high tensile strength. Novolak based adhesives are primarily used for organic fibres [2, 3]. Since shear rigidity of phenol-formaldehyde resins is high, they are usually used in modified form as adhesive binders [5]. They find major use in nonwoven laminates and in filters.

5.6 Amino

Melamine-formaldehyde and urea-formaldehyde condensates belong to this class. These adhesives fall into categories of thermosetting adhesives and mostly find use in making laminates, filters and for paper treatments in the field of nonwovens. They impart properties like flame and heat resistance, a wide range of colour, colour stability, resistance to boiling water and solvents, high impact strength, a wide range of service temperature and good dielectric properties to finished nonwoven fabrics.

5.7 Epoxy

Epoxy adhesives used in nonwovens are of thermosetting type. They need a curing agent and/or accelerator which further promotes crosslinking. They find use in nonwovens as such, but more so in modified form. They impart desirable properties including high shear strength, peel strength, flexibility, dielectric properties and fire resistance to the fabric. Epoxy binders are mostly used for nonwovens in laminating (mostly for printed circuit board), filament winding, interlining, filtering materials and insulating fabrics.

6. APPLICATION TECHNIQUES

These have been discussed in details elsewhere [1, 4] and will not be discussed here.

7. EVALUATION OF PROPERTIES AND TESTING OF BINDERS

Evaluation of binder adhesives is essential, (i) to assist in selecting an adhesive for a particular use, (ii) to monitor the quality of an incoming product, and (iii) to confirm the effectiveness of the bonding process [18].

The most commonly used tests for properties of adhesive materials measure viscosity, shelf life, pot life, tack, cure rate, per cent solids and applied weight per unit area.

Besides, to evaluate the performance characteristics of the binders, the following tests may also be carried out:

* Adhesion (peel, shear, tensile cleavage)
* Impact resistance
* Resistance to environmental effects (heat, condensing humidity, salt spray, temperature cycles)
* Flexibility
* Strength retention

It is beyond the scope of this write-up to mention all the test methods. However some of the important tests [19] required for nonwoven fabric as given by ASTM are presented here :

ASTM No.	Title
D896	Resistance of adhesive bonds to chemical reagents, test for
D897	Tensile properties of adhesive bonds, test for
D898	Applied weight per unit area of dried adhesive solids, test for
D899	Applied weight per unit area of liquid adhesive, test for
D903	Peel or stripping strength of adhesive bonds, test for
D950	Impact strength of adhesive bonds, test for
D1084	Viscosity of adhesives, test for
D1151	Effect of moisture and temperature on adhesive bonds, test for
D1183	Resistance of adhesives to cyclic laboratory aging conditions, test for
D1184	Flexural strength of adhesive bonded laminated assemblies, test for
D1488	Amylaceous matter in adhesives, test for
D1489	Nonvolatile content for aqueous adhesives, test for
D1579	Filler content of phenol, resorcinol and melamine adhesives, test for
D1583	Hydrogen ion concentration of dry adhesive films, test for
D1875	Density of adhesive in fluid form, test for
D1876	Peel resistance of adhesive (T-Peel test), test for

Table 5.3 presents a representative list of various binders and their applications in nonwoven field.

TABLE 5.3 Special Type Binders and their Applications

Sl. No.	Type of Binders	Applications	References
Acrylic			
1.	Acrylic acid grafted oxidised starched copolymers crosslinked with N,N', methylene bisacrylamide	Super absorbent wet lay nonwovens	20
2.	Alkyl methacrylate, methacrylic acid; C_{2-6} polyol methacrylate copolymer	Self sealing materials for water proofing cable lines, geotextiles, medicines.	21
3.	Copolymers of unsaturated water soluble carboxylic acid or derivatives and methacrylic acid hydroxy alkyl ester monomers combined with a SBR latex	Useful for bonding cellulose fibres and pulp in paper, wipes or towels, diapers	22
4.	Copolymer of 2-ethylhexyl acrylate, styrene, acrylic acid & vinyl acetate emulsion starch based binder	Web based wall paper with extending gluing time	23
5.	Acrylic polymer emulsion, paraffin emulsion and water	Moisture permeable-waterproof nonwoven fabrics	24
6.	Acrylic acid, Bu-arylate, styrene copolymer (Mol Wt 636000 and Tg 45°C)	Coated nonwoven emulsion binder with reduced flamability	25
7.	Aqueous 65% potassium acrylate crosslinked with 0.085% N,N', methyl bisacrylamide	Highly hygroscopic webs for disposable diapers	26
8.	Copolymer of C_{1-4} alkyl acrylates, C_{1-4} alkyl methacrylates and unsaturated C_{3-5} carboxylic acid	Binders for nonwovens with good impregnating properties	27
9.	Emulsion polymer of methyl methacrylate, ethylhexyl acrylate, methacrylic acid and acrylamide	Emulsion adhesive for heat sealing of tea bags	28
10.	Butyl-acrylate, styrene copolymer	Self crosslinking resin for porous separator material in batteries	29
11.	Butyl acrylate copolymer	Adhesive tape for waterproof fabrics	30
12.	Copolymer of Bu-acrylate, acrylonitrile and N-methylol acrylamide	Nonwoven material with improved ironability	31
13.	Emulsion polymer of acrylic unsaturated monomers (homo or copolymer; $Tg = 250°K$) and aqueous dispersion of polymers prepared by emulsion polymerisation of ethylenic monomers	Aqueous dispersion type pressure sensitive adhesives for nonwoven	32
14.	Acrylic acid ester copolymer; blended with 20% SBR emulsion	Interlining materials with good resilience; improved tensile strength	33
15.	Butyl acrylate-vinyl acetate copolymer dispersion	Air permeable nonwovens with shape memory	34
16.	Butyl acrylate, acrylonitrile, N-methylol acrylamide copolymer	Nonwoven fabric for lining with good laundering and drycleaning resistance	35
17.	Latex containing acrylic acid-2-ethyl hexylacrylate-vinyl chloride-vinylidine chloride copolymer	Polyolefin nonwovens with high wet strength retention	36

(Contd.)

TABLE 5.3 Special Type Binders and their Applications (Contd.)

Sl. No.	Type of Binders	Applications	References
18.	Carbonized sulfonated styrene-di-vinyl benezene copolymer resin and a synthetic copolymer latex or a suitable acrylate	Spun-bonded nonwoven protective fabric having flame resistant and flexibility	37
19.	Acrylic polymer emulsion blend with ethylene vinyl acetate copolymer	Stretchable wrinkled fibrous sheet	38
20.	Acrylic acid-acrylonitrile copolymer	Hygroscopic products for sanitary goods and sealing materials	39
21.	Acrylic resin modified with chlorohexidine	Antibacterial electric fibre webs for filters and wipers are prepared using the binder	40
22.	Emulsion polymer of acrylic acid ester, M.F. resin, organic amine	Laminated pattern paper for textile printing	41
23.	Acrylic polymer emulsion (*Tg*-80 to 0°C)	Two ply nonwoven fabric laminate	42
24.	Crosslinkable polyacrylates impregnated with binder containing 10% silicone dispersion	Nonblocking, noncrosslinking adhesively bonded fleeces	43
25.	Vinyl chloride emulsion blended with small amount of aminoplast	High loft polyester nonwovens. Good flame resistance better wash and drycleaning resistance, resilience and compression recovery	44
26.	Ethylene-vinyl chloride copolymer	Laminates of nonwoven fabric with wood composite base for rear package automobile interiors	45
27.	Polyvinyl chloride emulsion	Antistatic finish for textiles and carpet backings	46
28.	Vinyl chloride-vinylidine chloride-copolymer or Ethylene vinyl acetate copolymer	Chemical resistant fabric for protective garments	47
29.	Vinyl chloride homo or copolymer with plasticiser and chemical stabiliser	Fire resistant particulate binders for automobile felts	48
30.	PVC emulsion binders	Glass fibre nonwovens with good tensile strength, breaking strength	49
31.	Ethylene vinyl ester-vinyl chloride copolymer binder emulsion	Composition for fabric and paper	50
32.	Ethylene vinyl acetate copolymer emulsion	Synthetic nonwovens for retention of volatile liquids	51
33.	Ethyl vinyl acetate copolymer	Adhesives for bonding textiles (polyester cotton fabrics)	52
34.	Polyvinyl acetate aqueous emulsion	Thermal insulating nonwoven bulky product	53
35.	Ethylene vinyl acetate copolymer blended with 40% SBR latex	Coated nonwoven fabrics with increased oil adsorption	54
36.	Polyvinyl acetate, blended with lubricating oil, epichlorohydrin-polyamide copolymers	Reinforcing glass fibre material	55
37.	Copolymers of ethylene, vinyl acetate and N-methylol compound	Nonwoven textiles	56
38.	Aqueous latexes or emulsion of vinyl acetate and natural rubber	Aging resistant, cold sealable coatings for packaging material	57

(Contd.)

TABLE 5.3 Special Type Binders and their Applications (Contd.)

Sl. No.	Type of Binders	Applications	References
39.	Polyvinyl acetate hot melt adhesive	Interlining	58
40.	Ethylene vinyl acetate copolymer emulsion	Highly absorptive binders for polyester nonwovens	59
41.	Polymer of ethylenic unsaturated carboxylic acid with ethylene or vinyl acetate and compound containing atidirine	Water resistant binders for polyester nonwovens	60
42.	Vinyl butyl resin solution	Nonwoven reinforcement for composite (carbon fibre and glass fibre)	61
SBR Binders			
43.	SBR latex binder, mica, titanium pigment, kaolin clay, sodium pyrophate, casein, ammonia, antifoaming agent	Nonwoven coated paper or cloth with pearly gloss, good printed gloss and printability	62
44.	Binder comprises a copolymer of butadiene styrene, ethynically unsaturated carboxylic acid	Nonwoven webs for sanitary use	63
45.	SBR latexes of acrylate polymers	High strength, high modulus interlining fabrics	64
46.	Emulsion of styrene butadiene, MAA, N(butoxymethyl acrylamide)	Binders for nonwoven fabrics for imparting stiffness, water and solvent resistance	65
47.	Carboxylated SBR (carboxy content 0.5–2%)	Alkali resistance nylon nonwoven fabrics for elastic rolls	66
48.	SBR latex, U.F. resin, ethylene glycol, Na CM-cellulose	General adhesives for nonwovens	67
49.	Carboxylated SBR latex	Carpet backing adhesive	68
50.	Copolymer latex of butadiene, styrene and acrylamide	Hydrophobic nonwoven fabrics suitable for use as diaper coverstock, prepared by bonding polyester fibres with the binder	69
51.	SBR latex	Nonwoven fabrics for floor covering with good pilling and wear resistance (carpet water proofing siloxane)	70
NBR			
52.	Butadiene acrylonitrile latexes	Impregnating heat sensitive binder for nonwoven fabrics	71
53.	Carboxyl containing butadiene acrylonitrile latex and a dispersion of chloroprene-Me methacrylate copolymer	Polyester fabric nonwoven polishing material	72
54.	Different binder layers of vulcanised nitrile rubber and plasticised PVC	Laminated floor covering (Floor covering consist of a base of nonwoven needle punched fabric, a layer of vulcanised nitrile rubber, and a layer of plasticized PVC)	73
55.	Nitrile rubber phenolic blend	Abrasive nonwoven polyester fabrics with high tensile strength	74
		Nonwoven fabric lining and filtering material with high strength	75

(Contd.)

TABLE 5.3 Special Type Binders and their Applications (Contd.)

Sl. No.	Type of Binders	Applications	References
56.	Carboxylated nitrile rubber latex crosslinked with hexamethylol melamine		
Natural Rubber			
57.	Natural rubber	Adhesive tape coated on both sides with adhesive (adhesive was applied on silicone paper and a nonwoven cotton fibre textile carrier was pressed into the adhesive until it was coated on both sides. The resulting tape was wound into a roll)	76
Other Types			
58.	Phenol formaldehyde resin	Laminates of carbon fleece and graphite foil with improved flexural, compressive strength, thermal conductivity and permeability	77
		Nonwovens glass wool or rock wool for thermal insulation	78
59.	Water soluble phenolics, urea resins and optionally ureas	Thermosetting adhesive sheets	79
60.	Powdered adhesive containing hydroquinone diglycidyl ether polymer, phenolic novolak, 2-methyl imidazole	Impregnating compositions for nonwoven glass fabric with high flexibility, elasticity and improved deformation properties	80
61.	Bisphenol-A epoxy resin		
62.	Asphalt binder	Waterproof sheets are prepared by forming a nonwoven fabric from blends containing melt resistant synthetic fibres with low softening temperature and vinyl fibres on a paper making machine and then impregnating the web with melted asphalt	81
		Water resistant felt of nonwoven cloth	82
63.	Coal tar and coal pitch 100, PVC 8–14, calcium stearate and tribasic lead sulfate 0.5–2, plasticizer 4–12, talc 50–70	Filter media are prepared by dispersing inorganic microfibres (glass, titanate) having nagative zeta potential in the binder	83
64.	Thermosetting polyamine-epichlorohydrin resin. A precipitating agent is added to precipitate the binder and coat the fibres	Glass fibre, polyester fibre (50 : 50) laminates with improved bendability	84
65.	Bisphenol-A epoxy resins containing 30% epoxidised polybutadiene and 20% Br	Aramid fibre nonwoven laminates for printed circuit board	85
66.	Epoxy resin modified with phenol or cresol novolak	Adhesives for interlinings with improved softness, shear strength, flexibility, peel strength	86
67.	Epoxy modified silicone emulsion, polyether modified silicone oil	Insulating nonwoven fabric	87
68.	Epoxy resin	Filtering material (laminated with bulky nonwoven fabric from	88

(Contd.)

TABLE 5.3 Special Type Binders and their Applications (Contd.)

Sl. No.	Type of Binders	Applications	References
69.	Emulsion copolymer of epichlorohydrin, bisphenol—A modified with amino polyamide and glass beads	polyester fibres and nylon fibres)	
70.	Polyesters or epoxy resins modified with cis-3-methyl 4-cyclohexane, cis 1,2-di-carboxylic acid or its anhydride are grafted with styrene or its derivative or mixture with vinyl monomer to give a graft copolymer with styrene or its derivative or mixture with a vinyl monomer to give a graft copolymer which is mixed with ethylene-vinyl acetate copolymer	Useful for bonding acrylic nonwoven fabrics to polystyrene (Laminates having good bonding strength)	89
71.	Acrylic or vinyl binder	Luminescent nonwoven textile products (e.g. carpets, wall coverings) for improving orientation and safety in dark rooms, are prepared by adding a luminscent material having a long after glow, such as Cu-activated ZnS, to binder or dyeing the fibres with a luminscent dye	90
72.	UV curable binder, i.e. binders, are emulsion polymers (do not contain solvent, monomer, HCHO or other toxic materials)	Because of poor wet adhesion, these binders are used in PP nonwoven fabric. UV light or UV irradiation induced reaction between binder and PP by crosslinking	91
73.	Polyurethane	Leather substitutes or leather-like materials	92

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6

New Developments in Web Forming and Needle Punching

HANS HOENIG

The Fehrer company of Austria has been engaged in the production of machinery for manufacturing dry-laid nonwovens and needle punching machines for more than 30 years. These machines work on the aerodynamic principle. Description of SCH/MF/V12/R, RS-SP/MF/V21/R/K21 and RS-SP/MF/V21/R/K12 nonwoven machines is provided.

The Fehrer company is the pioneer in the manufacturing of modular designed needle looms. The machines developed include, regular needle looms for flat products, structuring needle looms and paper maker felt needle looms.

The main focus of the paper is on the new developments in manufacturing high-loft products and new design possibilities on the structured needle punched carpets.

1. INTRODUCTION

Nonwovens are the youngest group of textile products but according to statistics the fastest growing area in textiles. The average growth rate of nonwoven production is between 8 and 10% per annum.

World wide it can be said that approx 90% of the nonwoven products are produced in the United States, Europe and Japan, while the rest of the world is producing only about 10% of the world's market share. Keeping this in mind the potential in India and other South East Asian countries is tremendous.

When splitting nonwoven products according to production mode, dry-laid nonwovens have the major share, followed by spun-bonded products. If we consider the world nonwoven production in respect to the applied bonding technique, we can see that bonding by needle punching has the biggest share followed by thermobonding.

The Fehrer company in Austria has specialized for more than 30 years in two market segments, that is machinery for manufacturing dry-laid nonwovens and needle punching machines.

In this paper some general information about nonwoven and needle punching machinery is given, but the main focus is on the new developments in manufacturing high-loft products and new design possibilities on structured needle punched carpets.

2. NONWOVEN MACHINERY

Basically all nonwoven machines developed by Fehrer are working on the aerodynamic principle. These nonwovens machines are doffing the fibre from the main cylinder by means of centrifugal force assisted by suction and blow-off, if necessary. Three basic nonwovens plants available are:

A. SCH/MF/V12/R

This nonwovens plant configuration is designed to produce webs in a weight range of 500 to 3000 g/m^2 out of waste material, hard fibres as well as virgin material.

B. RS-SP/MF/V21/R/K21

The nonwovens plant incorporating the high-performance random card K21 is designed to produce webs from 10 to 100 g/m^2 out of synthetic fibres ranging from 1.7 dtex to 3.3 dtex as well as cotton and viscose.

C. RS-SP/MF/V21/R/K12 (FIG. 6.1)

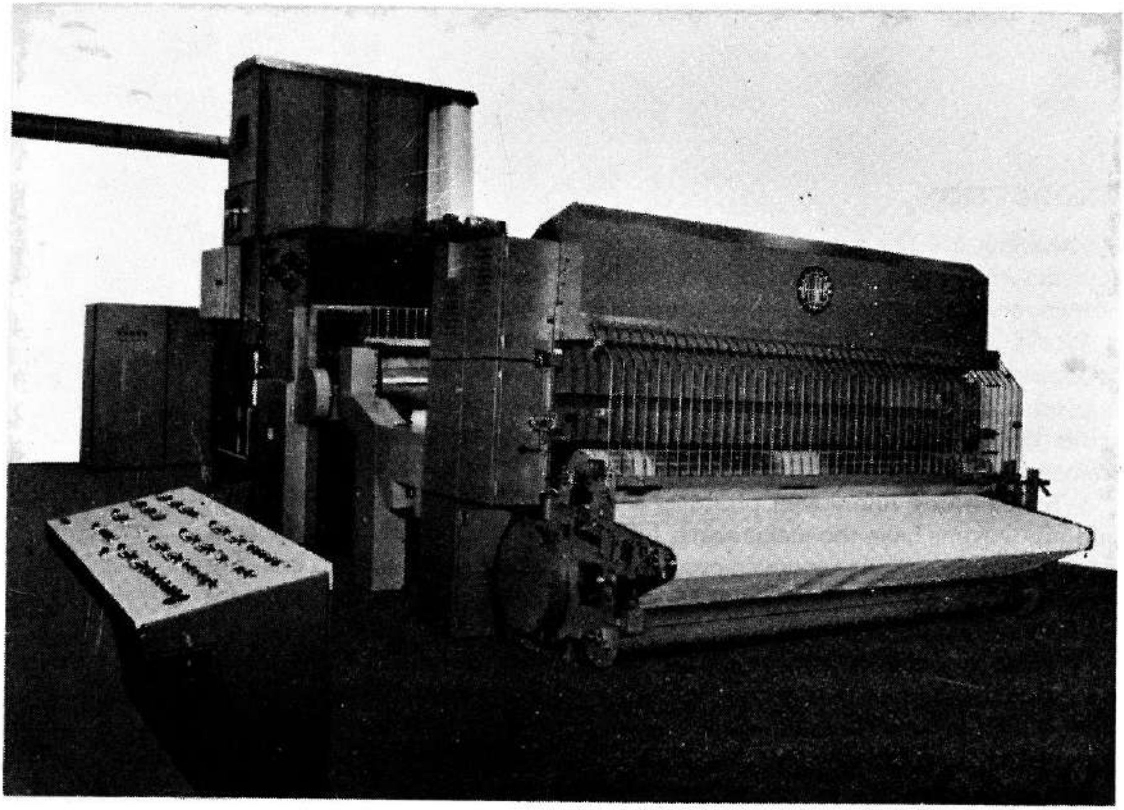

Fig. 6.1 FEHRER nonwoven plant RS-SP/MF/V21/R/K12 for manufacturing various nonwoven products

The nonwovens plant incorporating the random card K12 is the most flexible nonwovens plant in respect to denier and weight ranges.

Products from approx 20 to 2000 g/m^2 made out of synthetic or natural fibres can be produced. This nonwoven line is built up to 5.4 m working width and is avoiding a cross lapper which is of special importance when producing, for example, interlinings 40 or 50 g/m^2 as well as spray bonded waddings and needle punched products ranging up to 1000 g/m^2 on one and the same production line.

A special designed multipurpose line can produce interlinings, spray- and thermobonded waddings as well as needle punched material (filters, geotextiles, shoelinings, etc.) at high efficiency level and without keeping capital intensive equipment idle.

3. NEEDLE PUNCHING MACHINERY

The Fehrer company can be considered as a pioneer in modular designed needle looms where each driving module is fully balanced so that the needle loom does not require any foundation and each driving module is lubricated by oil, which is still the only medium assuring excellent lubrication and cooling at all speed levels of the excentric drive system.

A. Regular Needle Looms for Flat Products

Needle looms are considered as machineries with a random arrangement of the needles for mechanical felting. A wide variety of up- and down stroke-machines are available with needling densities ranging from 1,000 to 30,000 needles per linear metre and needle boards arrangements for down- or up-stroke motion alone, that is, up-and down-stroke motions in one machine.

B. Structuring Needle Looms

Here we have to make the difference between structuring needle looms with lamella bed and stripper plate configuration, like the NL11/SE as shown in Fig. 6.2, and structuring machines with a brush conveyor instead of the lamella bed plate, which needles randomly (NL21/SRV, shown in Fig. 6.3).

C. Papermaker Felt Needle Looms

With papermaker felt needle looms the modular design is of special importance as by lining up the modules any required working width can be achieved.

Papermaker felt needle looms are manufactured in widths up to 15.0 m and needle zone arrangements according to the customer's request.

4. NEW DEVELOPMENTS

4.1 Random Card K12 with High-Loft Device

When manufacturing high-loft products for waddings the main target to

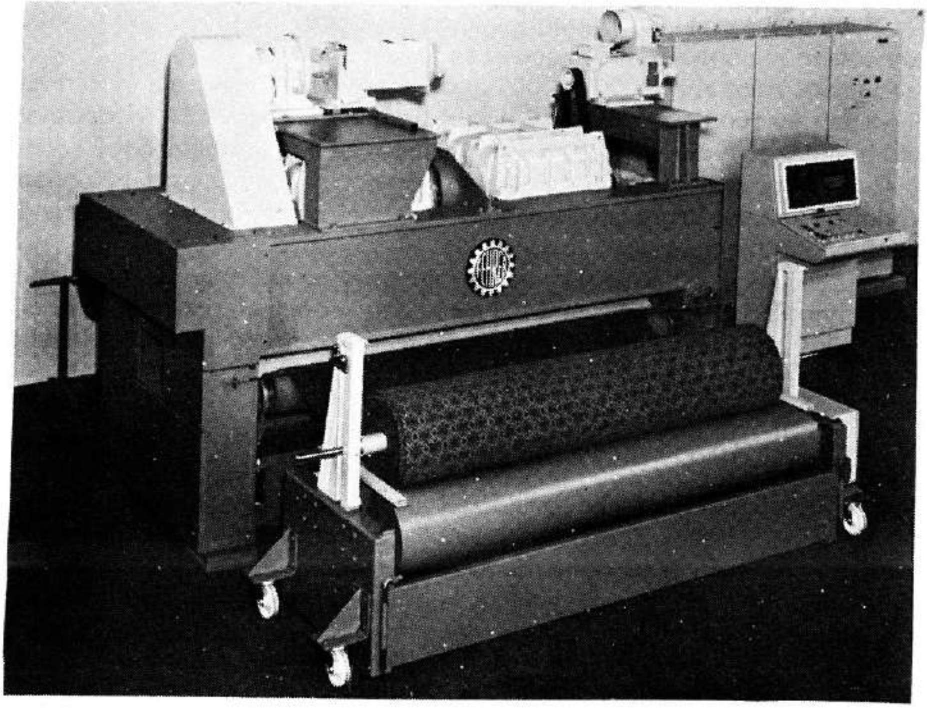

Fig. 6.2 FEHRER structuring needle loom NL 11/SE for manufacturing loop and velour carpet as well as carpets with various designs

achieve is to store air in between fibres in order to obtain a good insulation value of the product.

Generally, aerodynamically formed webs have a better resiliance and recovery than carded and cross folded webs because of fibres which are also laid in the third dimension.

The Fehrer K12, which is delivering the fibre from the main drum to a perforated conveyor, has been modified by adding a suction drum so that the fibre stream released from the main drum is divided and more fibres are laid vertically, which gives again a better resiliance and more loftiness.

The product itself is also more voluminous compared to a Random Card K12 web produced without the High-Loft device.

Practical tests have been carried out with great success and 6 months after introduction, already five wadding producers (mainly from Europe and USA) have this device in successful operation.

4.2 Computer Aided Patterning Simulation for Structuring Machine NL11/SE (CAPSIM)

The CAPSIM is actually a software program introduced by Fehrer to enable the development of designs for structured carpets on a computer which is built into the operating panel of the machine.

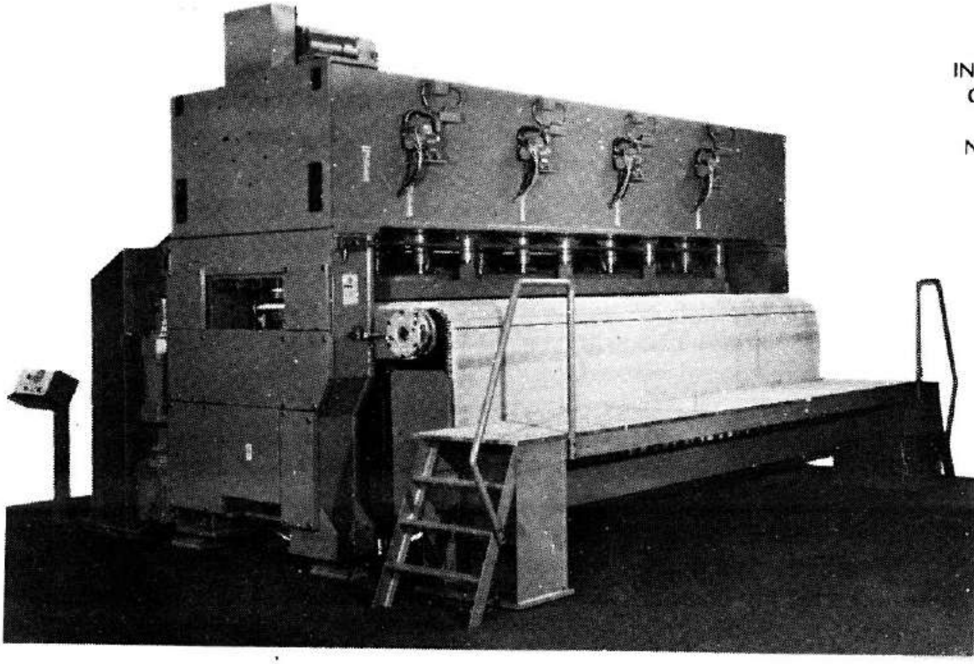

Fig. 6.3 FEHRER structuring needle loom NL21/SRV for manufacturing random-velour carpets

The program is laid out to have the possibility to make the needle arrangement on the computer and it can be simulated with the actual needle loom settings. This combination is showing the final carpet design on the screen.

The time and money saving is tremendous as up to now it was necessary to make the design on a piece of paper and to set the needle board accordingly for a trial run with material in order to see the outcome of the design.

With the CAPSIM the needle setting in the board, which is time consuming, can be avoided and furthermore waste of trial material is absolutely minimized.

4.3 Online Customer Assistance Link (ONCAL)

Machines which are produced nowadays incorporate more and more electronic components and are controlled by programs supplied by the machinery producer.

As everybody knows, electronic system can fail because of various reasons and usually the repair is simply done by reprogramming or changing some integrated circuits.

As a help for carpet producers who operate electronic structuring machines type NL11/SE, Fehrer has incorporated a remote service system (ONCAL) as standard equipment which allows to hook up with the Fehrer Service Centre in Linz by ordinary telephone connection with a modem in case of any electronic failure on the machine.

Fehrer has started this type of service several years ago for controls of papermaker needle looms and electronic structuring machines. Many machine manufacturers (not textile machine manufacturers) are offering this service as standard and the tendency is that devices like the ONCAL will be a standard feature of a machine in the future.

4.4 F9 Needle Pattern

The aim of plain needling is to achieve a mechanical interlocking of the fibres. A point which became more and more important, is the good surface. Specially products like synthetic leather, papermaker felts, filter material, require an optimum felt surface.

The idea when developing the F9 needle arrangement was that an infinite number of needles will leave absolutely no mark on the felt surface.

As there is no possibility to go to infinity with the needle density we have designed a needle arrangement where needles are packed in groups and the arrangement of this group of needles was optimized by computer simulation.

The F9 pattern is using standard needles with a shaft diameter of 15 gauge as used in any ordinary needle loom. The needle density on the F9 needle pattern is approx 10,000 needles per linear metre. One package contains five needles which are arranged again in a random manner.

As mentioned already, this type of dense needle board is predominantly used in areas where the felt surface is of great importance, that is, where high needling densities are necessary, like artificial leather, coating substrates, filter products, etc.

4.5 Variofelt Technology for Papermaker Felts

Since Fehrer is having a market share of about 95% on papermaker needle loom's supply all over the world, one of the major development in this field should be mentioned here.

The Variofelt system, which is built onto a papermaker felt needle loom, is allowing the user to design felts with cross orientated web layers as well as longitudinal laid webs.

It is possible to lay and needle webs with different fibre orientation in any sequence desired, without manipulating the felt. Any combination of MD, CD and random webs and needling passages is possible, with the felt tension being permanently controlled. The felt tension can be freely selected, determined only by the felt design, but independant of the Variofelt process.

Variofelts are primarily used where low-vibration run of the paper machine and a high quality of the felt surface and a high dewatering capacity are demanded, as for example, pick-up felts, felts for photographic paper, felts for board machines, etc.

Combined felts with MD, CD oriented and random webs have proved to show the best results in the papermaking machines.

Fehrer is investing about 8% of the turnover in research and development and is maintaining a demonstration room where all new developments can be tested and where trials with customers' material can be carried out.

Fehrer is delivering nonwoven plants and needle looms to more than 80 countries all over the world and the target for the future is to strengthen the position of Fehrer as the market leader in needle punching machines.

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7

Synthetic Leather and Products Using High Grade Heat Resistant Fibres

H.G. MITTERMEIER

Attempts to replace leather with a synthetic substitute were initially made in Germany, around 1940. PVC and polyurethane coated knitted fabrics were used. These products had fraying tendency. With the introduction of matrix fibres, it has become possible to produce effective leather substitute from polyurethane bonded needle punched fabrics. The synthetic leather produced is uniform and free from creases as well as odor.

The matrix fibres are bicomponent fibres. The micro-fibres having high degree of porosity, comfort and wear resistance are produced by dissolving the matrix in a suitable solvent.

The micro-fibres are opened, blended, carded and converted in a web. Then the fibres in the web are reoriented in the preneedling loom and needled with suitable needles. After completion of the needling process, the synthetic leather material goes through coating and impregnation processes, as well as press and slit operation, depending on the final applications the material is made for.

Meta- and para-structured aramid fibres such as Nomex and Kevlar are used for high grade products. For instance, para-aramids are used for aircraft and spacecraft industries, while meta-aramids are used for protective clothing and as electrical insulation. Synthetic leather from these fibres is produced by first converting them into web by the usual process and then needled with special needles, which can withstand extreme wear and tear. Additional fabric finishing processes, such as coating bonding or impregnation are not required, since these finishes cannot withstand the application requirements. For high grade heat resistant products one can use glass, carbon, steel, stone, and ceramic fibres.

1. INTRODUCTION

The efforts made, either to supplement or to replace genuine leather by the shoe and leather goods industry with needled fabrics started in Europe, especially Germany, around 1940. The development of artificial leather at that time was for political and economical reasons. For several years now, we have been experiencing a worldwide shortage, and consequently higher prices for genuine leather. The demand for synthetic outer fabrics has rapidly increased in the last few years because of the increase in usage on a *per capita* basis.

In the past, mostly layered woven and knitted fabrics coated with polyvinylchloride or polyurethane were used; however, the length and crosswise durability differed greatly and needed to be considered during the manufacturing process. These products were not suitable for the shoe industry because of their fraying effect.

At the beginning, in order to stabilize the fabric, a thin woven layer was laid in between the needled fabric and the top cover, which was either flat or napped.

Only through the revolutionising introduction of the matrix fibres, in connection with complicated polyurethane bonding, it was possible to produce needled outer fabrics which could be used in place of velour type leather. The application of this base material could be applied to the shoe and apparel industry because it fulfilled the necessary requirements like maintaining its form and shape, absorbing steam, porosity, and resistance to fading, etc.

Other advantages of synthetic leather compared to genuine leather are: crease free, odorless, and fabric uniformity. For example, qualitative and fashionable velour split leather products under the name of ALCANTARA or AMARA were developed. Another example which captured the market was sport and leisure shoes made out of fine fibre needled material.

During the mechanical stabilisation of the matrix fibres, which contain tiny elements of fibril, the matrix itself is dissolved, leaving very fine fibres of 0.01 denier behind. These micro denier fibres provide a high degree of porosity, which gives the fabric the desired comfort and wear resistance. The so-called matrix/fibril fibres are bicomponent fibres made primarily out of a polyester/polyamide composition in the 3-5 denier range.

The relatively low priced fine fibre needled material can be made out of a blend of polyamide, polyester, polypropylene, and viscose rayon. In most cases a higher percentage of polyamide and polyester is used in combination with a lower percentage of viscose rayon. The fibre denier size ranges between 1-3 denier with a material weight ranging between 200 and 600 g/m^2 for matrix/fibril fibres and also for fine fibres.

2. PREPARATION /MANUFACTURING

After the fibres pass through the fibre opening process which is shown in Fig. 7.1, they go on to the mixing chamber for the proper blend of denier size and colour. Figure 7.2 shows a typical mixing bin. The staple length of the fibres is between 40 mm and 90 mm. Longer fibres have the characteristics for better interlocking during the needling process, thus increasing the stability of the material.

Through the fine carding system and cross-lapping, as well as other feeding systems (Fig. 7.3) developed by the various machine builders, the established web is then fed into the preneedling machine.

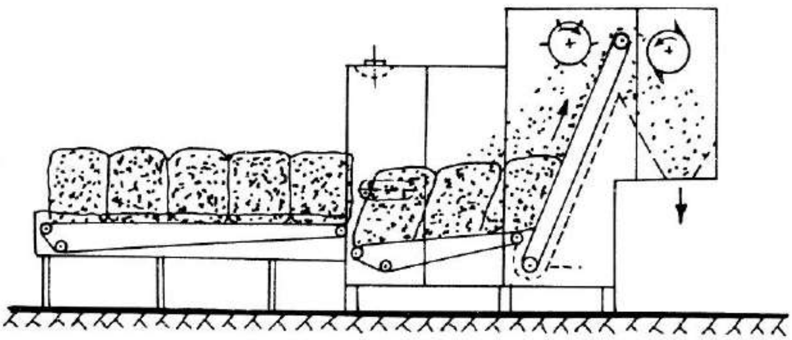

Fig. 7.1

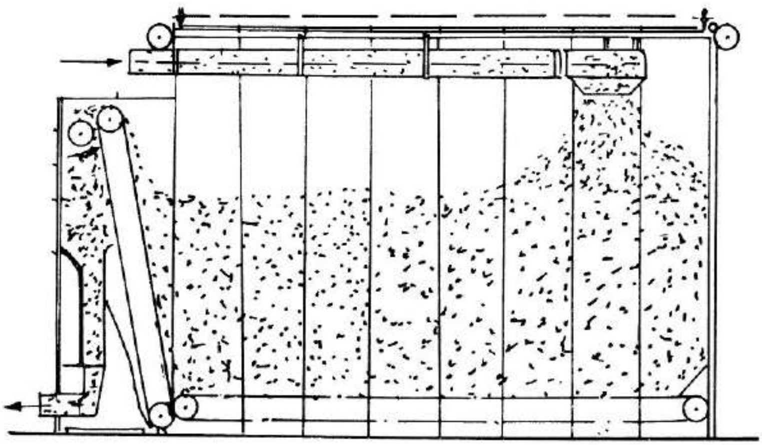

Fig. 7.2

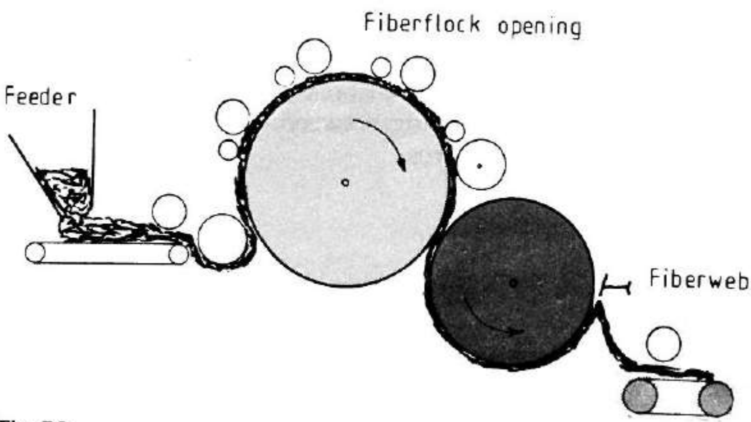

Fig. 7.3

3. NEEDLING PROCESS

The fibre orientation in the fibre web is basically in a horizontal position. In order to achieve the required high material density, the fibres need to be oriented from their original horizontal position to a vertical position. For this reason, penetrations per cm^2 (PPSC) of 1,500 to 3,000 are necessary. To achieve this on only one needle loom, the material needs to be run through the loom several times; therefore, it is advantageous to have 4-6 individual looms, preferably with top and bottom needling capabilities and needle board density of up to 10,000 needles/m. This arrangement makes it possible to produce the material in one or a maximum of two runs.

4. PRENEEDLING

The first compression of the fibres through mechanical needling takes place in the preneedling loom. Figure 7.4 shows the preneedling operation in principle. The fairly bulky fibre web requires needle looms with a stroke height of 60 mm to 90 mm and specially designed web feeding systems to avoid warping or distortion of the web.

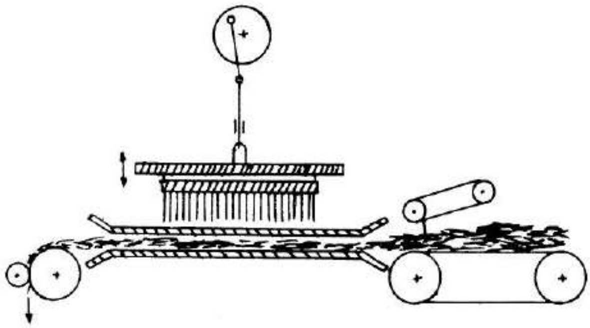

Fig. 7.4

Depending on the fibre size, the most commonly used needle sizes are 36 gg and 38 gg (Fig. 7.5). The working part length of the needle should be as short as possible since the load put on the needle, especially in the first

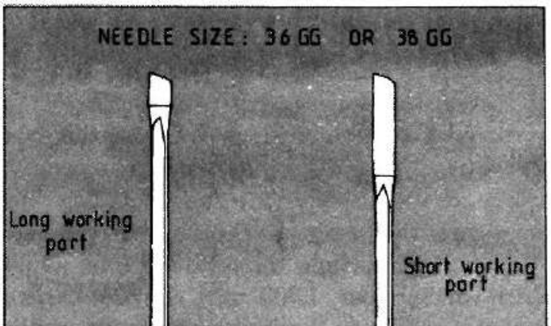

Fig. 7.5

3-5 rows, is extremely high due to the shifting force on the various layers of web. A shorter working part increases the stability of the needle.

The number of barbs on each apex for preneedling should be as low as possible. The load put on the needles with the usual three barbs per apex is too high for this application. It is recommended that needles with only one or a maximum of two barbs per apex are to be used. If needles with two barbs per apex are used, smaller barb sizes are recommended in order to compensate the penetration force in relation to needles with only one barb per apex. The barb spacing can be either R, M, or C.

During the entire needling process, the type of barb style is very important. For fibre protection and longer needle life, as well as an improved fabric surface quality, a three dimensionally formed barb is preferred over a conventional cut barb. The conventional or cut barb style has relatively sharp edges along the barb which damages the fibres, resulting in loss of fabric strength and an uneven surface. Both barb styles show the difference in fibre holding and fibre damage.

At a PPSC of 80-180 and a penetration depth of between 8 mm and 11 mm, the web volume and its density is drastically changed. The fibres in the web are now interlocked and fixed; therefore, the danger of needle breakage in the finishing loom is reduced.

5. FINISH NEEDLING

The next step in the needling process is the intermediate and finish needling. Since the preneedled material is reduced in thickness, the looms used for the intermediate and finish needling have a reduced length of stroke of approximately 40 mm, but run at higher operating speeds. The penetration per cm^2 in both operations at each loom are approximately 250–300, with a penetration depth between 4 mm and 11 mm. The penetration depth is gradually reduced from loom to loom in order to achieve a clean and even surface quality. The needles used can be 38 gg, 40 gg, or 42 gg, and for special applications can go as small as 43 gg with barb sizes of 46 gg or even 48 gg. These small barbs have very little fibre carrying capacity per penetration; therefore, they produce a very smooth and high quality material surface.

The number of barbs per apex can vary between 2 and 3, and in most cases have regular barb spacing. Needles with closer barb spacing like C or M normally produce a rougher material surface and also increase the load put on the needle (Figs. 7.6 and 7.7).

A very important factor especially for the intermediate and finish needling operation is the distance from the point to the first barb. The standard distance for this dimension is 6.36 mm (Fig. 7.8). Especially for needle looms which are running at a high speed which can be over 1,000 rpm, in most cases a shorter distance from the point of the needle to the first barb is required in order to make sure that the material is running without problems through the needle looms. With that shorter distance from the point to the first barb you can decrease the penetration depth by more than 3 mm but achieve the

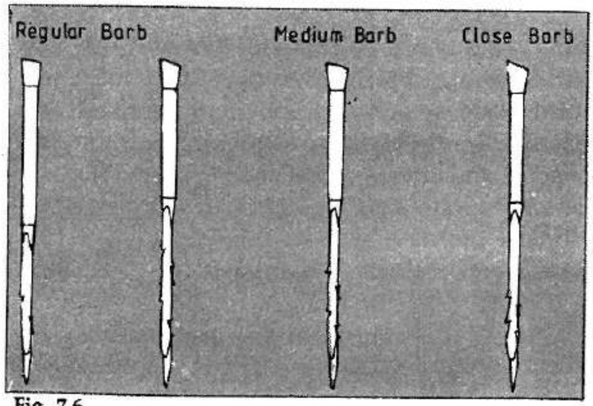

Fig. 7.6

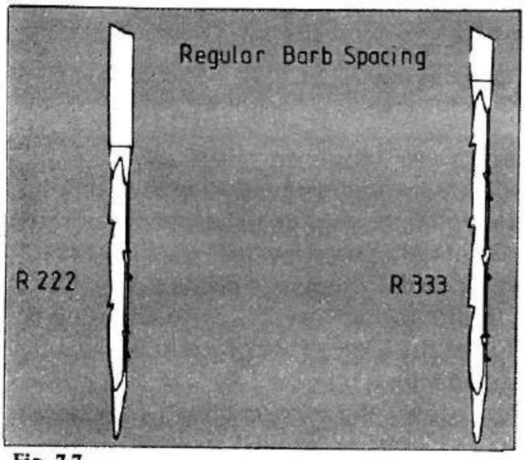

Fig. 7.7

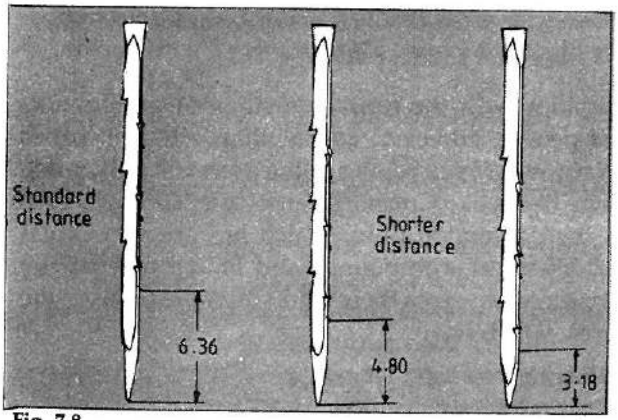

Fig. 7.8

same product properties as with a higher penetration depth. The other advantage of reduced distance from point to first barb is the fact that time is shorter when the needles are in the material during the continuous advance per stroke.

The point of the needle should be a sharp point style; this prevents any fibre transport by the point of the needle, which could negatively influence the surface quality. This point style selection applies to preneedling, intermediate, and finish needling. Figure 7.9 shows different point styles. The second point shape on the left-hand side is called sharp point style.

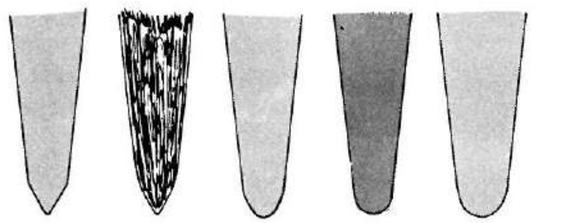

Fig. 7.9

Another important factor in regard to fabric uniformity during the needling process is a well established needle rotation system. The needle boards should be rotated at a predetermined operating time towards the direction of the output side of the loom. This method insures that new needles are always in operation on the input side of the loom and needles with the longest operating time are on the output side of the loom. This procedure certainly helps to produce the desired surface quality.

After completion of the needling process, the synthetic leather material goes through coating and impregnation processes, as well as press and split operations, depending on the final applications the material is made for.

6. SPECIALLY TREATED POLYAMIDE FIBRES : ARAMID

Most people are not too familiar with the term aromatic polyamide, also referred to as Aramid. Most people, however, are familiar with the names Kevlar or Nomex, these two types of fibres belong to the aromatic polyamide group, as well as other known fibres like Conex, Twaron, and Technora . All these fibres originate from the polyamide fibre, which has been modified through specially developed chemical compounds and linked together by amide linkages. This special procedure gives these fibres advantages over the conventional polyamide fibres, which have:

- good chemical consistency
- high and consistent heat resistance
- flame resistance
- high tensile strength
- low elongation, etc.

There are basically two modified fibre types. One of them is the aramid fibre with a meta-structure, which is an oblong fibre cross-section also known under the trade names Nomex or Conex. The other one is the aramid fibre with a para-structure, which is a round fibre cross-section sold under the trade names Kevlar or Twaron.

The achievement of these special chemical and physical characteristics was the result of a constant demand for high grade products for a variety of applications. For example, para-aramids are used by the aircraft and spacecraft industries because of their resistant characteristics against toxic gas, heat, and fire. Para-aramids are also used for productive clothing by the steel industry and as electrical insulation in transformers and motors.

Today para- or meta-aramids are used more and more for sporting equipment, ropes, and gaskets due to their high tensile strength and low elongation characteristics. Aramid products are used by the automobile industry for products such as clutches and brakes. Aramid fibres with a meta-structure, for example, are used for protective clothing in laundries or for various medical products, as well as sheets and face masks. Another important application for meta-aramids is the hot gas filtration. The non-flammable characteristics of the aramid fibres, especially with para-structure, makes the fabric produced from these fibres ideal for work clothes and upholstery. High density material made with aramid fibres is also effectively used for bullet-proof vests.

These aramids are being constantly improved. Just recently, for example, a German company developed a special fibre finishing process to increase their resistance towards chemicals. These characteristics are especially important for filtration material by immunizing the fibres and reducing the adhesion of dust particles. This makes the filters more effective and easier to clean.

Some of the unfavourable characteristics of the aramid fibres such as fibre colour are being improved. For a long time, a para-aramid such as Kevlar, for instance, was only available in a not too appealing shade of yellow. A meta-aramid such as Nomex was available only as unbleached white. Today, all of these products are available in a wide range of colours.

7. PRODUCTION

The fibre and web preparation is basically the same as for all needled products; however, there are certain characteristics of these aramid fibres that make it necessary to handle them more carefully during carding and cross-lapping because of their high tenacity, which is higher than steel. The carding and cross-lapping speed, as well as the web weight, needs to be controlled.

The felting needles are exposed to extreme wear and tear. For this reason, we recommend using special needles with a low fibre carrying capacity per penetration in order to minimize the load put on the needles and the machine. Special fibre lubricants are needed to reduce the resistance to needle penetration and fibre loss.

Needles with only one or a maximum of two barbs per apex in 36 gg or 38 gg are recommended (Fig. 7.10). The barb size is in most cases smaller than the working blade and in HL-style, meaning three dimensionally rounded

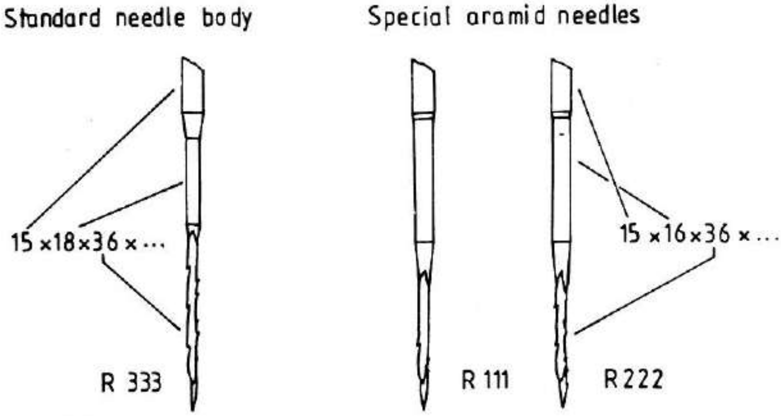

Fig. 7.10

edges. The working blade length should be as short as possible in order to increase the stability of the needle. A longer changeover taper from the working part to the intermediate blade reduces the breakage of the needle. Also to minimize deflection, the diameter of the intermediate section is equal to a 16 gg needle.

The denier size of the fibres made from para-aramid is between 1.1 and 1.3 denier and on meta-aramid fibres the denier size ranges between 1.6 and 12 denier. The staple length of both fibres is between 38 mm and 120 mm. The longer the staple length the more difficult it is to needle them, which also increases the load put on the machine.

The various applications require a wide variety of fabric weights, which range from 70 g/m^2 up to 4,000 g/m^2 and penetration of 70 to 600 penetrations per cm^2. Preneedling and finish needling are usually done with the same needle type at an average penetration depth of 11 mm. Most of the aramid products can be made on one or a maximum of two needle looms.

Additional fabric finishing processes such as coating, bonding, or impregnating are not required because in most cases, any of these applications would not stand up to the application requirements. Therefore, the specifications of the end-products such as thickness, density, weight, etc. need to be achieved through the needling process.

There are many other fibres available today used for high grade and heat resistant products made from glass fibres, carbon fibres, steel fibres, stone fibres, and ceramic fibres. Most of these fibres are already used by the US needle punching industry.

Groz-Beckert KG
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8

The Application of Needle Felting Technology for Technical Textiles and Home Furnishing

VIJAY P. GUPTA

Mechanical bonding of fibrous web started with coarse fibres and after multiple modifications was made applicable to waste and manmade fibres. The share of needle felting and other nonwoven technologies, namely thermal and chemical bonding, has become very popular.

Parallel to classical needle felted products more and more technical felts are developed and make our major business. Another development made by DILO, namely DI-LOOP (1969) gave great push to floor and wall coverings. One of the most unique and successful developments of DILO is the DI-LOUR technology for producing randomized velours. Automotive linings, home furnishing fabrics and decoration felts can be produced to compete with classic velours.

The DI-LOUR structured felts are produced for automotive uses between 200–800 gsm and are used in different car sections. As usual in DILO's research centre new velours products have been developed for home furnishing, apparel and shoe linings, etc.

This paper discusses the technological concepts for the production of multiple technical fabrics, like industrial filters, geotextiles, insulation materials and paper maker's felts as well as technologies to produce moulded car carpets and other car interiors and home furnishing fabrics made out of DI-LOOP and DI-LOUR.

1. INTRODUCTION

The major use of nonwoven technology and nonwoven products is no more dominating only in highly industrialized countries, although there is a considerable difference in production figures between durables and disposables. There are sturdy quality and economical reasons which make some durable nonwovens inevitable also for developing countries. This is specially the case with technical textiles, e.g. industrial filters, paper machine felts, geotextiles, insulation felts, automotive fabrics for insulation and interior decoration, roofing felts and floor coverings and a further large range of products. A table obtained through Edana/Hoechst shows for

Europe (Fig. 8.1) the growth of polyester fibres for classical textile sector and nonwovens sector between 1975–1995 [1]. For typical nonwovens fibre polypropylene (PP) the annual growth rate is still higher (Fig. 8.2). Another chart of Edana shows the growth of nonwovens between 1978–1990 (Fig. 8.3).

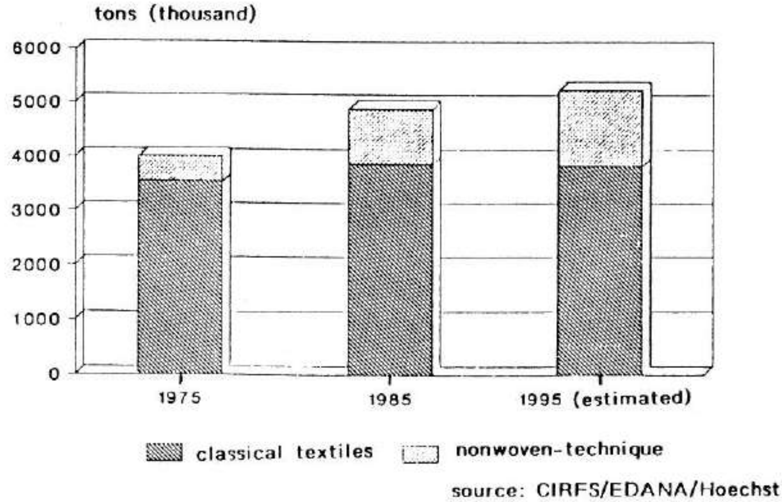


Fig. 8.1 Total fibre consumption in Western-Europe

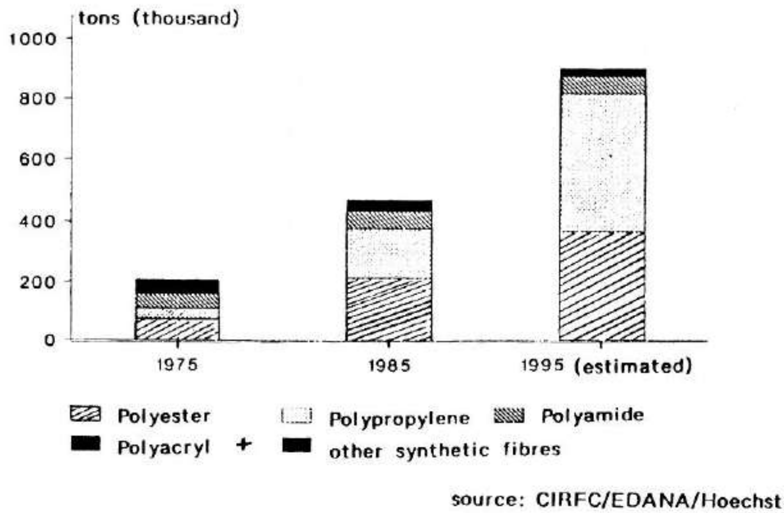
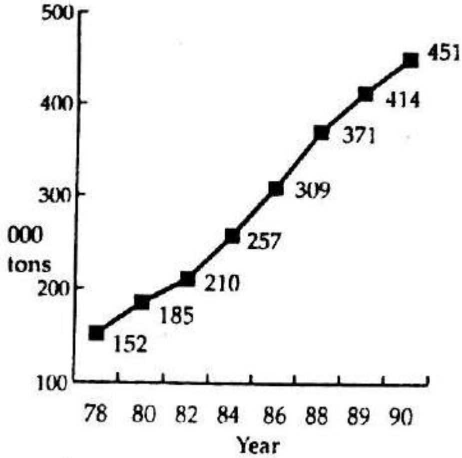


Fig. 8.2 Synthetic fibres in nonwovens in Western-Europe

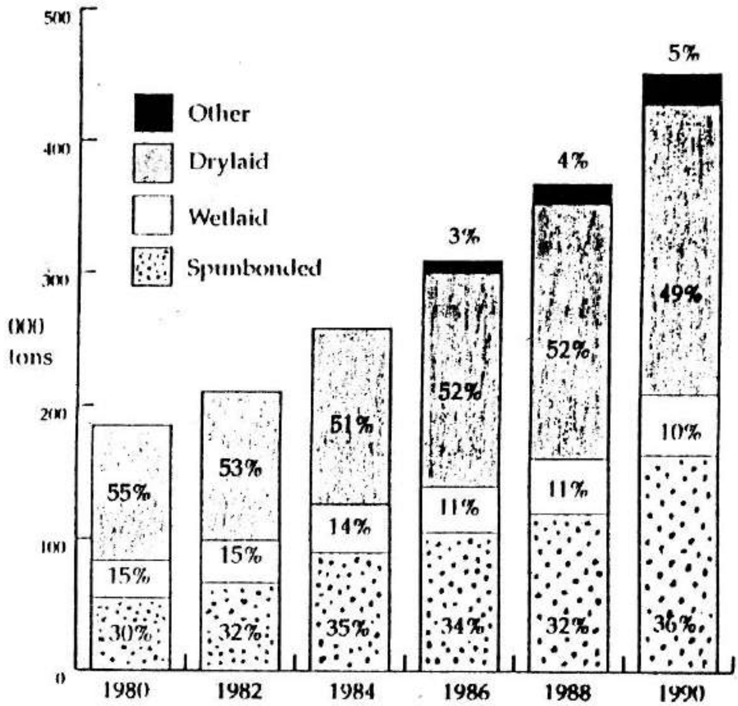
Amongst the three major technologies to produce nonwovens, the mechanical and thermal bonding processes are preferred due to environmental protection and economic reasons. Although the chemical bonding offers in some cases superior end-products and in many other cases is used as a finishing process to obtain the required product properties. As a result all three technologies are in practical use and have their justified applications.



Source: EDANA

Fig. 8.3 Production of nonwovens in Western-Europe

Figure 8.4 shows the share of nonwovens by manufacturing process including wet-laying and spun-bonding [2].



Source: EDANA

Fig. 8.4 Nonwovens production in Western-Europe by manufacturing process

2. NEEDLE FELTING FOR TECHNICAL FELTS

One of the main advantage of nonwovens and specially needle-felting technology is that one can utilize the fibre and felt properties in an optimum way and the manufacturing technique itself offers numerous ways to achieve the desired product profile. Geotextiles and aerosole filters are typical examples which are produced in large quantities with the needle-felting process. DILO introduced more than a decade ago its own process and majority of staple-fibre geotextiles are made today with this method. Figure 8.5 shows this production line, which consists of three processing steps [3].

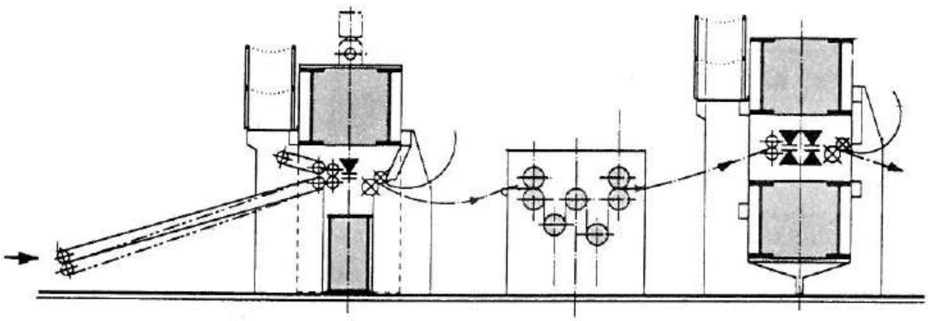


Fig. 8.5 Schematic illustration of DILO's needle felting line for geotextiles

The whole process is based on the carding and cross-lapping system in which the fibres are cross-laid by a cross-lapper in desired width. After the batt is made which should have almost double the area weight than required in the final product, it goes into a pre-needle loom through a special material feeding-system, so-called Compressive Batt Feeder (CBF). Pre-needling reduces the batt volume and a stitch density of 30–40 stitches/cm^2 imparts sufficient strength, so that an uniform drafting can take place. This pre-needled felt is fed into the following drafting machine type VE 4 which is of special design (Fig. 8.6).This machine has two pairs of rollers, one at the entry side and one at the delivery side. In the middle there are three rollers with a special grippy surface. Two of the middle rollers, namely 2nd and 4th, are adjustable in height so that the length of the drafting zone can be varied according to the felt properties. Totally 4 drafting zones are available and the drafting ratio is gradually increased from the entry side to the delivery side. For this purpose total 5 DC-drives are mounted so that the speed of each roller can be individually regulated. In practice a drafting ratio between 80 to 100% is set to obtain the required MD : CD ratio.

MD: machine direction
CD: cross direction

Following physical properties and characteristic values should be considered for optimization:

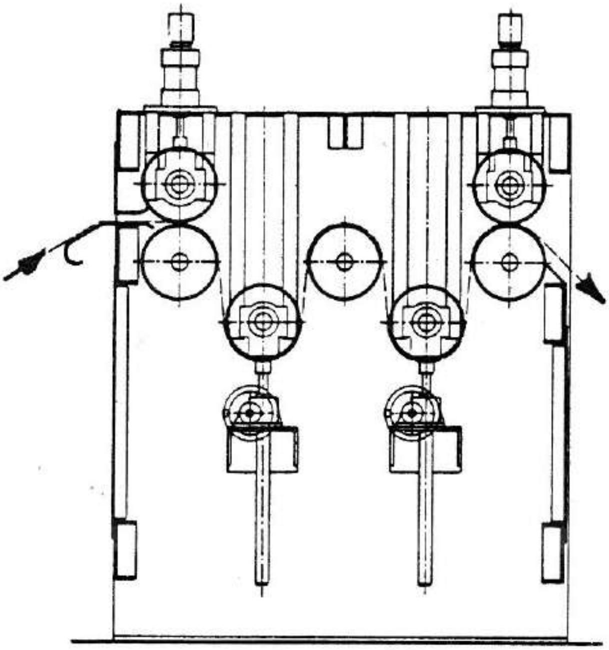


Fig. 8.6 Principle of DILO's drafting machine for pre-needled felts

* Isotropy: tensile strength and elasticity should be independent of direction. A MD:CD ratio of 1 : 1.25 is in most cases sufficient
* Homogeneity regarding area weight, tensile strength and elastic properties
* Tensile strength and elasticity, initial modulus
* Void ratio, effective width of opening, they determine the hydraulic properties and filter effect.

For most of the applications an approximation to isotropical tensile strength, i.e. approximately same tensile strength in all stress directions in the nonwoven plane is required. This requirement is almost fulfilled with spun-bonded and approximately achieved by aerodynamically laid nonwovens (tensile strength ratio 1 : 1.2–1.4). On the contrary by cross-laid batts with cross-wise fibre orientation (tensile strength ratio MD:CD 1 : 3–5), a subsequent reorientation of fibres is necessary.

The question whether an aerodynamical batt making or a conventional carding/cross-lapping method is better, cannot be answered in lump sum. Both the processes have their claims as well as advantages and disadvantages. The batts made with aerodynamical methods have a relatively random fibre arrangement. The fibre arrangement is not only horizontal rather also vertical. The share of these vertically oriented fibres, arranged so to speak in the third dimension, becomes larger with increasing area weights. While this phenomenon can be advantageous for certain end-uses it is an obstacle to achieve higher tensile strengths. These fibres contribute only minimum to the tensile strength. Moreover one should also consider that during needling a share of fibres is additionally transported from the horizontal to the vertical direction. There are also limits to fibre length which in fact imparts higher strengths.

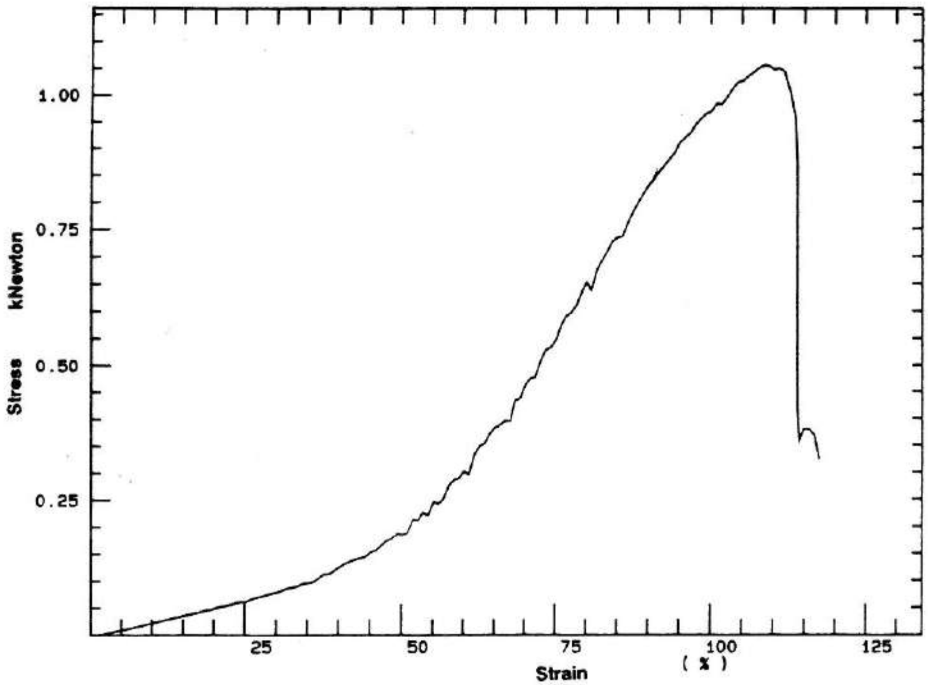
For high demands regarding tensile strength and initial modulus, one prefers the conventional carding and cross-lapping process.

3. FILTER FELTS

Nonwoven filters for dry and wet filtration have already reached a billion US-$ business and can be characterized as high-tech products. Due to strict environmental protection laws, the major share of these filters is obviously in the USA, Europe and some other highly industrialized countries. It is obvious that cleaning of polluted air or liquid costs money and only by valid and effective laws a contamination of our breathing air and drinking/bathing water can be avoided. Needle felting offers economic and technical superiority over conventional woven/knitted filters. The major use of needle-felted filters is in dry so-called aerosole filtration and liquid filtration. In addition to that there are so many other uses in day-to-day life like heating, ventilation, air-conditioning,vacuum cleaner, kitchen exhaust hoods, car engines and car interior, etc.[4].

The types of filter materials, fibre types used and methods to manufacture them is so vast that the theme can be handled in numerous papers. In short one can say that the filtering properties of a filter medium depends equally on fibre properties and on the bonding process. A combination of these two factors enables to achieve a defined product profile. One of the special features of filter felts is their 3 D-construction [5]. The filter effect is not only on the surface of the medium rather also in the felt itself. It is also possible to have a so-called progressive fibre build-up, coarse, medium and fine and ultimately to step by step filtering. The coarse dust particles are caught by the outside layer and the finer particles are captured by the inside layer. Through the third dimensionsal filter effect, it offers a large filtering surface, enables a high filtering efficiency at high air speeds and at the same time causing less pressure drop. The void ratio lies by needle felts, depending on the felt density between 60–90%. The pore size can be much larger, say, e.g., between 20–60μ and even with particle size of approx 1μ one can achieve high filtering properties. The separation of the dust is a phenomenon of bouncing, blocking and diffusion effects as well as electrostatic generation. An important development of needle felt filters is in the field of hot-gas filtration by using special thermic resistant fibres.

DILO's needle felting machines are used primarily for the production of reinforced needle felts, but also single layer felts without any scrim. The reinforced filter fabrics mean a needle felt using a woven fabric in it to give higher strength and low elongation. Figure 8.7 shows two curves showing the stress-strain diagrams of a typical needle felt and one with reinforcement. One of the main criterion of filter fabrics is comparable high densities which



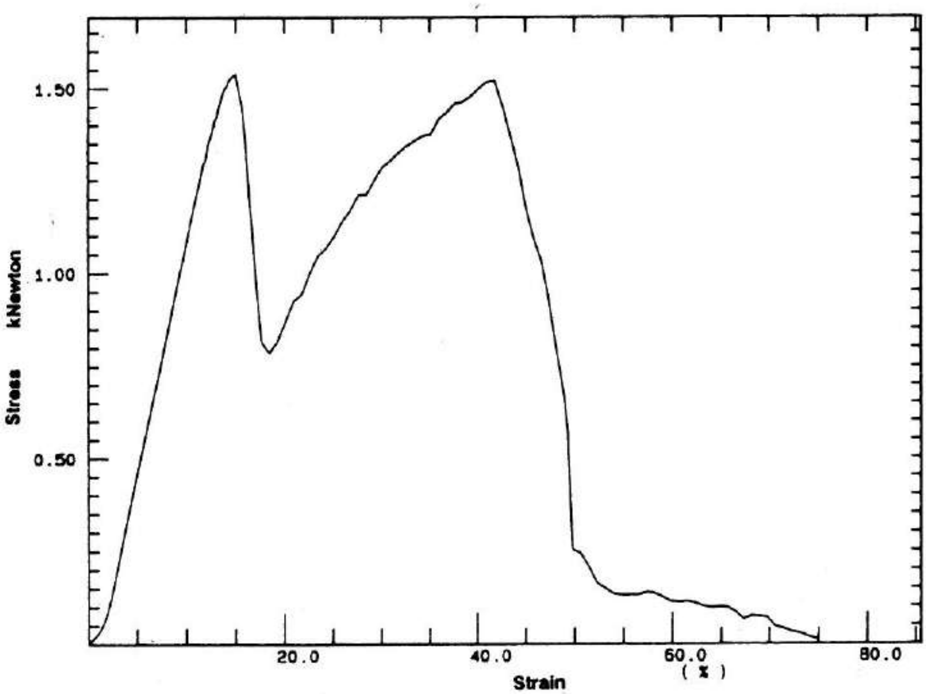


Fig. 8.7 Stress-strain curves of a normal (a) and a reinforced (b) needle felt

lead to the installation of a number of machines. For this reasons a double-sided needle loom type DI-LOOM OUG-II which works from top and bottom simultaneously (Fig. 8.8) is most suitable. This machine incorporates two machines in one and has following advantages:

— less space, energy, operating personnel requirement and low noise level
— investment costs saving
— maintenance and spare parts saving
— in many cases better product surface and higher felt density.

The typical construction of reinforced felts is that the scrim is imbedded between two fibre felts. For this purpose two felts from top and bottom are

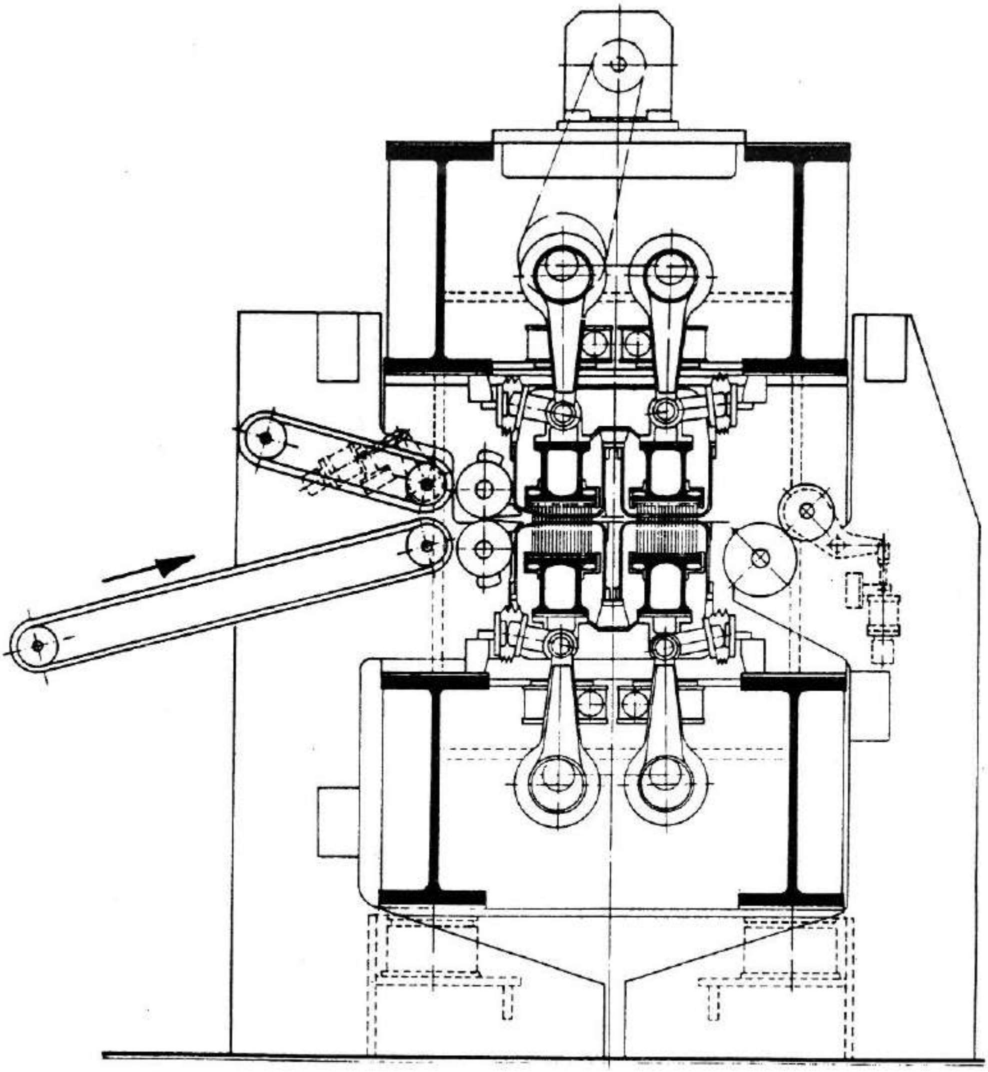


Fig. 8.8 DILO—double sided needle loom type OUG-II

required for which two alternative installations are most common (Fig. 8.9a and 8.9b). In the first installation the process is discontinuous and a pre-needled felt is produced and rolled-up. On an off-line double-sided needle loom, two pre-needled felts and scrim are fed together and needle felted simultaneously from top and bottom. In the second installation, one requires two cards, two cross-lappers and two double-sided needle looms. This is obviously more productive and requires less material handling, but at the same time is more capital intensive.

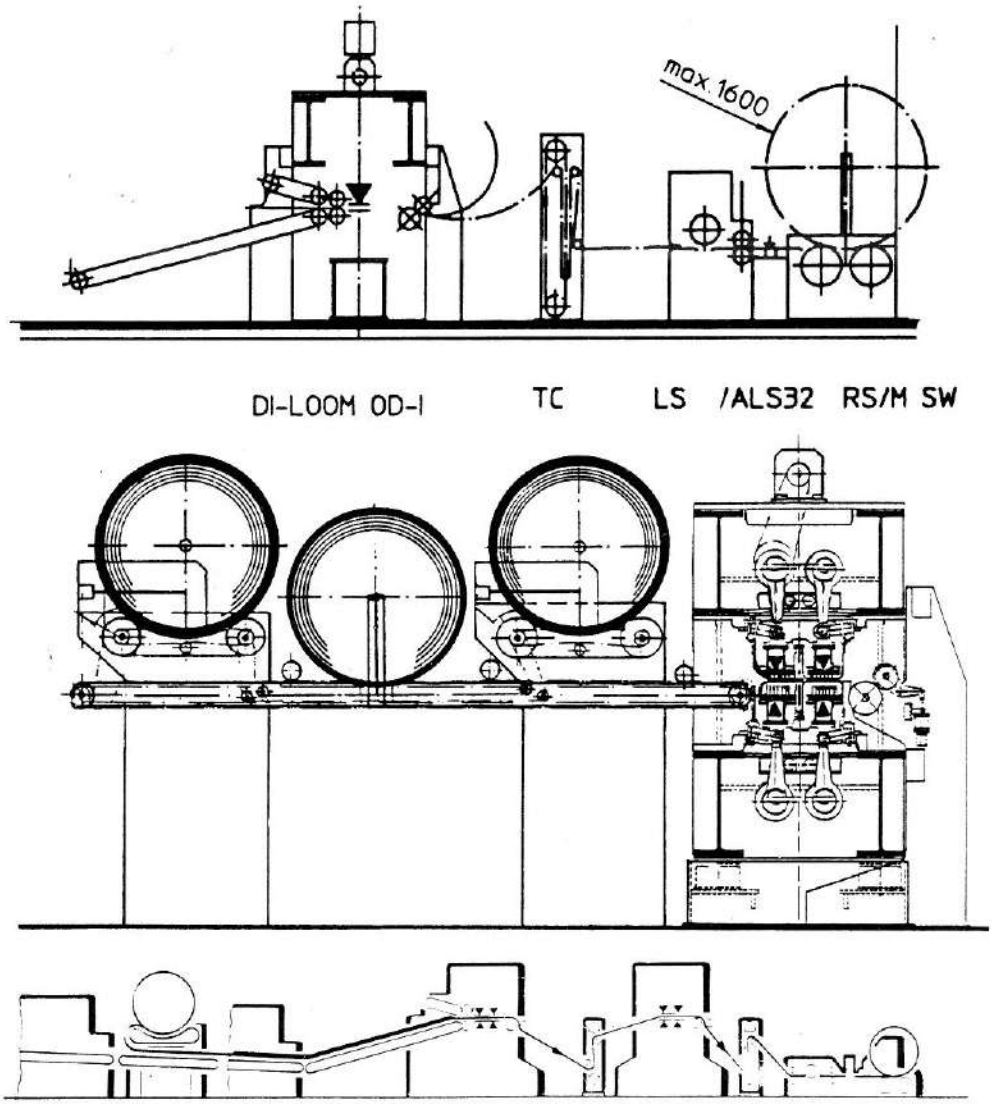


Fig. 8.9 Discontinuous production line for filter fabrics: (a) pre-needling line with batt-feeder and finish-needling line with three unwinders (b) continuous production line with two cards, 2 crosslappers and 2 double-sided needle looms

Technical felts represent a vast range and all products cannot be discussed here. Still I wish to mention the importance of glass fibre, rock-wool and ceramic fibre felts for insulation purposes which are increasingly needle felted [6]. This is cheap, rational and favourable to ecology. Also for this purpose our double-sided needle loom type DI-LOOM OUG has proven to be most successful (Fig. 8.10a&b). Needling parameters can be set in such a way that either the high voluminosity can be preserved or more denser and desired surface properties can be obtained. Specially for acoustic and thermal insulation the enclosed air volume gives a high damping or heat insulation effect.

After some constructive modifications and specially by changing mode of operation 'top and bottom simultaneously' it has been possible to give sufficient strength and desired (less) volume reduction to such insulation felts.

4. FURNISHING FABRICS

According to end-use requirements, all fabrics have some product profile and have to fulfil certain properties. Furnishing fabrics for upholstery furniture, car interior, car seats, decoration felts, etc. are areas where structured

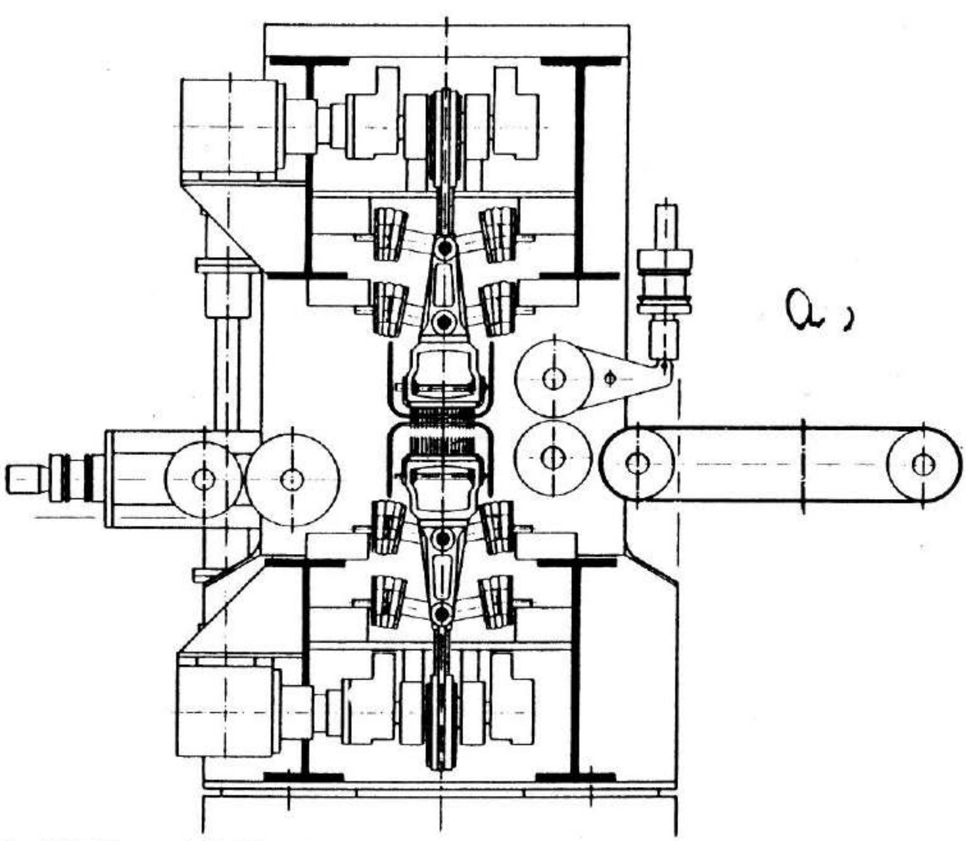


Fig. 8.10 (a) DILO's double sided needle loom type DI-LOOM OUG-I (one-board for downstroke and one board for upstroke needling): (a) alternative needling from top and bottom

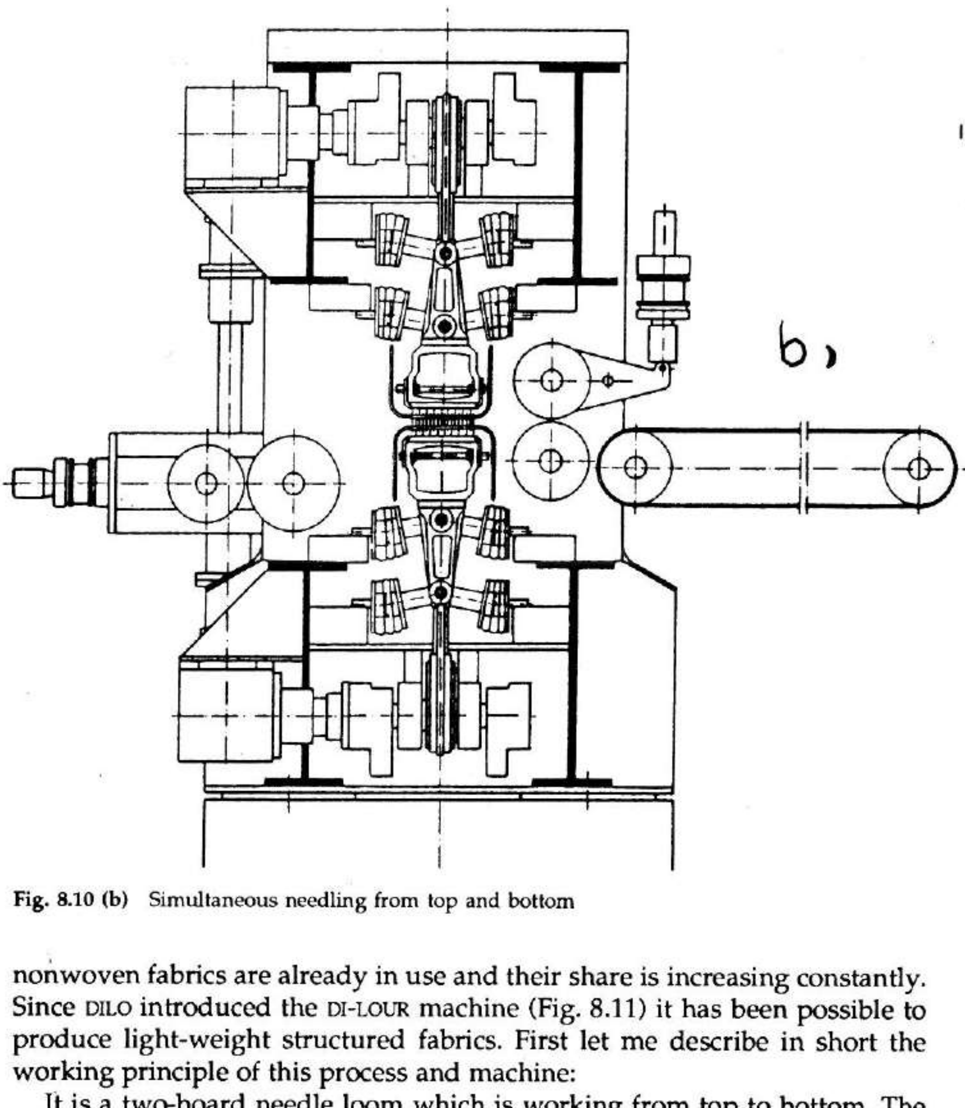


Fig. 8.10 (b) Simultaneous needling from top and bottom

nonwoven fabrics are already in use and their share is increasing constantly. Since DILO introduced the DI-LOUR machine (Fig. 8.11) it has been possible to produce light-weight structured fabrics. First let me describe in short the working principle of this process and machine:

It is a two-board needle loom which is working from top to bottom. The heart of the machine is a brush conveyor which serves as stitching base (Fig. 8.12). It means this machine has neither stitching (bed) plate nor a lamella table. The brush conveyor is moving and transports the material as well as accommodates the loops during the needling process. After the pre-needled or stitch-bonded felt has passed through the needling zone, one has to take-up the structured felt out of the brush conveyor and the pair of delivery rollers takes care of its take-off and further transportation.

Primarily crown needles (Fig. 8.13) are suitable when finer fibres are used. For coarse fibres, say 11 dtex and more, both crown and fine fork needles can be used. Emphasis is laid on the fact that normal fork needles of 25 or even 19 gauge are not suitable for DI-LOUR needling. The main reason is that the standard for needles have high fibre transport and hence brushes get bent

INTERNATIONAL CONFERENCE ON NONWOVENS

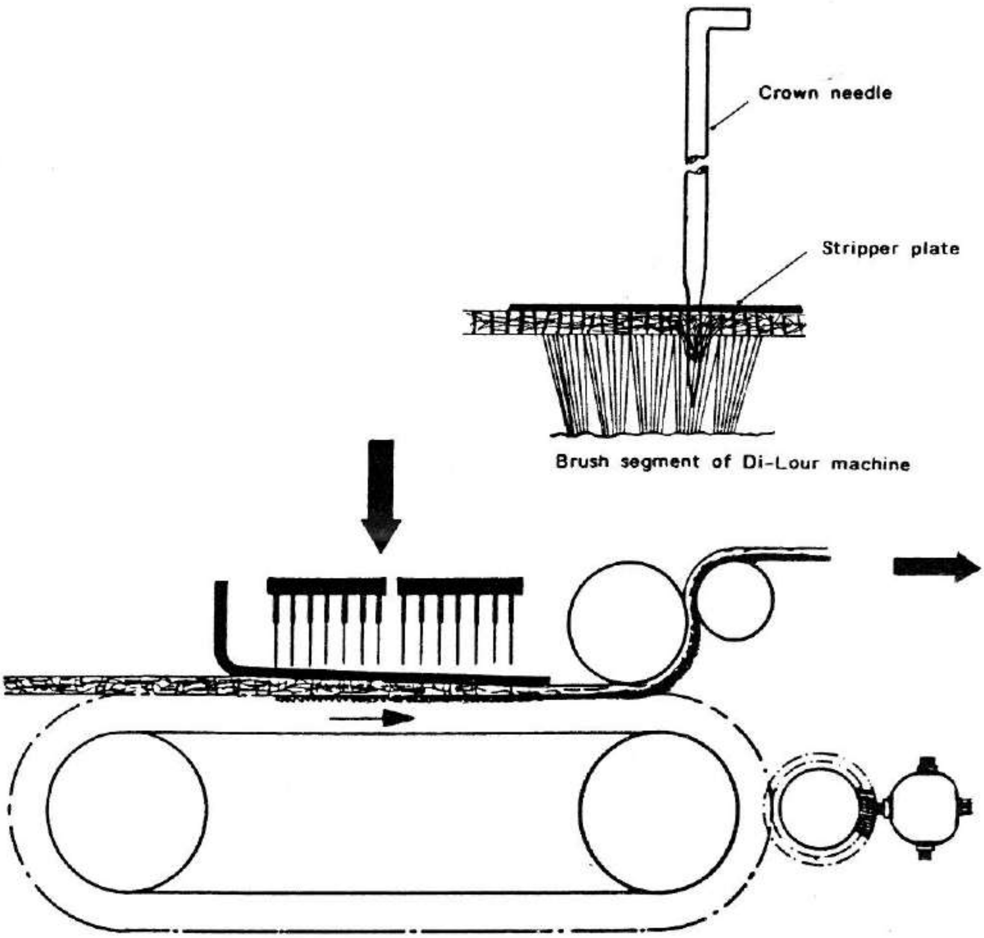


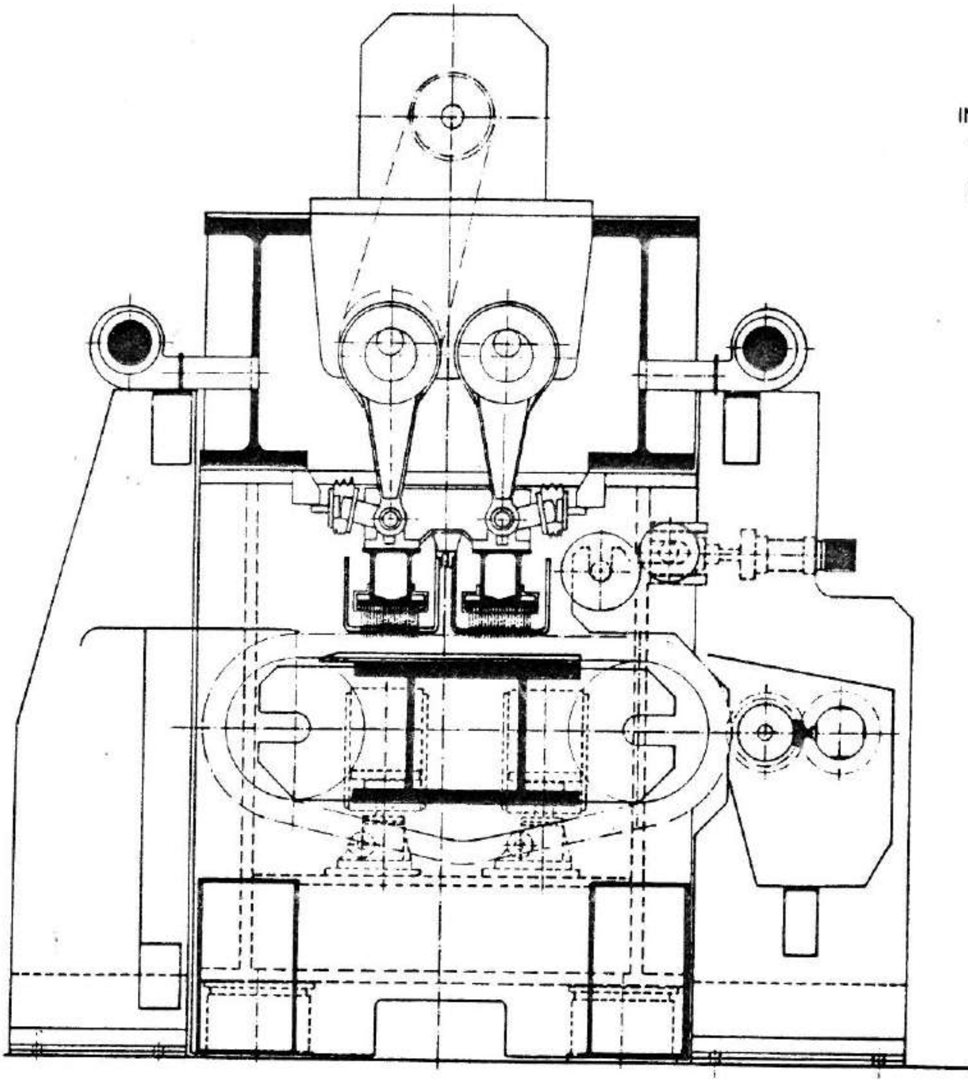
Fig. 8.11 Principle of DI-LOUR needling: (a) brush segment of the conveyor belt and needle penetration, (b) total schematic view of needling principle

and no pile formation is possible anymore. One should not ignore that in DI-LOUR machine we have two needle boards in comparison to one board in DI-LOOP machine. In other words the number of loops is much higher in the DI-LOUR process and also due to this reason the loop size can be kept much smaller here.

DILO has done intensive development work on light weight nonwovens. As far as the automotive linings are concerned, they are more or less all one-side impregnated and followed by moulding. Large quantity of such material is used in seat backs and other areas in passenger buses.

DILO's development work aim to enter the large upholstery fabrics either in automotives or in house-hold areas.

Before reporting on some test results I would like to mention two main groups of factors which influence the application of upholstery fabrics:



DI-LOUR-II S

Fig. 8.12 Constructive features of a DI-LOUR needle loom type DI-LOUR-IIS

(a) SUBJECTIVE PARAMETERS

* fashion trend
* harmony with existing furniture
* optic and colour
* feel/handle
* comfort
* price

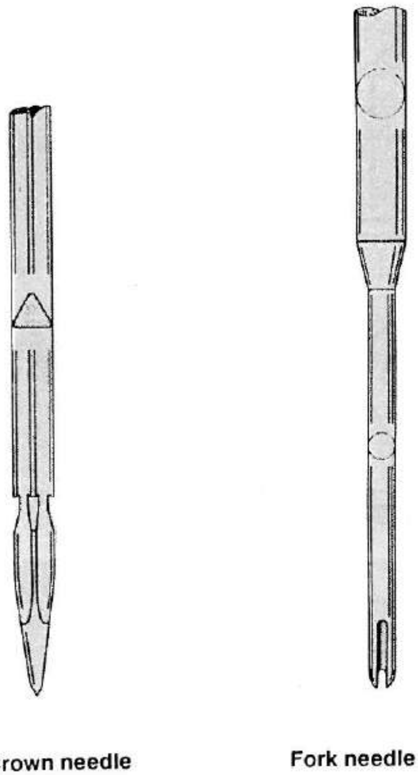


Fig. 8.13 Crown and fine fork needles for DI-LOUR needling

(b) OBJECTIVE PARAMETERS

* cleaning and anti-stain properties
* wearing resistance
* durability
* recovery from pressure loads
* folding and crease recovery
* bulging properties
* light and colour stability
* inflammability

These two groups represent a part of still larger influencing factors and characteristics which can be very different from end-product to end-product. A family without little children may select altogether different fabrics than one with children. Similarily a luxury car will have a more costly product than a middle class car.

If we see these fabrics from the point of view of influencing factors, following factors can be listed:

— Fabric specific factors, e.g. raw material and construction data. These may vary depending on the manufacturing technology.
— Finishing specific factors, e.g. stability against UV-rays, rubbing, sweating, solvents, strains and spots as well as water repellency.

— Safety and toxic specific factors, e.g. inflammability, gas and smoke generation in case of fire and reaction with various chemicals, etc.
— Further processing properties
— physiological properties, in fact a very important factor which also may be quite different in tropical and cold climates.

This whole description should only give an idea about the complexity of the theme.

In the frame work of a graduate thesis by Riedel [7], a large number of trials were conducted which included polyester fibre as the main raw material and for comparison polypropylene fibres. As low-melting fibres which serve as bonding fibres were used.

— co-polyester and co-polyamide from M/s Ems—Grilon
— bi-component fibres with core and sheat structure, type polyester of Hoechst
— high-shrinking PES fibres

Depending on the fibre parameters, chemical and thermal treatments were carried out. A summary of these trials led to the following results:

(a) For DI-LOUR structured products a chemical or thermal after-treatment is indispensable to achieve the required products' properties. Best results were obtained by blending low-melting fibres (approx 10%). Comparison was made with high-shrinkable and bi-component fibres.
(b) Fibres specially for nonwovens led to better results than conventional spinning fibres.
(c) Thermal treatment shows in comparison to chemical treatment, superior properties with respect to wearing behaviour, pilling tendency and buldging out properties.
(d) If at all chemical bonding was required then one-sided foam bonding in the gap of a padder with intensive binder, penetration on the backside gave better results.
(e) Finer fibres and the fibre length limited to 60–70 mm led to better needling behaviour and superior pile building and filling. It is obvious that finer fibres give better and softer handle.
(f) The volume and thickness of nonwoven DI-LOUR products is higher and as such a foam lamination is not absolutely necessary. One should see this aspect specially by considering the recycling problem. Laws are under preparation which will force the manufacturer to use same polymers in hard and soft parts inside the passenger room.

By discussing and evaluation of various manufacturing methods, one should put the ecological aspects in forefront more than ever before.

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9

The Development of Web Scanning Technology for Nonwoven Monitoring and Control

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This paper describes the application of scanned laser monitoring system, for the measurement of uniformity of fibrous web and nonwoven fabrics. The system's reliability, accuracy and limitations are discussed.

1. INTRODUCTION

To maximise the quality of textile products, inspection and testing of the finished product has always taken place, to a greater or lesser extent. Since the last decade, considerable efforts have been made towards the expansion of the nonwovens industry and to enhance product quality.

Systems have been developed before for this purpose, based either on radiation or optical technology. Radiation technology, although technically successful, was perceived (probably not justifiably) by the trade as a health risk. Optical technology is based on variation in light transmission, and sometimes reflection, which is related to the variation in weight as well as the 'web cover'. Although in the past, this principle was proven right and simple for application, the systems were prone to drift, i.e. for a constant web density, output signal varies over a period of time. The reason for drift could be one or more of the following:

(a) Instability of light source, e.g. fluorescent source, tungsten lamp, etc.
(b) Interference from ambient light source,
(c) Instability of electronic circuitry, etc.

Optical systems were based on either two [1] or multiple [2] detectors with a single light source. Another non-commercial system [3] was based on one source divided equally across the web using fibre optics with multiple detectors. The main problem with multiple detectors was drift. Furthermore, in industrial conditions, mechanical vibrations result in fractures of the fibre optic filaments. In subsequent developments, [4, 5] high-speed rotating polygonal mirrors were used with complicated optics for scanning action. Unfortunately, such systems were not economically viable.

A primary requirement of the nonwovens industry is to produce a nonwoven fabric with 1 : 1 tensile strength ratio both in lateral and longitudinal direction of the fabric. This might be achieved with random distribution of perfectly opened fibres in both directions. An industrial requirement consequently exists for equipment capable of monitoring nonwoven fabric (or fibrous web) with high precision and long-term accuracy, but without a necessity for fine resolution and high-speed.

2. LASER SCANNER DEVELOPMENT

2.1 System Configuration

The drift mentioned above can be minimised to some extent by proper design of the electronic circuitry and careful selection of light source and detector. However, from the beginning it was clear that it would be advantageous to use ONE SOURCE and ONE DETECTOR to simplify the system hardware and to minimise the problem of drift. A monochromatic light source was felt to be more easily filtered against the interference from ambient light. Further, a laser beam is used as a light source because of the following main advantages:

- (i) the beam divergence is very small and can be directed from considerable distances,
- (ii) since it is monochromatic, interference from ambient light can easily be avoided.

With the combinations of one source and one detector, a number of design configurations are possible but we decided to use the scanner type approach for both economic and practical points of view. The system is configured as follows:

- (a) LASER: 3.0 mW He-Ne red laser, Class II, 623.8 nm, beam diameter 0.6 mm, working range—up to 50 ft
- (b) DETECTOR: Photo detector, using single band filter to separate the laser light from the ambient light
- (c) Revolving reflector (mirror) at a speed of 20 revolution/sec,

Cycle completion time (360 degree)	:	50.0 m sec
Usable scan time (90 degree)	:	12.5 m sec

- (d) Interface box
- (e) Computer and Visual Display Unit (VDU)
- (f) Reflective tape (Signal Returning Unit or BALLATINE)

2.2 Working Principle and Operation

The scanning equipment was designed to be used as a single-sided monitoring device. The laser beam, on passing through the fibrous web was returned by a retro-reflector rather than a silvered mirror as shown in Fig. 9.1. This allowed simplification and cost reduction of the optical arrangement. The operation

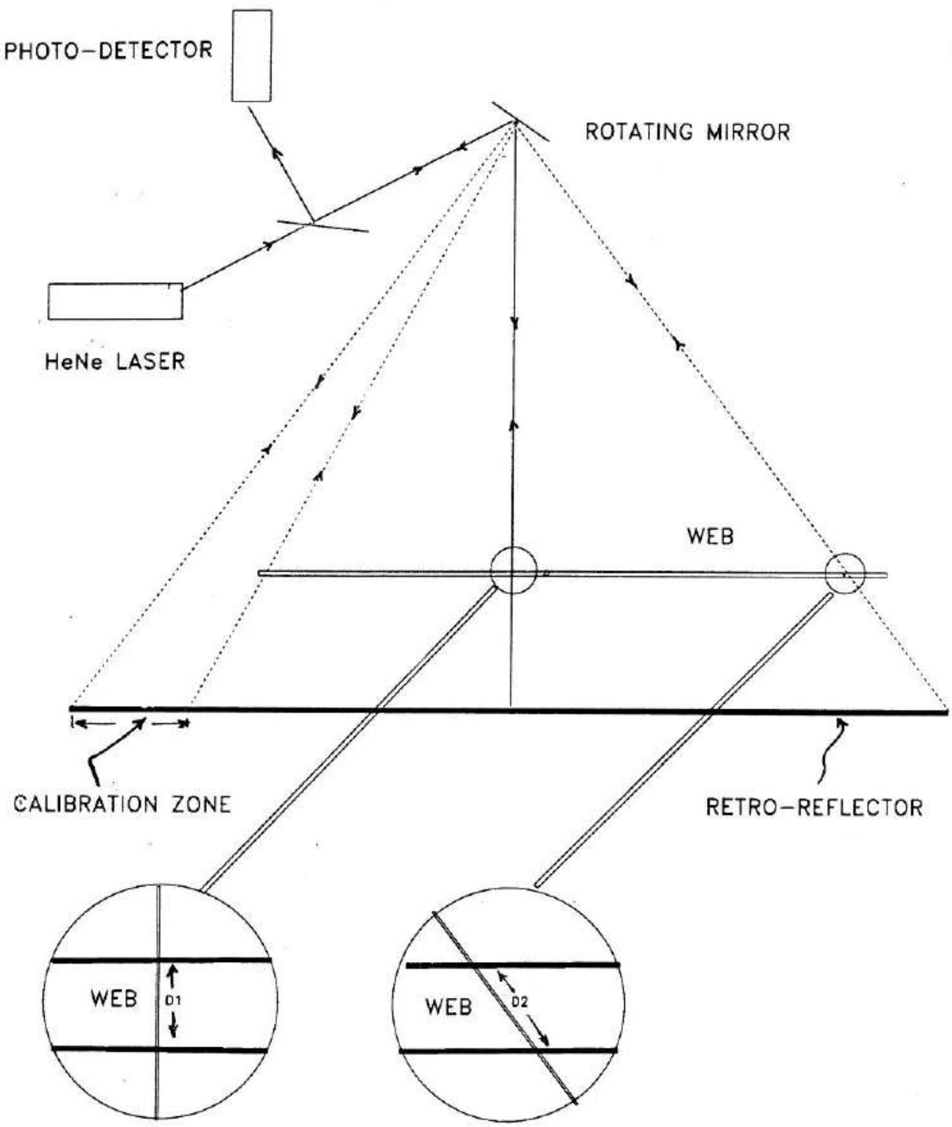


Fig. 9.1 Laser scanner

of a retro-reflector is based on the familiar principle of total internal reflection which deviates a ray of light through 180 degrees, making the reflected ray parallel to the incident ray. The retro-reflector is discussed in detail in the following section. The laser beam scans the web 20 times/sec, however the laser beam is only active over one quarter of each cycle, i.e. 90 degrees, which is scanned in 12.5 m sec at constant angular displacement. Hence the vertical height of the scanner (maximum 50 ft) decides maximum width of the web to be scanned.

At present 28 readings are captured across the width. This was regarded by the industries as sufficient. The actual readings are captured by specially designed hardware at precise locations across the width, so that pro cessor timing, which is subject to memory refresh signal and interrupt, is not crucial. The beam size is approximately 3 mm in diameter (when the laser is placed 2 m above the web), but with extra filtration the scan profile is about 30 × 3 mm. The distance between the scans depends on the speed. For a web running at 100 m/min, detection is achieved at approximately 8 cm intervals.

3. PHYSICS OF RETRO-REFLECTOR

3.1 Behaviour of Retro-reflector

The retro-reflector comprised a two-dimensional monolayer of reflector units secured in an adhesive binder. There are two types of retro-reflector available—corner-cube and spherical reflectors Fig. 9.2. There are limitations on how far off the axis of the incident beam (solid angle of acceptance) can be allowed, before reflections are reduced significantly. The spherical reflectors have a higher solid angle of acceptance (± 50 degrees) than the corner-cube (± 30 degrees) but are less reflective in nature.

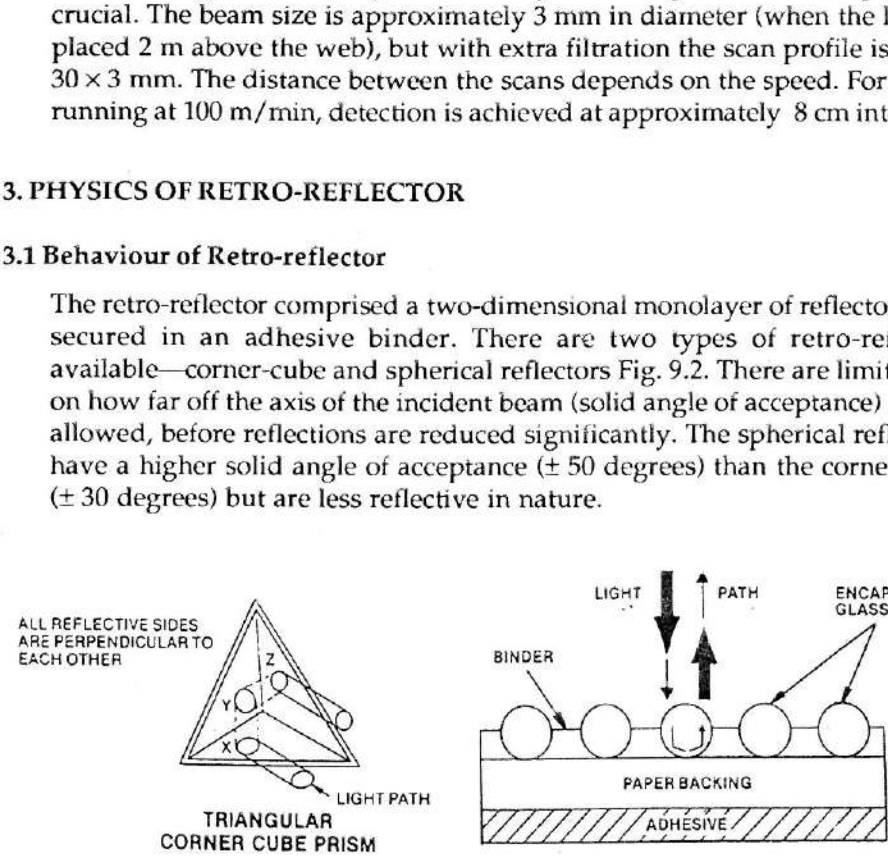
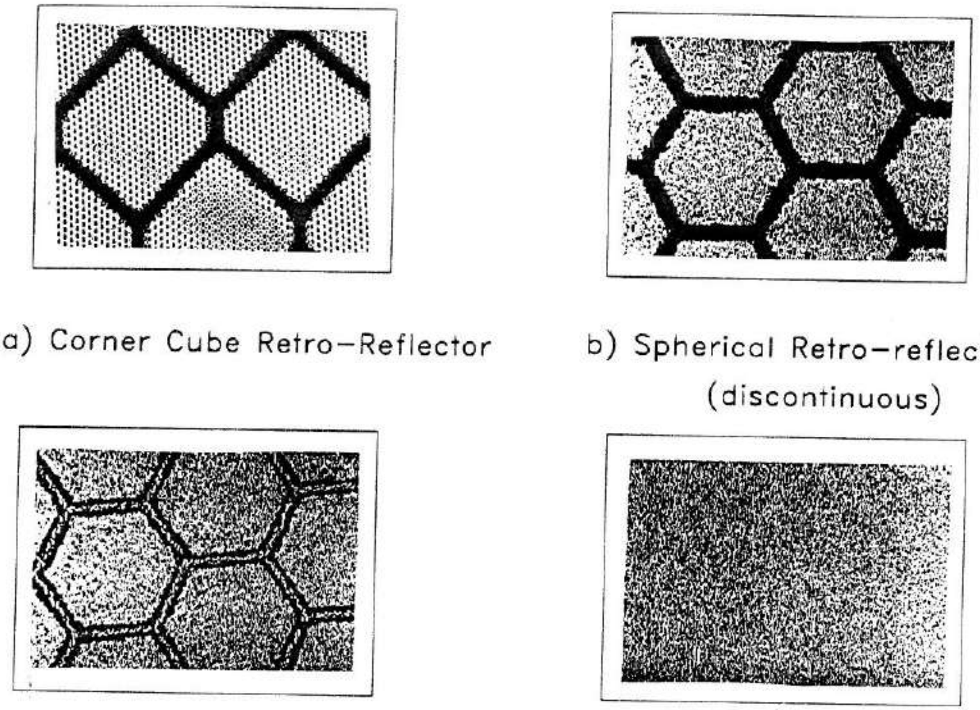


Fig. 9.2 The retro-reflector

3.2 Selection of Retro-reflector

Different ranges of retro-reflectors of both corner-cubes and spherical type were tested for the minimum signal noise and optimum reflection. It was found that the signal noise and the droop (the maximum difference of the reflection in a solid angle of acceptance) was higher in the case of corner-cube reflectors compared with spherical. The reason for this may be attributed to 'boundary discontinuity' in the case of corner-cube reflectors and leads to non-uniform reflection of incident light. It was therefore decided that a spherical reflector would be more suitable for our application though it is less reflective compared with corner-cubes. Further, different types of spherical retro-reflector with varying reflector densities and different binding arrangements for the reflectors (continuous or discontinuous) were studied. It was found that the retro-reflector with maximum reflector density and continuous binding arrangement (see Fig. 9.3) gives reasonably good reflection power with minimum electrical noise and droop percentage.



a) Corner Cube Retro–Reflector

b) Spherical Retro–reflector (discontinuous)

c) Spherical Retro–Reflector (partially filled boundaries)

d) Spherical Retro–Reflector (continuous)

Fig. 9.3 Different types of retro-reflectors

4. SYSTEM CALIBRATION

4.1 Calibration for System Stability

A small portion of the reflective tape which lies outside the web is used for on-line calibration (see Fig. 9.1). The signal detected in this zone is reflected directly to the scanning device and therefore gives an indication of the long-term drift expected. This drift as compared with the signal received from this portion of the reflector after switching on, is used to compensate the values obtained from the actual web.

On starting our work with this system we have found that the calibration technique used, i.e calibrating from a specific zone, did not actually work. This was quite puzzling until careful investigation showed that the laser tube exhibited randomised short bursts of intensity change, the duration of which is shorter than one scan. Further investigation suggested that some polarised lasers were more stable for short-term variation and consequently the tube was replaced. The calibration technique was then working and proved itself extremely well with long term drift of less than ± 0.3% of full scale. This was regarded as more than adequate for the purpose.

4.2 Calibration for Transmission and Web Weight

The next problem was to translate the electric output from the laser and to relate it to transmission rates. This was achieved by using neutral density grey type calibrated filters placed, instead of the web, on top of the reflective surface (see Figs. 9.4 and 9.5). As discussed in Section 3.1, the properties of

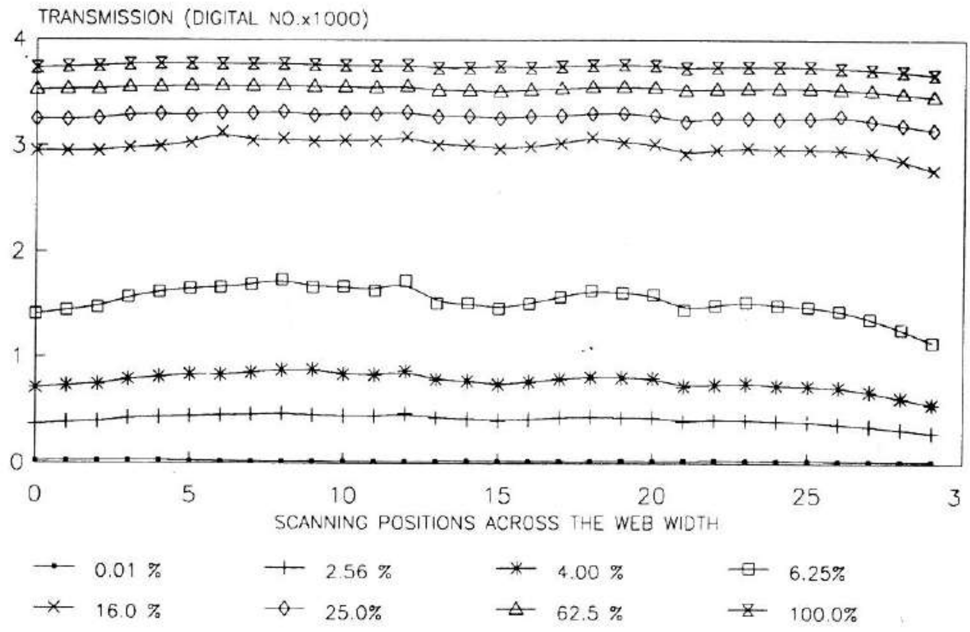


Fig. 9.4 System calibration for transmission with standard filters, scan angle = 60°

the reflective tape properties changed slightly across the web width and did not exhibit the same reflectivity for all light intensities (Fig. 9.6). However, for the actual working range, i.e. up to 20% transmission, the variations proved very small and the system was calibrated for individual points accordingly.

When, instead of grey filters, pieces of nonwoven fabric were placed across the web, there was a more pronounced difference in transmission values near the edge, as the path of the beam is increased as shown in Fig. 9.7. It

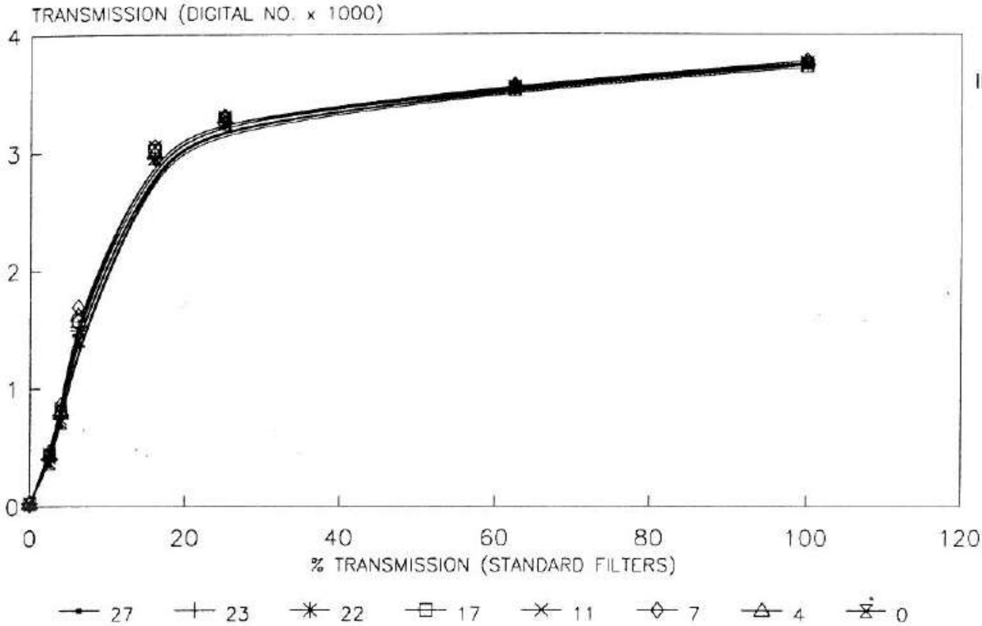


Fig. 9.5 Transmission at different scanning positions (0–27) across web width

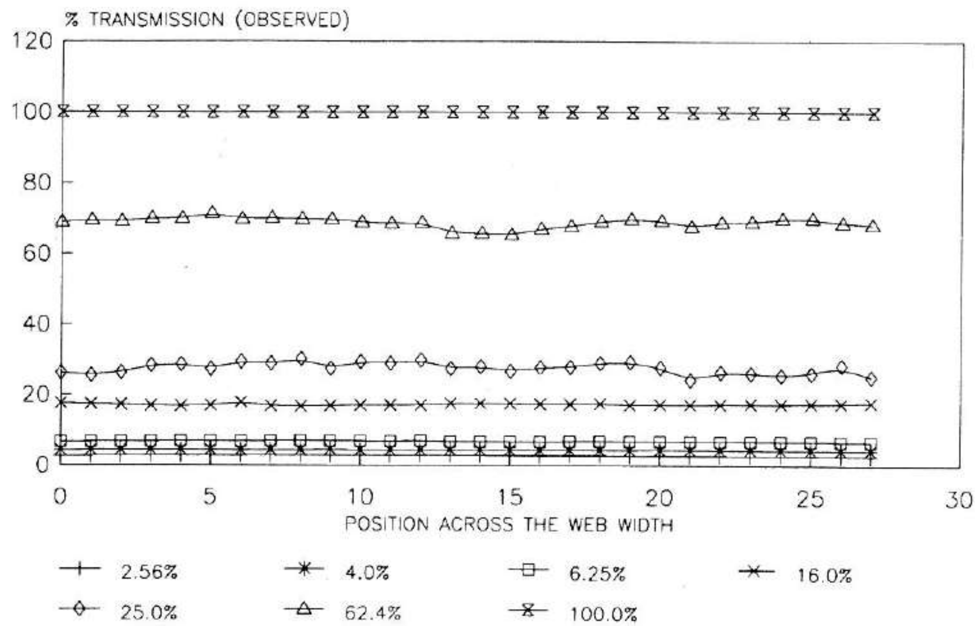


Fig. 9.6 Transmission across the web width with standard filters (2.56%–100%)

seems that a general purpose calibration could be worked out based on the Fig. 9.8, but to provide precise calibration, either a sample piece of the fabric to scan should be placed across the web width for scanning and a calibration

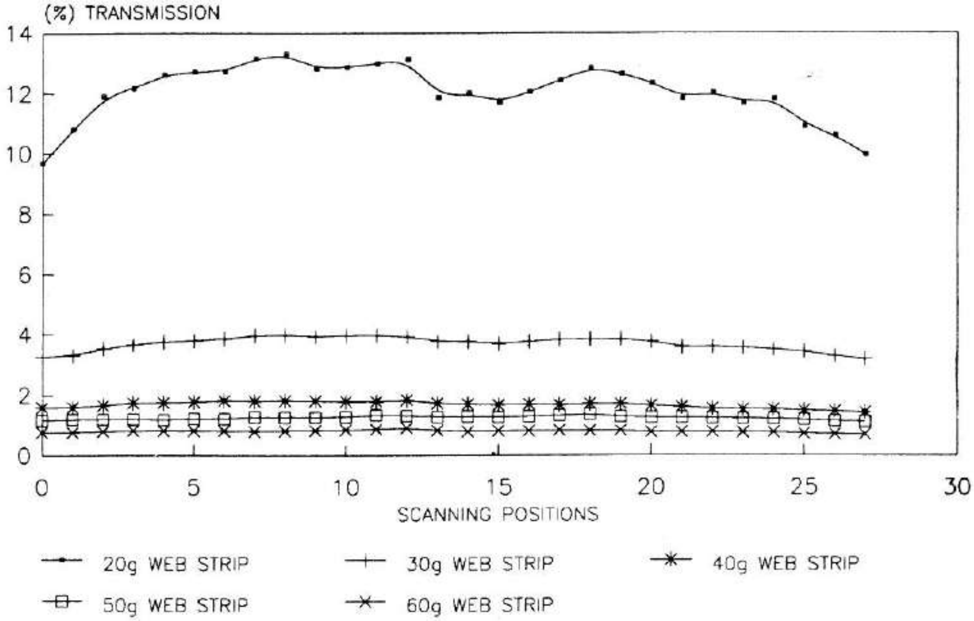


Fig. 9.7 Transmission of different web weights at different scanning positions

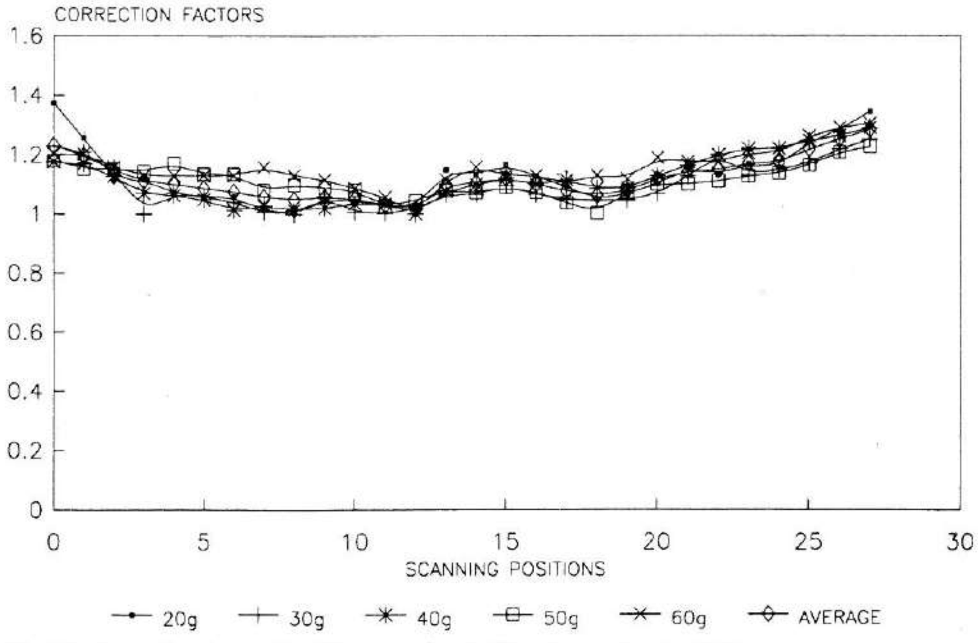


Fig. 9.8 Correction factors for different webs at different scanning positions

method computed, or another solution is to provide a teach mode so that an acceptable web will be monitored for say 10 or 20 m and an averaged transmission rate followed by a correcting factor, will be computed. In most applications this probably will not be required.

The next level of calibration relates to the relationship between weight and transmission level and this of course varies somewhat with the fibre type, fibre diameter, and the process applied to the nonwoven. A typical relationship is shown in Fig. 9.9.

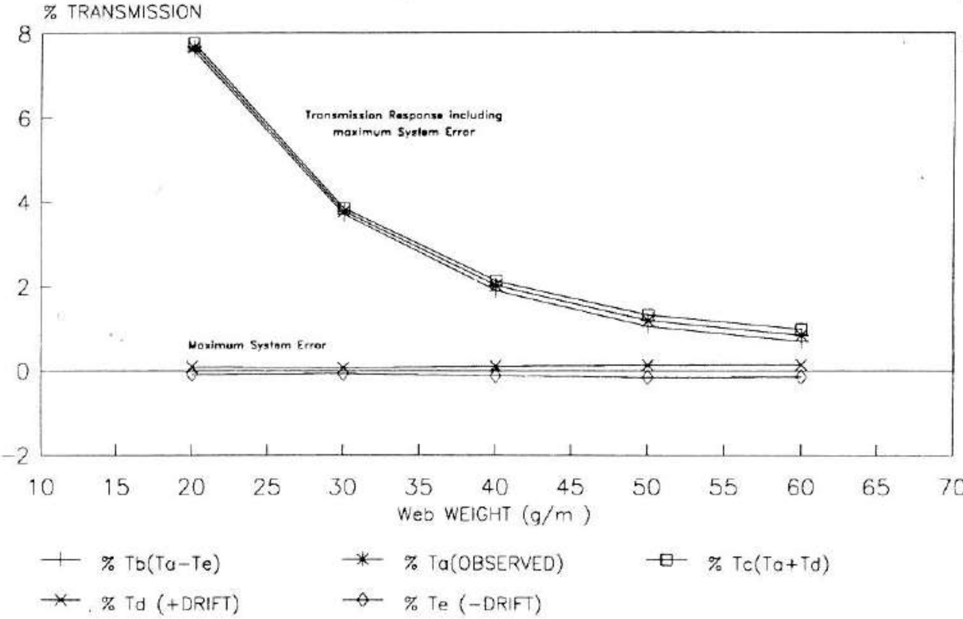


Fig. 9.9 Relationship between web weights and % transmission (calibrated)

From the data obtained it was possible to compute the uncertainty of the system as a weight measuring device, taking into account the measured drift as shown in Fig. 9.10.

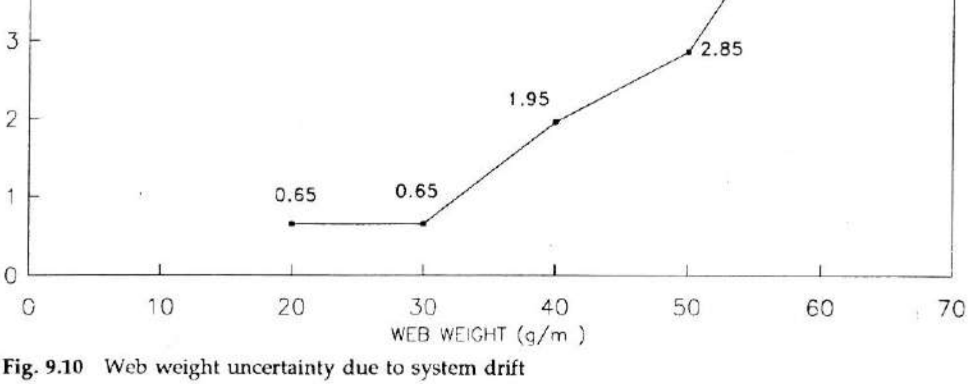


Fig. 9.10 Web weight uncertainty due to system drift

5. SYSTEM PERFORMANCE

The other problem which potentially affects the system performance is reflectance. Generally speaking the thicker the web the more light is reflected back to the detector. Since this phenomenon increases with web thickness (as opposed to transmitted light), it should be kept at a minimum. The reflectance to the system was investigated by positioning the nonwoven fabric (or web) on top of a black material preventing the beam from reaching the reflective strip. The values obtained depend on the reflectance curve of a particular web and those which exhibit no measurable reflectance in the red wavelength used, will obviously exhibit no problem. Our measurements on a typical white web which can be regarded as close to the worst case are shown in Fig. 9.11. It can be seen that this becomes a more serious problem with heavier webs, although the contribution to the actual transmission value for say 40 g/m is about 10% of the total transmission reducing to less then 2% for 20 g/m web. This phenomena does not reduce the accuracy of the system, since calibration takes reflection into account. It has, however, the effect of reducing the sensitivity of the system with heavier webs.

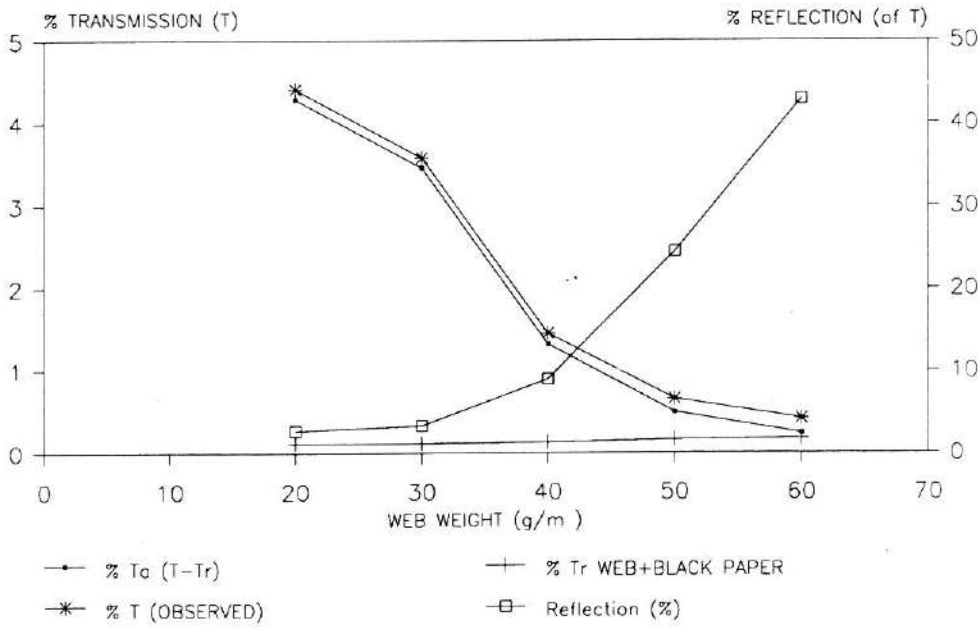


Fig. 9.11 Study of reflection from web surface (spun-bonded)

Taking into account reflection and the limitation of drift on system accuracy the system's limitation for commercial exploitation was set at fabric with no less than double transmission values of 1%. This corresponds, pending on processing conditions, to web weighing between 40–70 g.

6. RESULT OF INDUSTRIAL TRIAL

Industrial trials of the system were encouraging with stability figures confirming those achieved in the laboratory tests. This device can provide relative uniformity information across and along the web. This information is no doubt useful, but what can it be used for? The nonwovens industry is in many ways in a similar situation to the yarn industry in the fifties, before the emergence of the yarn evenness tester and the USTER standards. Clearly these standards should be next on the agenda.

7. SCOPE FOR FUTURE DEVELOPMENT

The system could also be connected to volumetric feeders to provide along-the-length feedback control for example. It should also be possible to provide feedback control for across-the-width calibration, but this is not yet possible, as there are no sectionalised feeders (but for one potential example) to be able to achieve this.

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10

Theoretical and Experimental Analysis of Absorbtion of Infra-Red Radiation in Needle Punched Nonwovens

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Some nonwoven fabrics, during their manufacture and finishing, are thermally processed by infra-red (IR) radiation.

In the study reported, the absorbtion of IR radiation in needle punched and thermally bonded PES nonwovens was theoretically and experimentally studied. Nonwoven webs were, during the theoretical analysis idealized as large particles, enabling a relatively simple evaluation of the reflection and dispersion of IR rays on their surface.

During the experiment, 32 textile samples containing PES fibres of four different diameters and different mass per unit area were measured by means of an IR-spectrophotometer.

The theoretical and experimental results were found to be in relatively good agreement.

1. INTRODUCTION

The parameters of IR radiation in nonwoven textiles, such as the absorbtivity, A, transmittance, T, and reflectance, R, play an important role during IR thermal treatment, the measurement of surface temperature by pyrometer while being treated by IR radiation and for the proper utilisation of nonwovens as heat insulators. In spite of the importance of the precise knowledge of these parameters, few papers are dedicated to this problem [1, 2]. The direct experimental evaluation of these parameters is, practically, missing from literature.

IR absorption properties of objects, generally, depend on the wavelength, λ, of the radiation. In this paper, the transmittance, T, of nonwovens was investigated for the limiting wavelengths $\lambda_1 = 3\ \mu m$ and $\lambda_2 = 10\ \mu m$. These correspond, according to Wien's Law, to the maximum wavelengths reflected for the temperatures of IR thermal processing (around 700°C) and utilisation as thermal insulators (27°C).

2. THEORETICAL

Because the spaces between the fibres in nonwoven webs are generally larger than 3 fibre diameters, d, they can be, according to MIEU [3], considered as a large particle system if, simultaneously, the following is valid.

$$\frac{\pi d}{\lambda} > 5 \tag{1}$$

Thus the resulting coefficient of absorbtivity, K_α and dispersity, K_ρ of IR rays on fibres can be calculated as the sum of the contributions of individual particles. Because for reflected λ_1, λ_2 and the applied fibre diameters the relation (1) is valid, we can use the above mentioned procedure in the next analysis.

For fibres lying in the plane perpendicular to the IR radiation the following rule can be applied:

The coefficients K_α, K_ρ are given by their hemispheric absorption and reflection parameters, α and ρ, multiplied by the projected area of all particles to this plane. Thus we obtain

$$K_\alpha = \alpha \frac{S}{\pi} \qquad K_\rho = \rho \frac{S}{\pi} \tag{2}$$

where S is the specific fibre surface $[m^2\, m^{-3}]$.

To calculate α and ρ, we apply the Fresnel's relations for dielectric materials:

$$\alpha = 1 - \frac{(n-1)(3n+1)}{3(n+1)^2} \qquad \rho = \frac{(n-1)^2}{(n+1)^2} \tag{3}$$

Here n is the IR refraction index, generally $n = 1.5$ except for PVC. Thus we have

$$\alpha = 0.855 \qquad \rho = 0.040$$

The so called albedo ω is then given by Eq. (3)

$$\omega = \frac{K_\rho}{K_\alpha + K_\rho} = \frac{\rho}{\alpha + \rho} \tag{5}$$

Because the majority of dispersed radiation follows the direction of the original beam, the coefficient, b, describing the amount of radiation passing will be lower than 1:

$$b = 1 - \omega = 0.955$$

The next coefficient m, characterising the radiation decrease, embraces both the effect of absorbtion and dispersion and is as follows:

$$m = (K_\alpha + K_\rho)\cdot h$$

where h is the thickness of the nonwoven fabric.

This coefficient can now be applied in the well-known Lambert-Boguer Law to calculate the required transmittance T, of the nonwoven layer:

$$T = \frac{I_2}{I_1} = \exp(-m) \tag{8}$$

To calculate the reflectivity R, a special relation derived in [3] will be used:

$$R = -\int_0^h \frac{\omega}{2} E_i(bm)\, d\,[\exp(-m)] \tag{9}$$

where E_i is the second exponential integral.

For $bm > 2$ and after integration this relation has the form:

$$R = \frac{\omega}{2}\left[1 - b \ln\left(1 + \frac{1}{m}\right)\right] \tag{10}$$

The required value of surface absorbtivity and simultaneous emissivity for the majority of objects A, for IR radiation can be calculated from the Kirchoff Law:

$$A + T + R = 1 \tag{11}$$

Before the absorbtion parameters can be calculated, the relation for specific surface, S, should be derived in the form:

$$S = \frac{4M}{Dhd} \tag{12}$$

where M is the mass of 1 m^2 of web, and D is the fibre density.

Introducing the values of dispersion coefficients and density of PES, and after other arrangements we obtain the theoretical value of transmittance, T.

$$T = \exp \frac{-3.940M}{\pi d D} \tag{13}$$

This parameter theoretically does not depend on the wavelength, λ. Other absorption parameters can be calculated from Eq. (10) and Eq. (11).

3. EXPERIMENTAL

To verify the theoretical results 32 nonwoven PES/POP samples were prepared for testing [4]. After carding, the webs were transversely layered and firmly reinforced by needling. The needle penetration depth was 1 mm and the punch density 80/cm^2. The proportion of 30% POP fibres, 3.3 dtex, was used for thermal-bonding at the temperature 170°C, the dwell time being 30 sec. To find out the dependance of IR radiation absorbtion on the fibre diameter, PES fibres of the following fineness were used.

TABLE 10.1

Fineness (dtex)	Fibre Diameter [μm]	Fibre Length [mm]
1.7	12.6	38
3.6	18.3	65
4.4	20.2	65
11.0	32.0	85

During the measurement, one or two web layers with mass 0.0907 kg ± 8% of 1 m^2 were placed in a special fixture, enabling the variation of the total thickness of the layer.

The samples were investigated by means of the IR-spectrophotometer SPECORD 75 and the relative level of IR radiation after having passed through the sample, the transmittance, T, was recorded. The IR wavelength during the measurement ranged from 2.5 to 25μm.

It was found, that this parameter is not affected by the actual thickness of the absorbing layer. Therefore the thickness was later held at $h = 3\ \mu$m. The dependance of the decrease coefficient m, see Eq. (8), on the mass of web M per m^2, fineness of fibres and wavelength for $\lambda_1 = 3\ \mu$m and $\lambda_2 = 10\ \mu$m were processed by means of two-dimensional regression analysis. The results are given in Table 10.2.

TABLE 10.2 Experimental Results

$\frac{M}{d} \cdot 10^{-4}$	0.72	1.44	0.496	0.99	0.45	0.9	0.283	0.567
m $\lambda = 3\ \mu$m	4.44	4.90	3.63	5.26	3.26	4.35	2.77	3.90
$\lambda = 10\ \mu$m	6.17	5.96	6.71	6.62	5.71	5.62	4.00	5.44

And the form of the resulting relation for the transmittance, T, is:

$$T = \exp\left[(3.519\lambda^{1.274}10^{-4})\left(\frac{M}{d}\right)^{1.381}\right] \tag{14}$$

The limits of the validity of this relation are given by Table 10.2. The correlation coefficient for m is $r = 0.910$, which can be accepted as a good correlation.

4. DISCUSSION

In spite of the theory, the experimental values of T depend on the wavelength. This indicates that the introduction condition (1) was not justified (e.g. the lower fibre diameter is less than 16 μm).

Generally, the theoretical results are 5–40% lower than the experimental ones in this investigation. Because of many idealisations, e.g. considering the fibres as particles, this could be taken as a good agreement between the theory and practice.

However the results cannot be extrapolated for other kinds of nonwovens, especially for the chemically bonded nonwovens, where the chemicals create large agglomerates.

It was found during other unpublished measurements [5] that the reflectivity, R, of needle-punched nonwovens with natural, not smoothened, surfaces is very often close to zero. Thus the absorptivity, A, which should be as high as possible during the IR thermal treatment or during the pyrometer measurements, can be calculated as

$$A = 1 - T \tag{15}$$

5. CONCLUSIONS

It was found that the IR radiation absorption properties of needle-punched nonwovens depend mainly on their mass per unit area and the fineness of the fibres used. Therefore light web absorb the IR radiation quite poorly, and also do not protect objects sufficiently against IR radiation heat losses.

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11

Analysis of Structure–Absorbency Relationships in Disposable Hygienic Products

ROSHAN L. SHISHOO

The purpose of this paper is to describe and discuss various modes of liquid distribution mechanisms which characterize the performance of absorbent type health care/hygienic products. Understanding of the mechanism of body-fluid/ absorption in absorbent products is important for designing products of good quality and fit. The general consideration for proper evaluation is the analysis of how well the test liquid, under suitable hydrodynamic conditions gets absorbed in the products when the fluid transport is accomplished by capillary and diffusion mechanisms.

The absorbent structures in most disposable absorbent products contain fluff which may include one or more components of chemical and mechanical pulps. Inter-fibre liquid transport in fluff absorbents is the most effective distribution mechanism because of the capillary flow system built in the absorbent structure by appropriate fibre arrangement.

The main aim of the studies at TEFO has been to develop relevant test procedures for evaluation of liquid penetration and surface dryness of cover stock materials used in absorbent products.

1. INTRODUCTION

Variety of individual test methods and apparatus have been reported in the literature for measuring absorption rate and absorption capacity of absorbent products [1–9]. The results and discussion in this paper are, however, based on series of test methods which have successively been developed at Swedish Institute for Textile Research (TEFO) since 1980 [10–12].

The purpose of this paper is to describe and discuss various modes of liquid distribution mechanisms which characterize the performance of absorbent type health care/hygienic products. These products are often made of composites containing different elements including nonwoven fabric, tissue, wood pulp, textile fibres, superabsorbents, foams, plastic film, etc. However, all absorbent products invariably contain three main functional components, namely; an absorbent structure, a liquid impervious membrane and a facing layer. Mechanisms of liquid flow through the interface between these three components and particularly within the absorbent component, under the conditions of use, are the determining factors for product performance. The absorbent structure in many products has a complex design and heterogeneous material distribution. There might also exist nonuniformity in the morphological, chemical and physical characteristics of individual absorbing constituents in a given structure. The absorbent structure also can undergo significant physical and structural changes as a result of wetting and body pressure. Hydrodynamics of body fluids, i.e. flow rate, void volume, frequency of fluid discharge as well as fluid parameters such as electrolyte concentration, pH, surface tension, viscosity and temperature will all have significant influence on the liquid distribution mechanisms. Because of the factors mentioned above, the known liquid flow theories for idealized fibrous or porous structures are not directly applicable when predicting the performance criteria of different absorbent products.

2. MECHANISMS OF ABSORPTION/DISTRIBUTION OF LIQUIDS IN ABSORBENT PRODUCTS

2.1 General Considerations

Understanding of the intricate mechanisms for body-fluid absorption/ distribution in absorbent products is important for designing products of good quality and fit. Diapers, incontinence aids and feminine pads are designed with aim to fulfil the main requirement of receiving, absorbing and retaining body fluids under different conditions of rest and activity of the wearer. The general consideration for proper evaluation is the analysis of how well the test liquid, under suitable hydrodynamic conditions, gets absorbed in the products when the fluid transport is accomplished both by capillary and diffusion mechanisms. The important criteria would then be, (a) liquid absorption/retention capacity of the absorbent structure of the whole product, (b) liquid distribution pattern and rate under various end-use conditions, and (c) studies of reversible liquid flow mechanisms through the interface between the facing and the absorbent structure. The rate at which liquid is absorbed has to be analysed in relation to a particular set of hydrodynamic parameters. For relatively large liquid dosages, the geometrical shape of the product around the crotch area will be a determining factor governing the liquid distribution mechanisms and consequently the leakage propensity of the product. The ideal bucket shape at the crotch area can easily be achieved both as one of the design parameters and by the manner of product fixation.

3. WETTING AND FLUID PENETRATION

3.1 Contact Angle Phenomenon

Generally speaking, wetting means that the contact angle between a liquid and a solid is zero or so close to zero that the liquid spreads easily along the solid surface. Three interfaces are involved in the contact of liquid with a solid, and the behaviour of the liquid is determined by the energy per unit area of the interface. The energies are:

γ_{LA} for the liquid—air interface
γ_{SA} for the solid—air interface
γ_{LS} for the liquid—solid interface

The control relationship for the case of a finite contact angle situation is the Young Dupré equation:

$$\cos \theta = (\gamma_{SA} - \gamma_{LS}) / \gamma_{LA} \tag{1}$$

Qualitatively speaking, then for good wetting and spreading, i.e., $\cos \theta$ approaching 1 or θ approaching zero, γ_{LS} and γ_{LA} should be as small as possible. Reverse is the case of non-wetting.

3.2 Capillary Action Phenomenon

For wetting of a fibrous assembly such as nonwoven facing and pad, more than just the contact angle is involved in the basic mechanisms of the action. The phenomenon is related to that of capillary rise, where the driving force is that of the pressure difference. For a bundle of capillaries of average radius r, from the Laplace equation.

$$\Delta P = 2\gamma_{LA} \cos \theta / r \tag{2}$$

Where, depending on the value of θ, ΔP is the pressure required to force entry of the liquid or to restrain its entry.
For wetting liquid, $\cos \theta = 1$

Hence
$$\Delta P = 2\gamma_{LA} / r \tag{3}$$

In addition to ΔP being large, for promoting capillary penetration it is also desirable that the rate of liquid entry is large. If the contact angle is > 90° (ΔP is-negative) the liquid will tend not to penetrate between the fibres, whereas if the contact angle is < 90° (ΔP + positive), the liquid will pass through easily.

The penetration of liquid into a solid matrix when contacted from one side involves the displacement of air through the open spaces. If the porous solid can be modelled as a bundle of capillary pores of uniform radius the rate of entry of a liquid along the capillary is given by the Washburn equation:

$$\frac{dl}{dt} = \frac{r\gamma_{LA}(\cos \theta)}{4\eta l} + \frac{r^2 \rho g \cos \beta}{8\eta} \tag{4}$$

Where l is the distance from the surface of liquid reservoir, η is the liquid velocity, ρ is the liquid density, g is the constant of gravitational acceleration and β is the angle between the direction of liquid movement and the downward vertical. The first term of Washburn equation describes the spontaneous wicking effect while the second describes the resistance (if $90° < \beta \leq 180°$) or assistance (if $0 < \beta < 90°$) of gravity.

When gravity effect is neglected, the Washburn equation becomes:

$$\frac{dl}{dt} = \frac{r\gamma_{LA}(\cos\theta)}{4\eta l} \tag{5}$$

Substituting $\cos\theta$ from Eq. (1), one gets

$$\frac{dl}{dt} = \frac{r(\gamma_{SA} - \gamma_{LS})}{4\eta l} \tag{6}$$

Which means that increased absorbency rate must be due to the increase in $(\gamma_{SA} - \gamma_{LS})$.

The liquid-absorbing ability in compressed absorbent assemblies of a number of different fibres was analysed [13–14]. It has been shown that a successful way of improving the liquid-absorbing capacity of a system of fibres would be to maintain greater inter-fibre capillary volumes in the wet state. This can be achieved by increasing the wet stiffness of fibres by either chemical or physical means.

3.3 Sorption of a Drop of Liquid into Porous Substrate

Sorption of a limited liquid quantity such as a drop of liquid into fibrous assembly, was used by Minor *et al.* [15] to investigate the wicking pattern. Either the time needed for the drop to sink into the fabric or the area covered by the spreading drop have been measured to test the wettability of fabrics. Difficulties with measuring spreading of the liquids on porous substrates, especially for cases of nonisotropic surfaces have been discussed in the literature [16,17].

4. WETTING, NON-WETTING AND SOAK THROUGH ASPECTS OF NONWOVEN FACINGS

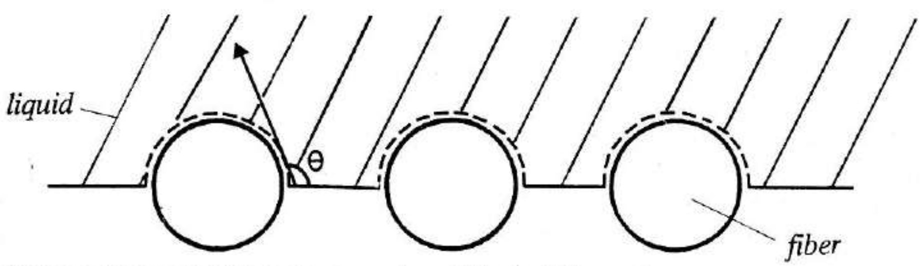
The terms wetting, non-wetting or non-reemergence, and soak through for a cover stock material have to be defined and discussed in terms of the effects desired and conditions during the use of the absorbent product. In addition to low surface energy at the body fluid—cover stock interface (low contact angle), it is very desirable to promote capillary and void penetration so that the rate of body fluid entry towards the absorbent core of the product is as high as possible. The latter aspect is particularly important when the body posture of the absorbent product wearer is lying on side or lying on back. Body fluid can penetrate the cover stock material only at points where imperfections in spacing and alignment between the fibres occur. The fluid will move across the fabric with a rate proportional to the frequency of such intersection or degree of imperfection. Once the cover stock material is ideally permeable, the body fluid will run through it, if sufficient hydrostatic pressure is applied.

In practice the liquid flow through the cover stock will be significantly affected by the absorbency and wicking characteristics of the absorbent medium which is in physical contact with the top sheet.

Liquid barrier property of the cover stock material in the flow direction absorbent core to skin, with and without the influence or external pressure, would determine the amount of moisture in liquid phase nearest to the skin of the wearer. For this purpose it is desirable to design the absorbent core/ adjacent surface of the cover stock to behave like liquid repellent and non-absorptive. Cover stock back surface can be made liquid repellent by reversing the conditions suitable for the promotion of wetting. This can be done by selecting the material so as to give as large γ_{LS} as possible.

Other important design parameters which affect wetting and liquid repellence are non-uniformity and structure of the surface of cover stock materials. Non-uniformity can be represented by a coefficient giving the ratio of actual to apparent projected area. In cover stock materials this can be achieved by producing net or mesh structures and uneven, textured and embossed surfaces of fabrics and polymer films.

Wenzel [18] showed how a rough surface can result in large apparent contact angle at the boundary between a liquid and the surface. Cassie and Baxter [19] extended Wenzel's analysis to porous surfaces as shown in the figure below:



Liquid under zero pressure resting on surface of idealised fibre system

Supposing f_1 is the total area of solid-liquid interface when water has come to rest on a porous surface under zero hydrostatic pressure, f_2 is the total area of liquid-air interface and θ_A is the advancing contact angle for the solid-liquid interface.

The apparent contact angle, θ, may be defined as

$$\cos \theta = f_1 \cos \theta_A - f_2 \tag{7}$$

It has been shown [19, 20] that apparent contact angle for water drops on textile fabrics, paraffin metal screens and embossed polymer surfaces do vary with f_2 as predicted by Eq. (7).

5. TEFO'S ANALYTICAL PROCEDURES

The methods developed at TEFO for liquid absorbency measurements are explained in details elsewhere [10–12].

5.1 Test Liquid

The test liquid used in our experiments consists of 0.9% saline solution having pH in the range 6.1–6.4 and used at a temperature of 20 ± 2°C [21]. The pH can easily be adjusted by adding following buffering agent to the test liquid:

2.7 g potassium dihydrogen phosphate (KH_2PO_4) and 1.1 g disodium hydrogen phosphate (Na_2HPO_4). For further adjustment of pH, small quantities of KH_2PO_4 or Na_2HPO_4 can be added for decreasing or increasing pH value, respectively.

As an aid for visual and photographic evaluation, a biological stain (e.g. C.I. 42685) may be added to the solution at concentration level of 0.1 g/l. The pH of the dyed solution is checked and adjusted if necessary using above mentioned phosphate buffers.

5.2 Liquid Dosage Unit

The schematics are shown in Fig. 11.1. This unit can be connected to various test equipments described below and the aerodynamic parameter such as flow rate, dosage volume and dosage time can easily be varied and controlled.

5.3 Liquid Absorption and Retention Capacities of Absorbent Structures

According to this method (Fig. 11.2) measurements are made to determine mass of liquid contained and retained by a circular test piece of absorbent product measured under specified conditions of liquid dosage and pressure. The results are expressed in terms of absorption capacity C and retention capacity C_{rm}. C is measured under a pressure of 100 Pa, and C_{rm} under pressure levels of 3 kPa and 5 kPa.

5.4 Rate of Liquid Absorption

The principle of this method (Fig. 11.3) is to measure the time needed for a given quantity of test liquid, fed at a certain flow rate, to enter through the facing material into the underlying absorbent structure constituting an absorbent product, and then get completely absorbed in the structure [11].

5.5 Surface Dryness of Facing Material

This method is used to measure the cover stock's hydrophobic and liquid-barrier properties at the point closest to the absorbent core of an incontinence product. The results provide an indication of dryness on the cover stock, which is the side that is closest to the user. The test procedure is shown in

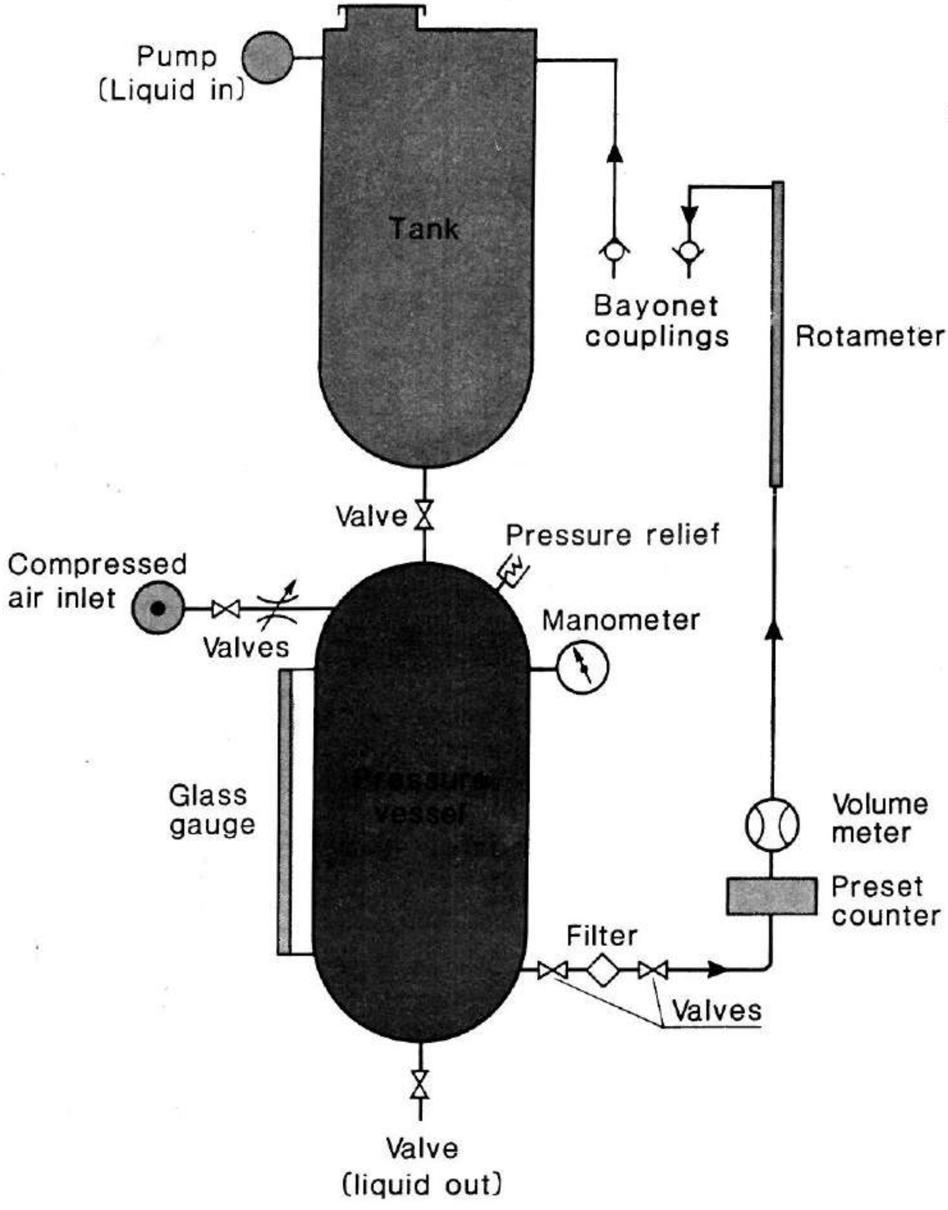


Fig. 11.1 TEFO's liquid dosage unit

Fig. 11.4. A 100-cm^2 circular sample of an incontinence aid (cover stock, absorbent core, and plastic back sheet) is placed on the device used in the liquid-retention tests. Test liquid is fed at a flow rate of 7 ml/sec. The amount of liquid fed to the sample depends on the absorbent structure's weight per unit area. The specimen is loaded to a pressure of 100 Pa, and the liquid is allowed to soak into the absorbent core for 2 min. The cover stock layer is removed with a pincer and placed on a perspex sheet. A preweighed filter

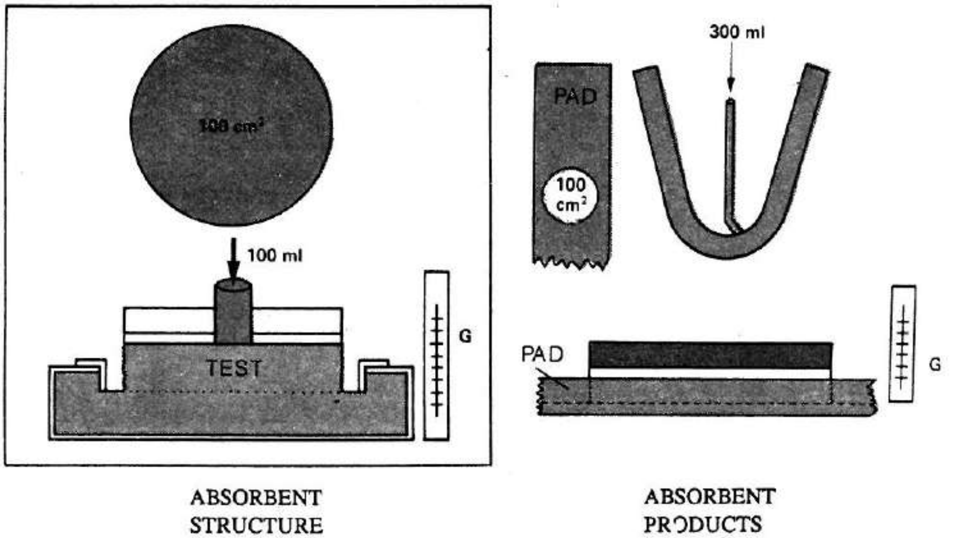


Fig. 11.2 Principles of methods used for measurements of liquid absorption and retention in absorbent structures and products

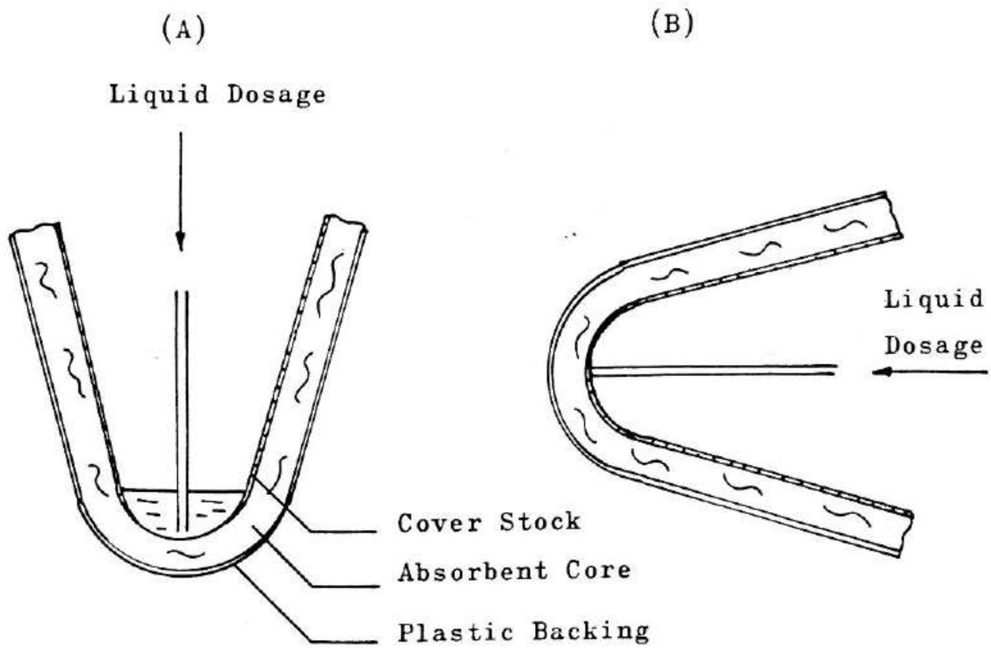


Fig. 11.3 Principle of testing liquid absorption rate in samples

paper (Munktell No. 5, A3-730-1000) is then placed on top of the moist cover stock sample, and a 100-cm^2 circular plexiglass load of 20 g is placed on top of the filter paper for 60 sec. The moistened filter paper is weighed again, and the difference in weight between the moist and dry filter paper is

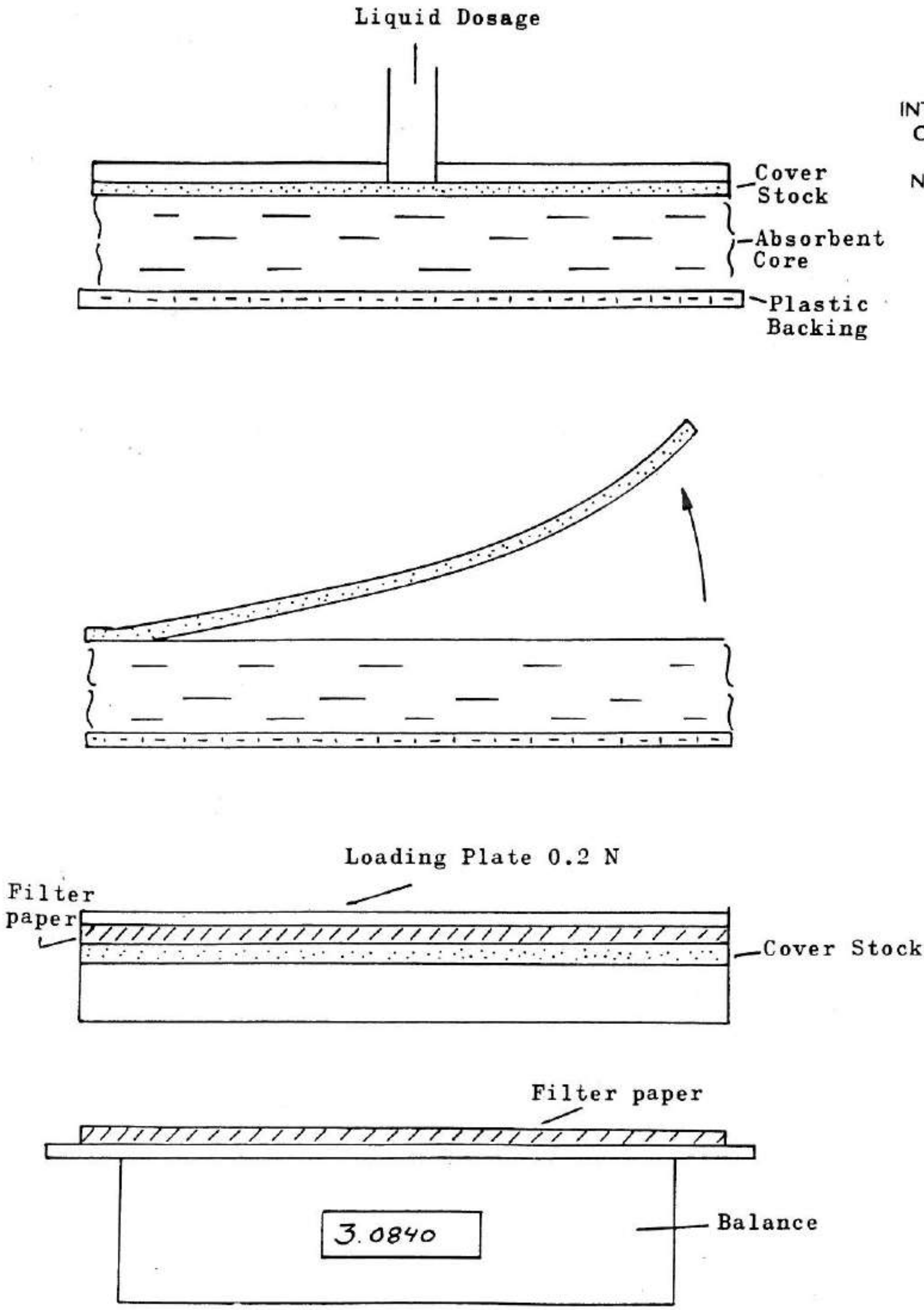


Fig. 11.4 Measurements of surface dryness in cover stock

calculated and reported to the nearest 0.001 g. This quantity, or the percentage weight increase, is used as an evaluation parameter for surface dryness.

The liquid dosage used in these tests depends on the absorbent structure's weight per unit area. Samples weighing approximately 250 g/m^2 receive 20 ml of test liquid. Samples weighing approximately 800 g/m^2 receive a 75 ml dosage. At weights near 1200 g/m^2, the dosage of test liquid is increased to 100 ml.

6. RESULTS

For a given combination of product design, facing material and aerodynamic parameters, the liquid distribution in absorbent products is mainly determined by the absorbency characteristics of the absorbent core namely liquid absorption and retention capacity as well as the rate and level of liquid spreading or wicking. Some typical absorbency results obtained on 3 different commercial products are shown in Table 11.1.

TABLE 11.1 Liquid Absorption and Retention Capacity (C_{rm}) of Some Commercial Absorbent Structures [14]

Product	C(ml)		C_{rm},(ml)			
	100 Pa		3 kPa		5 kPa	
	Mv	s	Mv	s	Mv	s
X	100	0	90.8	2.5	79.4	4.32
Y	100	0	59.0	2.2	51.6	2.40
Z	60.8	1.8	37.4	1.1	33.4	1.14

Mv = Mean value of 5 measurements
s = Standard deviation

6.1 Nonwoven Facings in Absorbent Products

The role of facing materials in absorbent products has been extensively investigated at TEFO. As a result of this work, test procedures were developed for evaluation of liquid penetration and surface dryness of the facing material [11]. Liquid distribution mechanisms in the interface absorbent core/ nonwoven facing have been studied for a number of different combinations of these elements. For example, rate of liquid absorption and surface dryness evaluations have been made on products containing a certain cover stock but different types of absorbent structure and vice versa. Some of the results obtained are shown in Tables 11.2, 11.3 and Fig. 11.5.

Material specification of some cover stocks used in this study is given in Table 11.4. Absorbent pads containing the above materials were manufactured on an industrial pad forming machine. The absorbent core consisted of fluff and tissue (nearest to the cover stock) combination with an average weight distribution of 340 g/m^2. Thus seven samples of absorbency pads were obtained which contained the same absorbent core and plastic backsheet but with varying cover stock.

TABLE 11.2 Rate of Liquid Absorption in Products Containing Same Facing Nonwoven but Different Fluff Types

Pulp	Absorption Time (sec)
Sulphate	35
CTMP I	36
CTMP II	> 300
CTMP I + CTMP II	
54 46	186
Sulphate + CTMP II	
59 41	85

Flow rate: 15 ml/sec

TABLE 11.3 Surface Dryness of Facing Material and Rate of Liquid Absorption in Products with Different Chemical Fluff Qualities

Product	Weight (g/m^2)	Surface Wetness (mg)	Absorption Time (sec)
A1	892	92	54
A2	877	74	38
A3	892	38	22

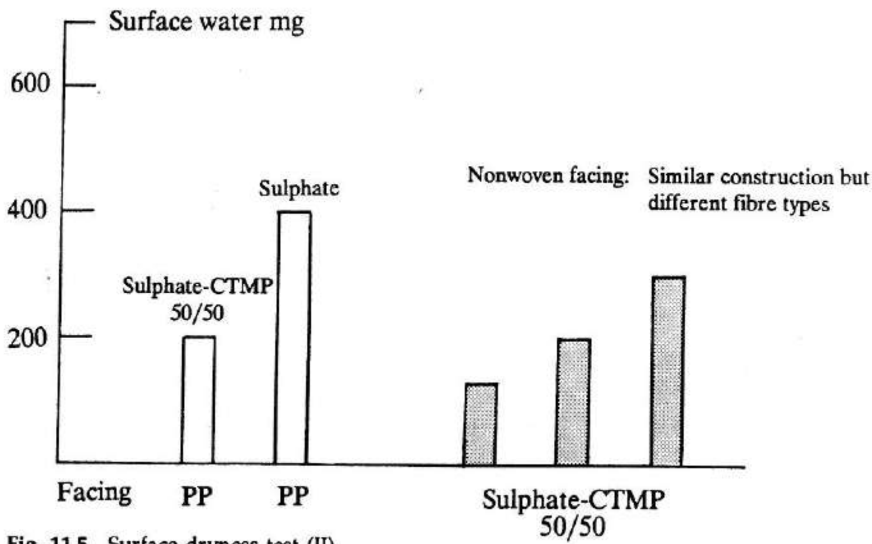


Fig. 11.5 Surface dryness test (II)

In addition to these samples, absorbent structures were produced at TEFO by combining the test cover stock materials with fluff core of weight distribution of 800 g/m^2 and 1200 g/m^2, respectively. Some of the results obtained are described below.

6.2 Drop Absorbency Test

The values of time needed for a liquid droplet to spread and penetrate in

TABLE 11.4 Specifications of Cover Stocks

Sample Designation	Product Type	Weight (g/m^2)	Thickness (mm)
A	Wet-laid Rayon/PES/Cell. latex bonded	20	0.40
B	Wet-laid Rayon/PES/Cell. latex bonded	19	0.37
C	Dry-laid Rayon latex bonded	23	0.25
D	Dry-laid Polyester latex bonded	27	0.41
E	Dry-laid Polypropylene/Rayon thermal bonded	22	0.27
F	Polyethylene Net	12.5	0.15
G	Polypropylene/Polyethylene Web	19.5	0.32
H	Polyethylene/Perforated Plastic Sheet	28	0.5
I	Polyester spun-bonded	19	0.5

different specimens and for various types of underlying materials are shown in Table 11.5.

TABLE 11.5 Drop Absorbency Time (sec)

Cover Stock	Underlying Material	
Specimen	Polyacrylic Plastic Sheet	Tissue and Fluff
A	46	2
B	37	< 1
C	4	< 1
D	2	< 1
E	8	< 1
F	> 180	< 1
G	50	2

The drop absorbency test results give the following ranking for wettability of different cover stock specimens:

Increasing degree of wettability

F G A B E C D →

The results show that liquid drop absorbency test can be used to distinguish the wetting behaviour of a cover stock material depending on which underlying material is used during testing. The important parameters of the underlying material which determine the feasibility of drop absorbency test are critical tension, surface structure and liquid absorption and wicking capabilities. It is seen from the results in Table 11.5 that when the underlying material is represented by typical absorbent core in an absorbent product structure, the ranking of wettability becomes difficult. However, if the critical surface tension value of an underlying material is low ($\gamma_c < 40$) and has a plane solid surface then the values obtained for wetting time of different facing materials are significantly different.

A separate investigation was made to test wettability of a perforated and embossed plastic film cover stock (specimen H) which has been obtained from a commercially available absorbent product. The results obtained are shown in Table 11.6. The results indicate that cover stock materials having

TABLE 11.6 Drop Absorbency Time (sec)

Specimen	Facing	Back
H	> 180	> 180
H + Tissue	3	> 180
H + Fluff	1.5	> 180
H + Polyester knitted fabric	> 180	> 180

such perforated pattern show wetting time for a drop > 180 sec even in combination with tissue and fluff on the facing surface which is in contact with tissue and fluff.

Results in Tables 11.7 and 11.8 show how different cover stocks rank as regards their resistance to liquid penetration and surface dryness.

TABLE 11.7 Rate of Liquid Penetration

Absorbent Product with Cover Stock	Soak Through Time, (sec)
A	45.0
B	49.0
C	42.5
D	38.0
E	43.5
F	70.0
G	53.0

These values indicate the following ranking of resistance to liquid penetration: Increasing resistance to liquid penetration.

D C E A B G F
$\longrightarrow$

TABLE 11.8 Increase in Weight of Filter Paper (mg) Cover Stock Surface Dryness

Cover Stock Sample	Fluff: 248 g/m^2 Dosage:20 ml	Fluff: 800g/m^2 Dosage: 75 ml	Fluff: 1200g/m^2 Dosage: 100 ml
A	339	333	319
B	262	102	178
C	769	556	453
D	801	759	512
E	519	473	349
F	42	38	48
G	144	87	140
H	23	9	12
I	44	91	67

The results give the following ranking of surface dryness for different cover stock specimens: Increasing surface dryness.

D C E A B G (F I) H
$\longrightarrow$

7. DISCUSSION

The absorbent structures in most disposable absorbent products contain fluff which may include one or more components of chemical, CTMP and mechanical pulps.

Inter-fibre liquid transport in fluff absorbents is the most effective distribution mechanism because of the capillary flow system built in the absorbent structure by appropriate fibre arrangement. Inter-fibre absorption will be influenced by a number of parameters such as fibre length, fibre orientation, fibre thickness, fibre stiffness, surface properties.

Dry and wet stiffness of absorbent structure in a product will greatly influence the product performance. In designing absorbent products one has to keep in mind that most products are not disposed only after first body leakage. If the absorbent structure in wet state has been excessively deformed then the chances of it functioning as a good receptor for further body fluids are low.

The main aim for our studies with cover stock materials has been to develop relevant test procedures for evaluation of liquid penetration and surface dryness of cover stock materials used in absorbent products. Test materials used in our investigation have been randomly selected primarily for the purpose of developing testing methods and as such no attempts have been made at this stage to comment on the feasibility of various technical design parameters of these products. It is shown that cover stock materials can be ranked on the basis of their two main functional properties by following the testing procedures presented.

The important aspect of liquid flow towards absorbent core of an absorbent product is its *rate of penetration* through the cover stock. The critical variables affecting this flow rate from the non-leakage behaviour of products are the body posture of the wearer at the time of fluid discharge and the nature of absorbent media. In other words for body postures standing or sitting, there is enough time available for the fluid to penetrate through voids and structural imperfections of the cover stock into a good performing absorbent medium. For body posture lying on side, the wetting and liquid transport properties of cover stock become more critical but here again the sorption characteristics of absorbent medium play an important role for product behaviour.

8. ACKNOWLEDGEMENTS

I wish to thank my colleagues, Kurt-Rune Magnusson, Jörgen Ohlsson, Birgitta Lindsjö and Lena Bergendahl for their invaluable experimental contributions.

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Analysis of Physical and Mechanical Properties of Nonwovens for Use in Protective Garments

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In order to understand the physical and mechanical behaviour of protective garments in use it is important to analyse how garments designed for various functions interact with the human body and what interactions exist between these functions and the relevant fabric properties. The user's demands have to be transformed into appropriate technical specifications of fabric properties as well as the structural design of the protective clothing .

In this paper the above mentioned aspects have been discussed in relation to the nonwoven-based protective garments. Because of some inherent characteristics of nonwovens, their use in protective clothing offers both opportunities and challenges for meeting various consumer demands. Material and garment functions such as barrier, transmission, drape, fit and formability have been discussed. Some technical challenges regarding design and making up of nonwoven-based protective clothing have also been presented.

1. INTRODUCTION

It is widely predicted that the market for protective clothing products in general and nonwoven protective apparel in particular will continue to grow. Some of the key forces in this direction are increasing awareness of workers protection and safety in the industrial and hospital environments. The world-wide consumption of nonwoven materials is expected to expand at the rate of approx 7% per year during the 90's and nonwoven-based protective garment constitute one of the potentially high growth sectors.

The important manufacturing techniques for nonwoven apparels with balanced functional characteristics depend largely on the criticality of the use and the consumer sector involved. Some of the features of structure that effect the functional properties of nonwovens for protective clothing are inherent in the fibre and fabric structures while other required high- functional characteristics can easily be incorporated by means of appropriate technologies.

Lately, a range of sophisticated speciality fibres, tailor-made to specific end-use situations, have been developed by many producers. With the synthetic fibres it is now possible to get almost any functional property by modifications of the molecular and morphological features of a fibre. Many sophisticated techniques are presently used world-wide for spinning fibres which are then incorporated in differently engineered nonwoven structures. By designing new processes for nonwovens preparation and finishing, and due to advances in technologies for production and application of polymeric membranes and fluorochemicals, one can now successfully combine the protective, safety, aesthetics and comfort functions of many nonwoven-based protective clothing.

As technical design options for optimum performance, the manufacturer of a protective clothing can bring about the necessary improvements not only by selecting appropriate fibres, fabrics and finishing combination but also by appropriate garment design and production technique. Nonwoven technologies give one wide options for producing functional materials. A continuous upgrading of commercial nonwoven-based protective garments has taken place but some unresolved factors based on consumer demands still remain to be technically elucidated. Some of these aspects, particularly those related to garment design and performance are discussed in this paper.

2. CONSUMER NEEDS

In order to understand the physical and mechanical behaviour of protective clothing in use, it is important to analyse how protective garments designed for various functions interact with the human body and what interactions exist between those functions and properties of nonwovens. The garment styles that exist include those providing minimum coverage of the body to the ones covering the entire body surface.

There are a number of consumer demands that have to be fulfilled by a protective clothing. The most important ones are listed below.

Barrier	Liquids, biological fluids, microorganism, particles
Safety	Flammability, mechanical, resistance to chemicals
Transmission	Heat, moisture, air
Hand	Compressibility, elongation
Tactility	Softness, smoothness
Durability	Tear and tensile strength abrasion resistance
Appearance	Garment shape, drape wrinkles
Fit	Mechanical comfort freedom of movement

By means of a functional analysis one can quantitatively relate appropriate fabric properties to a given function. In this way it is possible to obtain a property profile of performance related to a specific function. In practice most protective garments are designed for more than one functional requirement and consequently one has to adjust individual property profiles to comply with all functional requirements. The consumer demands often require the balance of a complex optimization of different properties. The seemingly contradictory requirement of creating liquid barrier on one hand and breathability in nonwovens on the other has placed challenging demands on new technologies for producing nonwoven-based protective garments.

3. CONSUMER PERCEPTION OF GARMENTS IN WEAR

Technical solutions for producing nonwoven fabrics with good barrier properties are practically unlimited. However , consumer's total perception of nonwoven-based protective clothing is generally based on human reactions related to specific perceptions of wear comfort. In particular its perceptive merits relative to a cotton/polyester woven fabric garments play an important role.

Many consumer studies have pointed out that the European consumer is even more sensitive to the well-known comfort notion. Problems in using nonwovens in protective clothing have been not only related to physiological comfort characteristics, deficiencies of barrier nonwoven but also to its deficiency in tactile acceptance, low tear strength; inadequate garment size and shape and unacceptable drape. [1, 2]

4. MECHANICAL PROPERTIES OF FABRICS AND GARMENT PERFORMANCE

The shape and size of protective garment relative to the shape of the body will be strongly influenced by the physical and mechanical properties of nonwoven material. This means that certain fabric properties such as tendency of nonwoven to stretch, buckle, distort and drape due to stresses induced during use and static and dynamic situations are to be taken into account when drafting patterns for a nonwoven-based garment.

The mechanical properties of nonwoven fabrics are important from the point of view of stresses applied to fabrics in the making up processes including load-extension, buckling, shearing, compression as well as physical changes in the fabrics that result from the application of outside forces on the fabric in a garment during use due to gravity and by body fit and body movements.

Prediction of tailorability and garment performance based on objective measurements of fabric mechanical properties [Fig. 12.1] has been a subject of research at many R & D institutions worldwide [3]. The work done at Swedish Institute for Textile Research (TEFO) in this field especially over the last three years has resulted in a formability function* that describes the ease of formation of fabrics into three dimensional shapes and the garment appearance [4, 5].

*log (B × EMT/2HG5) [Shishoo & Choroszy]

where B = Bending stiffness
EMT = Extensibility
2HG5 = Shear hysteresis

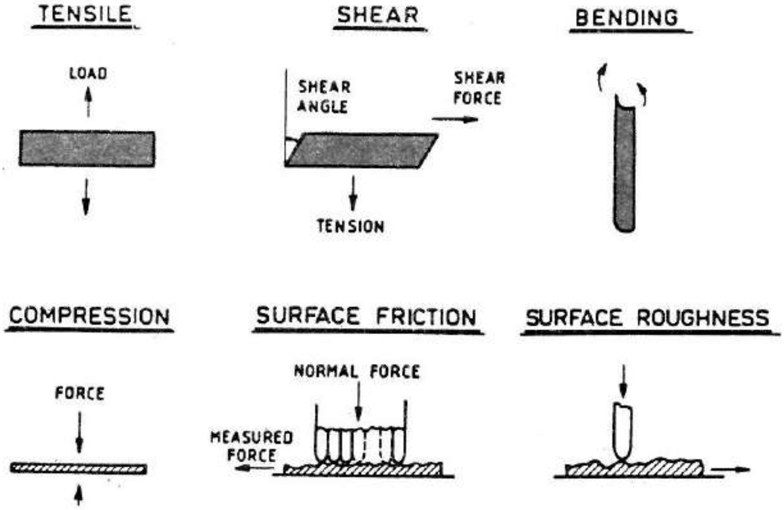

Fig. 12.1 Measurement of fabric mechanical and surface properties

All these parameters have been obtained on Kawataba's KES-F instruments.

Most of the work in this field reported earlier by the author and his coworkers has been done on woven fabrics. Investigations have also been made on the interaction between, on one hand the mechanical properties of a series of nonwoven fabrics and on the other their tailorability, formability and garment shape.

Table 12.1 contains the list of eight different commercially produced nonwoven and nonwoven-based materials for protective garments used in industrial and medical sectors. Objective measurements of some mechanical properties of these fabrics were carried out using KES instruments and the resulting parameters were used to calculate the formability of fabrics according to the equation given earlier.

TABLE 12.1 Nonwoven Test Fabrics

	Specimen Number
Spun-bonded PP 8% print-bonded area	A
Spun-bonded PP 27% print-bonded area	B
Spun-bonded PP calendered	C
Spun-bonded/melt-blown/spun-bonded PP	D
Spun-laced PES/wood pulp	E
Print-bonded rayon	F
Print-bonded rayon/PE-film	G
Print-bonded rayon/PE film/tissue	H

4.1 Results

The results of some KES parameters calculated from tensile, bending and shear measurements on the test fabrics are given in Tables 12.2, 12.3, 12.4 and 12.5. These properties will to a great extent determine the appearance and freedom of movement of the protective garment.

TABLE 12.2 Tensile Properties of Test Fabrics

Specimen	Extensibility (%) EMT 50		Elastic Recovery RT(%)	
	MD	CD	MD	CD
A	1.08	2.05	47.5	42.8
B	0.64	0.56	62.6	63.3
C	0.57	0.50	75.0	74.6
D	0.84	1.35	69.2	70.3
E	0.55	1.22	40.2	39.4
F	0.75	4.13	70.8	53.1
G	0.80	1.15	68.3	71.0
H	0.71	0.72	73.9	75.0

TABLE 12.3 Bending Properties of Test Fabrics

Specimen	Bending Stiffness B ($gf/cm^2/cm$)		Bending Hysteresis 2 HB ($gf \cdot cm/cm$)	
	MD	CD	MD	CD
A	0.14	0.10	0.19	0.10
B	0.29	0.30	0.31	0.29
C	0.31	0.34	0.17	0.16
D	0.22	0.12	0.15	0.07
E	0.30	0.08	0.30	0.08
F	0.08	0.01	0.07	0.01
G	0.29	0.14	0.35	0.15
H	0.42	0.23	0.41	0.31

TABLE 12.4 Shearing Properties of Test Fabrics
Shear Angle ± 1 deg, G(0–0.25 deg)

Specimen	Shear Stiffness G ($gf/cm \cdot deg$)		Shear Hysteresis 2 HG 0 (gf/cm)	
	MD	CD	MD	CD
A	12.4	15.4	5.2	8.4
B	44.0	40.0	9.5	7.5
C	44.5	49.5	14.2	10.0
D	27.5	34.5	5.2	6.5
E	17.4	21.5	6.7	10.2
F	10.0	14.4	2.7	4.5
G	31.0	30.5	12.0	11.2
H	50.5	48.5	9.0	8.7

It can be seen from these tables that extensibility, bending stiffness and shear stiffness of the fabrics vary quite significantly. These differences have to be taken into consideration while drafting patterns and appropriate manipulations must be made in order to avoid problems with garment fit

TABLE 12.5 Shearing Properties of Test Fabrics
Shear Angle ± 2 deg, G (0.25–1.25 deg)

Specimen	Shear Stiffness G (gf/cm · deg)		Shear Hysteresis 2 HG 0.25 (gf/cm)	
	MD	CD	MD	CD
A	6.9	8.5	7.8	9.2
B	20.5	16.5	10.0	8.0
C	18.7	18.5	11.5	12.0
D	12.3	15.4	6.9	8.9
E	10.1	11.5	9.5	12.4
F	5.8	8.9	3.8	7.5
G	11.0	12.0	10.0	12.5
H	15.5	12.0	10.5	8.0

and appearance. These properties will also influence conformation of the fabric and the fabric distortions produced in a garment during use.

Comparing the properties of specimens A, B and C in Tables 12.2, 12.3 and 12.4, it can be noted that an increase in fibre-fibre bonded area in nonwoven fabrics results in decrease of extensibility and increase of bending stiffness, shear stiffness and shear hysteresis. Specimen D is a typical example of a successful commercial product which in spite of being a 3-layered composite structure still possesses relatively good extensibility and relatively low values of bending stiffness, bending hysteresis , shear stiffness and shear hysteresis. Comparing the properties of specimens F, G and H, it can be seen how the introduction of barrier properties by plastic film increases the extension, bending and shear stiffnesses of the print-bonded rayon specimen.

It can also be noted from the results in Tables 12.4 and 12.5 that in all the specimens tested the shear stiffness is significantly greater at shear angle of 0.25 deg than at shear angle of 1.25 deg.

Figure 12.2 shows the values of formability/tailorability obtained for different test fabrics. It is obvious from this figure that the ease of making garments out of these material varies very significantly. For example, increasing print-bonded area in a spun-bonded PP from 8% to 27% decreases the formability which is further decreased if the material is calandered.

The value of formability is greatest for spun-bonded/melt-blown/spun-bonded material followed by that of PE film/tissue reinforced rayon.

The most important work regarding drape characteristics of fabrics is due to Cusick [6]. He showed that bending length obtained in cantilever type bending deformation is a major factor in determining 'drape coefficient' of fabrics. This means that laminating or adhesive bonding will strongly influence drapability of nonwoven fabrics.

An example of mechanical anisotropy in the test specimen as regards extensibility and bending length is shown in Figs. 12.3a and 12.3b, respectively. As expected, the extensibility is greater along CD as compared with MD, whereas the values of bending length (a measure of fabric drape) are greater in MD as

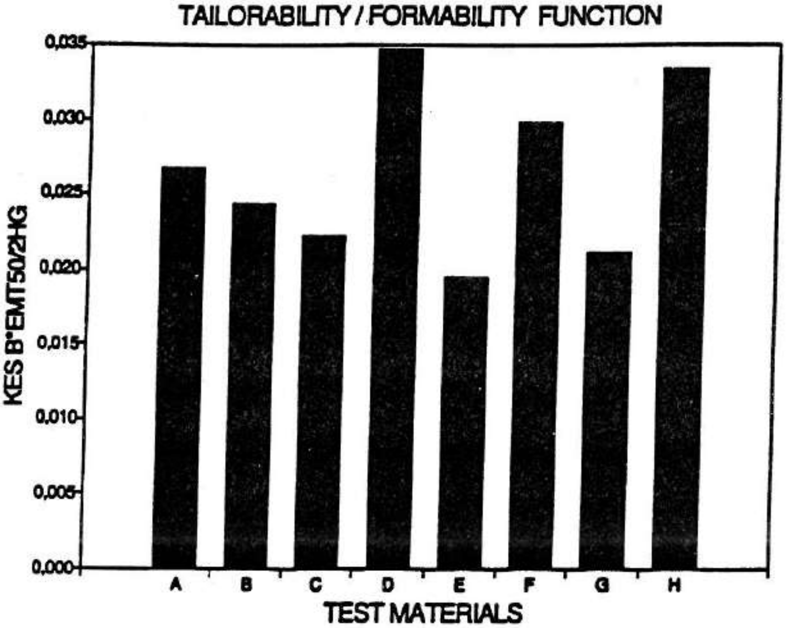

Fig. 12.2 Shishoo and Choroszy's tailorability functions for different nonwoven test specimens. Higher the value, greater is the formability

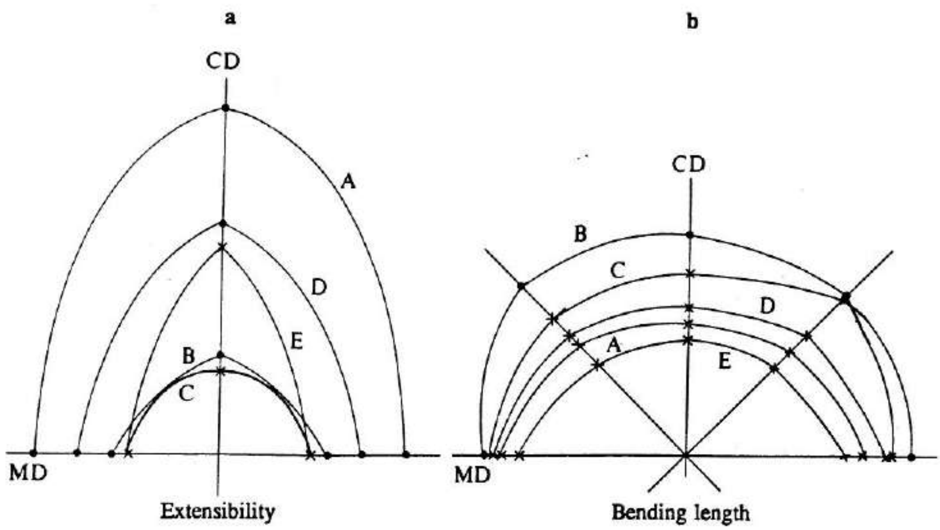

Fig. 12.3 Mechanical anisotropy in nonwoven test samples

compared with CD. It should be noted that samples B and C which are more isotropic in their mechanical behaviour compared with samples A, D and E, however, possess high stiffness. It can be seen that the anisotropic behaviour in bending differs significantly between the tested samples implying that the shape and fit of garments of a given size made up of these fabrics will be different.

5. TECHNOLOGICAL DEVELOPMENTS

5.1 Liquid Barrier

Nonwoven-based protective clothing developments are both consumer and technology driven [7]. Despite the excellent liquid barrier properties of garments manufactured from plastic reinforced nonwovens, these products are often judged to be uncomfortable due to lack of air permeability (Table 12.6). The importance of comfort in protective clothing systems cannot be over emphasized. There is enough evidence in the literature showing that a significant reduction in post-operative infection rate can be achieved by replacing woven fabric clothing with a nonwoven-based clothing. But again wear comfort becomes an important consumer requirement.

TABLE 12.6 Liquid Barrier and Air Permeability of Spun-laced Nonwovens

Material	Oil Repellency AATCC 118	Hydrostatic Resistance ISO 811–81	Air Permeability BS 5636 (l/min)
Spun-laced $70\ g/m^2$ PES/wood pulp	2	16 cm	39
Above reinforced with 100% PE film $115\ g/m^2$	8	80 cm	0

AATCC Scale 1–8, 8 being the best

Table 12.7 shows the values of resistance to water penetration in case of some spun-bonded samples. It can be concluded that the liquid barrier property improves by increasing the fibre-fibre bonded area (C > B > A). Even higher resistance is shown by the composite nonwoven structure D.

TABLE 12.7

Sample	Resistance to Hydrostatic Pressure ISO 811–81	
	Face 1	*Face 2*
A	16	14
B	20	17
C	23	21
D	40	35

The seemingly contradictory requirement of creating liquid barrier and breathability of protective clothing has placed challenging demand on new technologies. Major nonwoven structures used in protective clothings such as SMS spun-bonded 100% PP/melt-blown microfibre mat/100% PP spun-bonded, spun-lace wood pulp/polyester with or without lamination with 100% PE-film and spun-bonded 100% PE plexifilamentory linear high density fibres, may have some shortcomings in terms of their mechanical properties relevant to garment making. Whereas it is possible by lamination and coating procedures to obtain liquid impervious nonwovens with good barrier, against liquids such as water, saline, blood and alcohol, it may not be [8] possible to produce comfortable protective garments out of these fabrics without appropriate design manipulations.

5.2 Microfibre-based Materials

New techniques for spinning extremely fine filaments even as low as 0.1–0.3 dtex have resulted in interesting developments of woven and nonwoven structures of high functional requirement. The arrangement of superfine fibres and filaments tightly packed in nonwoven structure, for example, Freudenberg Microfibre Spunwebs develops high hydrostatic resistance together with good air and water-vapour permeability, mechanical isotropy and drape. Mechanisms of water proofness of this superfine fibre based high density structures can be explained as follows:

From Laplace equation for the penetration of a liquid into a capillary

$$\Delta P = \frac{2\gamma \cos \theta}{r}$$

where r = radius of the pores
γ = surface tension of the penetrating liquid
θ = contact angle between the liquid and pore walls.

From this equation it is obvious that the liquid resistance of the fabrics will be increased by reducing the inter-filament pores or by increasing the contact angle through the use of water repellent finishes. By designing new processes for fabrics preparation and finishing, and due to advances in technologies for production and application of polymeric membranes and fluorochemicals it should be possible to combine the consumer driven technologies for aesthetic comfort, barrier functions of nonwoven-based protective clothing.

Because of the fashion and function demands, many developments have taken place for producing thin but high insulating fibre-fills. A number of coweb-like nonwoven structures have superfine fibres where heat insulating property has been imparted by confining as much air as possible in the microspaces between the fibres thereby checking heat losses by convection. These new materials can have 2–3 times the thermal insulation as given by conventional polyester fibre-fill of the same thickness (Table 12.8). This

TABLE 12.8 Thermal Resistance According to BS 4745 : 1971

Material	Thermal Resistance K m^2/W/cm
PES conventional	0.15
Microfibre based PES Burst fibre process	0.32
PES 0.1–0.5 dtex	0.52

development has resulted in consumer satisfaction because of the balance achieved in functional and aesthetical characteristics.

5.3 Yarn-reinforced Nonwovens

Specially designed machines using warp knitting technology have been developed by Karl Meyer for Yarn reinforcement of nonwoven fabrics (Fig. 12.4). One of the ideas behind this technique has been to create a single membrane that performs much better than any of its components. At TEFO extensive work has been done in this field mainly on reinforcing dry-laid wood pulp fibres but also some nonwoven materials. The resulting materials have shown much improved tear and tensile strength, better drape, lower bending stiffness and high abrasion resistance compared with non-reinforced nonwoven structures. This technique has a lot of potential in imparting good apparel characteristics into nonwoven structures.

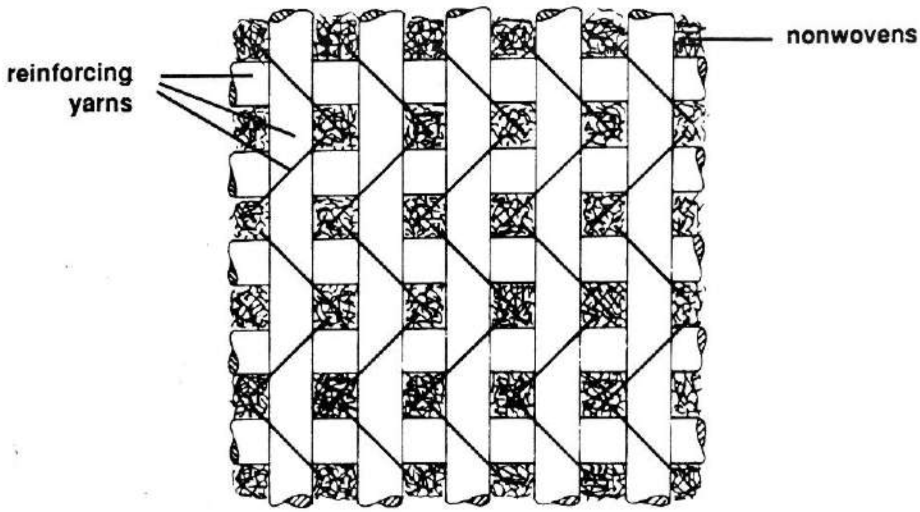

Fig. 12.4 Yarn-reinforced nonwoven structures

6. TECHNICAL CHALLENGES

Some of the factors regarding development of new technologies for manufacturing nonwovens and nonwoven-based functional clothing are summarized below [9].

FIBRE TECHNOLOGY

* Bicomponent and binder fibres
* Thermoplastic high temperature resistant fibres
* Synthetic fibres with high resistance to chemicals
* Microfibres

NONWOVENS FABRIC FORMING TECHNOLOGY

* Surface treatment of nonwoven such as grafting, plasma

* New lamination and coating techniques, microporous and hydrophilic coatings
* Engineered structures
  multilayer/multifunctional
  mechanical isotropy
  Improved drape characteristics
  Improved tear and tensile strength
  Yarn-reinforced nonwovens

GARMENT MANUFACTURING TECHNOLOGY

* New methods of pattern drafting
* Functional garment design
* Novel manufacturing techniques
* Form-shaping of garment parts

Whereas many technological solutions exist for imparting the functions of barrier, safety and strength in nonwovens for protective clothings, the technical problems faced in combining these functions with satisfactory wear comfort characteristics are still not completely resolved.

Analysis should also be carried out of finding novel making up processes for nonwoven-based protective garments. For example, the designer of such a garment should study the pattern drafting procedures that are specific to the characteristics of nonwoven and plastic reinforced nonwovens. Development of nonconventional shaping, sewing and fabric-joining procedures should constitute an integral part of the future technical challenges regarding nonwoven-based protective clothing.

7. CONCLUDING REMARKS

Satisfactory performance of nonwoven protective garments will depend on their functional characteristics and functional design. Future consumer and market demands will necessitate some new priorities in research and development work. The problem of disposability or the chances of recycling will be major factors determining the future choice of materials and products.

Segmentation of protective clothing market will result in the development of technologies based on the nature and level of protection required in use. Some fundamental changes in nonwoven material type and design of the protective clothing are forthcoming and these are expected to result in products of aesthetically pleasant shape and good fit, and which are comfortable in use and easy to dispose.

8. ACKNOWLEDGEMENTS

The author would like to thank his colleagues Malgorzata Choroszy, Jörgen Ohlsson and Ewa Tobisson for their contributions.

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13

Study of Absorbency in Nonwovens: The Role of Structural Factors and Fluid Characteristics

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A large fraction of nonwoven products are used in applications in which the capacity to retain large volumes of fluids (body or otherwise) under pressure and rapidity of imbibition are highly important. Absorbency being the result of absorbate/absorbent interaction, optimum ultimate performance of an absorbent product should depend upon an effective interplay of three groups of variables. These are the fibre material and geometry related, the fabric structure related, and the end-use related variables. The most important of the variables of the last group is the nature of the fluid absorbed.

Discussed in this paper are the results of important factors falling in each of these groups. The results obtained are used in conjunction with a structural model and the classical theory of capillary absorption in developing an understanding of the absorbency phenomena in fibrous materials.

1. INTRODUCTION

The capacity to retain large volumes of fluids (body or otherwise) under pressure and rapidity of imbibition are important factors in nonwovens used in absorbent applications. Although these requirements could be met in several different ways, there are restrictions which limit the choice. There are limitations on the weight and the bulk of most of the absorbent products, as well as limitations on the cost. Furthermore, problems have been encountered and concerns have been expressed with products containing special polymers and additives. Some approaches have succeeded and some have not, but the one which has not been seriously pursued is the optimization of the fabric structure for highest performance in a given product.

Absorbency being the result of absorbate/absorbent interaction, optimum ultimate performance of an absorbent product should depend upon an effective interplay of three groups of variables: the fibre material and geometry related, the fabric structure related, and the end-use related. The most important of the variables of the last group is the nature of the fluid absorbed.

Presented here are selected results from studies conducted at the North Carolina State University in the general area of absorbency. Although the materials used in these studies were fibres of textile dimensions and properties, the effects found and the conclusions developed should also be generally applicable to structures containing fluff pulp and 'superabsorbent' polymers or fibres, the materials often found in absorbent products.

A section is included which presents a structural model which could be used to predict pore characteristics of a fabric. The parameters computed from this model, when used in conjunction with classical equations from the physico-chemical literature, provide a means for predicting the absorbent characteristics of textiles. Comments on the gaps that exist in our understanding of the absorbency phenomena and the future direction of the work are included in the discussion section at the end.

2. FIBRE AND FABRIC STRUCTURE FACTORS

The variables examined were the fibre type (hydrophobic, hydrophilic, and the blends of the two), needling parameters layering, uniformity of mixing, and environmental pressure. In our earlier studies [1–3], the fibres employed were rayon (1.5 denier,1.5") and polyester (3 denier, 1.56"). The base structure used was an air-laid web (3.8 oz/yd^2) from a Rando Feeder-Rando Webber line. Samples consisting of uniformly dispersed blends of rayon/polyester (R/P) of 0/100, 20/80, 40/60, 60/40, 80/20, and 100/0 were prepared which were needled from both sides to a total needling intensity of 244 needles per square inch. The depth of needle penetration was varied from 1 barb to 3 barbs through the thickness of the web.

In our first set of studies, the test apparatus used was similar to the one described by Bernard Lichstein [4] but had modifications incorporated for holding specimen in exact position and for greater ease of operation. The apparatus (Fig. 13.1) [2] consisted of a buret which was connected by a fluid transport tubing to an opening in the specimen cell. An aluminum cylinder was fitted over the opening. The sample was die-cut to fit the cylinder exactly. A stainless steel piston fitting closely inside traversed downward and exerted a uniform pressure of 2.16 kN/m^2 (22 gf/cm^2). Additional cylindrical weights with holes drilled in the centre and fitting on the piston rod allowed provisions for systematically varying the 'environmental pressure'. Three levels of these were used: 22, 70 and 170 gf/cm^2 (2.16, 6.87 and16.69 kN/m^2, respectively).

The fluid used in this study was distilled water. From the amount of liquid absorbed and the time of absorption, the following quantities were determined:

Absorbent capacity, c(g/g), given by the total mass of fluid absorbed divided by the mass of the sample.

Average rate of absorption, Q ($g/g\text{-}sec^{1/2}$), given by the absorbent capacity c (g/g) divided by the square root of the time of absorption [2, 4].

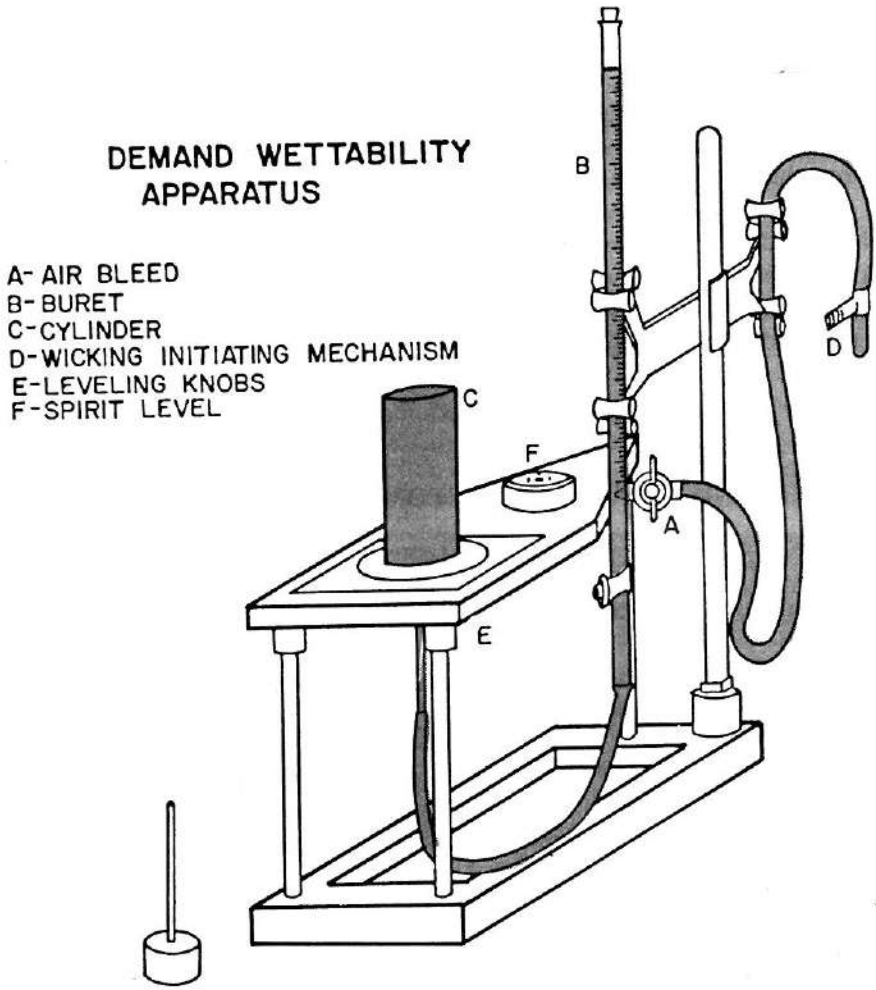

Fig. 13.1 Demand wettability apparatus [2]

2.1 Effect of Blend Ratio, Needling Depth, and Environmental Pressure

Preliminary examination of results showed that the web containing 100% polyester fibre did not absorb any fluid and the web containing 80% polyester/20% rayon fibres absorbed fluid sporadically—in some cases very high amount and in others none at all. All other blends absorbed water uniformly and fell in a regular pattern. The effects of variables of interest were evaluated in the latter, i.e., R/P of 40/60 to 100/0. The statistical analysis carried out on the data showed that all major variables, namely blend ratio (BR), needling depth (ND) and environmental pressure (EP), produced highly significant effects ($P > 99.9\%$).

In the model of the absorbent capacity (C), the predominant factor having greatest effect was the environmental pressure, with ND and BR coming in second and third. The effects of the interactions were not significant except that of BR*ND to a small extent. In the model of Q, on the other hand, the depth of needle penetration assumed the most important role followed by EP and BR, in that order. All two-way interactions were also significant, but to a greatly reduced extent. The strongest of the interactions was EP*ND.

Selected results are plotted in Figs. 13.2 to 13.5. As the proportion of rayon in the blend increased, C decreased (Fig. 13.2). The effect of increasing the fraction of rayon in the blend on the value of Q was to increase the latter (Fig. 13.3).

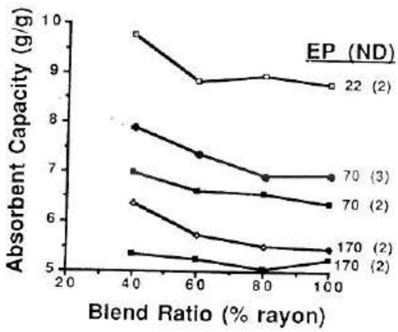

Fig. 13.2 Effect of blend ratio on absorbent capacity [1]

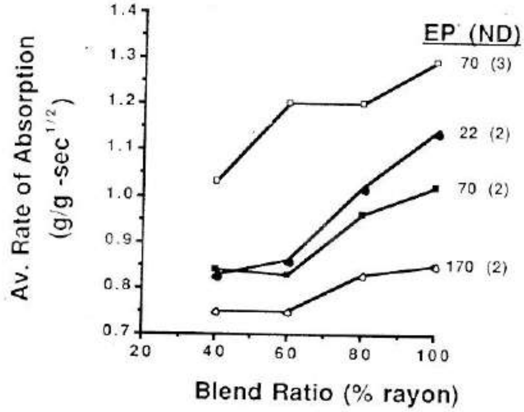

Fig. 13.3 Effect of blend ratio on absorbency rate [1]

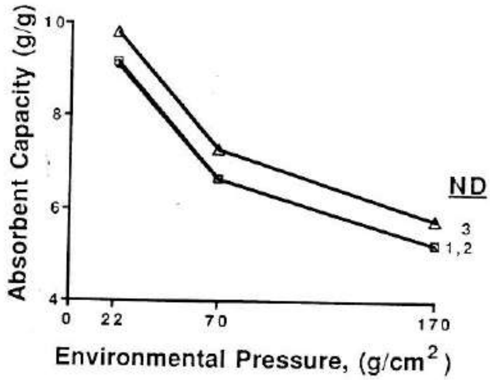

Fig. 13.4 Effect of environmental pressure on absorbent capacity. Values averaged over all blends [2]

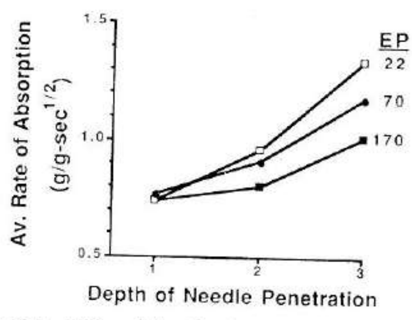

Fig. 13.5 Effect of depth of needle penetration on absorbency rate. Values averaged over all blends [2]

For all combinations of EP and ND, the highest value of C was obtained in blend containing 40% rayon and 60% polyester. The four blends containing lower fractions of polyester gave values of C which were lower but not varying on an average by more than ± 0.5 (g/g). As pointed out earlier, the two blends containing higher fraction of polyester showed, on an average, very little absorption.

The average rate of absorbency, Q, increased as the percentage of hydrophilic fibre in the web increased (Fig. 13.3). Generally the maximum value of Q was found in the blends containing 80 to 100% rayon. These results were in contrast to those of C, in which case the higher percentage of polyester fibres seemed to provide an advantage.

The results in Fig. 13.4 show that as environmental pressure increased, absorbent capacity decreased for all levels of BR and ND. The absorbency rate also decreased with increase in EP; however, the rates were different at different levels of ND.

As needling depth increased from 1 to 2, only a slight and irregular change took place in the value of C (Fig. 13.4). However, as the level increased to 3, a definite increase occurred in absorbent capacity (for all combinations of BR and EP). The average absorbency rate increased steadily as the needling depth increased from 1 to 3 (Fig. 13.5).

2.2 Effect of Uniformity of Blending

In one experiment the effect of blend uniformity on absorbent characteristics was examined. Two webs containing 80/20 blend of rayon/polyester fibres were prepared by passing the mix through the Rando line once in one case and three times in another case, presumably giving the latter web a more uniformly blended structure. These webs were needled to an intensity of 488 needles/inch^2 and to a depth of 2. The tests for absorbency were performed with environmental pressure of 6.87 kN/m^2. The results given below [1] showed that less sample-to-sample variation in values of C and Q were obtained in the blend produced by three passes as compared to the single pass. The values of C in the two were about the same. The blend uniformity did, however, significantly influence the value of Q, which was about 9% higher in the more uniformly blended web than in the other.

Number of Passes through the Line	C (CV%)	Q (CV%)
1x	6.94 (3.83)	1.62 (8.61)
3x	6.98 (2.78)	1.76 (3.84)

2.3 Effect of Layering

Absorbent products usually contain layers of hydrophobic and hydrophilic materials. To examine the effects of such structures, the performance of a number of patterns involving layers of 100% polyester and rayon were determined [2]. Two separately needled webs of polyester and rayon were superimposed and needled together to penetration level of 2 and two different needling intensities (244 and 488 needles/sq. in.). These two layered structures, and a third one, obtained by the same procedure but without needling of the final composite structure, were tested in two different ways: (1) with polyester side down (polyester layer next to the fluid hole), and (2) with rayon side down. The results given below show some interesting trends.

Layer Down	244 Needles/in.^{2}		488 Needles/in.^{2}		Separate	
	C	Q	C	Q	C	Q
Polyester	4.156	1.156	3.756	1.094	0.000	0.000
Rayon	4.912	0.494	4.268	0.560	6.820	0.800

In both the lightly and the heavily needled structures, the samples with the polyester side down gave higher rates of absorption. Although the samples tested with the rayon side down showed more absorption, the test proceeded relatively very slowly—at more or less half the rate.

Comparing the values of the lightly with the heavily needled webs, the former absorbed significantly more water than the latter. The rate, however, depended upon the layer that was down. The rate with polyester down was higher in the lightly punched web, and with rayon down was higher in the heavily punched web.

The results on the composite structure in which two separately needled webs were layered together without further binding, showed that when the tests were carried out with the polyester side down, no absorption took place. On the other hand, tests carried out with the rayon side down gave more or less normally expected values. The results found with the polyester side down were commensurate with those found with the 100% polyester web earlier.

3. FLUID VARIABLES

Absorbency being the result of absorbate-absorbent interaction, optimum performance in an absorbent product could only be obtained if this interaction was optimized. Much of the research in absorbency, however, has emphasized the composition and the structure of the product; relatively little attention has been paid to the fluids which must be absorbed into them. The fluids generally used have been water or dilute saline solutions which do not represent body-like fluids in either the chemical constitution or the physical characteristics. Furthermore, as the medical literature shows, the composition of body fluids is not constant but varies from person to person, and with the dietary habits and the age of the individuals [5, 6]. A study was therefore conducted [7, 8] in which the role of fluids in absorbency was investigated.

The fluids chosen in this research varied in properties over a broad range. Some of the fluids were pure compounds, some were mixtures, and yet some others were specially formulated to represent body-like fluids.

The recipes for the latter (Table 13.1) were selected from the information available in the patent literature [13–16]. The fluids and their properties, measured and/or obtained from the chemical literature [9–12], are given in Table 13.2.

The fabrics used in this study were composed of air laid, needle punched (244 needles/in.^{2}), webs of 100% rayon (3 denier, 2"), 100% polypropylene (4 denier, 2") and 50/50 blends of polypropylene and rayon. The

TABLE 13.1 Constitution of the Synthetic Body Fluids [7, 8]

Synthetic Urine	*Grams*
Urea	19.4
Sodium chloride	8.0
Calcium chloride	0.6
Magnesium sulfate	1.0
Water	971.0
Synthetic Menstrual Fluid	
Sodium chloride	10.0
Sodium carbonate	4.0
Glycerol	100.0
Carboxymethyl cellulose	4.0
Water	880.0
Colouring	trace

TABLE 13.2 Properties of Fluids (25°C) [7, 8]

Fluid	Vol. Ratio	γ_{lv} mN/m	pH	θ^{o***}	ρ(g/cc)	η (cp)
Ethanol		22.9	6.01	6	0.79	1.20*
Ethanol/water	25/75	44.6	7.08	39	0.86	2.31
Ethanol/water	50/50	30.6	7.02	12	0.85	2.56
Ethanol/water	75/25	28.7	6.47	5	0.85	2.11
Formamide		58.5	7.20	29	1.13	3.30
Formamide/water	25/75	67.9	5.52	59	1.02	1.62
Formamide/water	50/50	64.1	5.98	54	1.06	2.56
Formamide/water	75/25	61.1	6.45	35	1.08	3.01
Water		71.9	7.09	61	1.00	0.89
Dimethyl phthalate		42.3	4.25	14	1.19	17.0*
Hexadecane		26.7	4.96	6	0.77	3.59**
Saline 1%		72.2	6.90	58	1.01	1.02
2%		72.9	6.69	58	1.01	1.03
3%		73.6	6.32	59	1.02	1.04
4%		74.5	6.29	60	1.02	1.04
5%		75.3	6.09	61	1.03	1.05
Synthetic urine		72.5	6.49	65	1.01	1.42
Synthetic menstrual fluid		70.2	9.95	78	1.06	8.55

*given at 20°C; **Given at 22.2°C; ***obtained with acetate film.

polypropylene fibres had a small amount of hydrophilic finish (0.43–0.75%). The depth of needle penetration was varied over two levels. In the lightly needled webs, one set of barbs of the needle penetrated through the thickness of the fabric (ND1), while in the deeply needled webs, all three sets of barbs penetrated (ND3).

Absorbency was measured using two different environmental pressures (EP of 9 and 22 gf/cm^2) and zero hydrostatic head on the Gravimetric Absorbency Testing System (GATS) (Fig. 13.6) [17, 18] manufactured by M/K Systems.

3.1 Effect of Fluid Characteristics and Fabric Structure

Selected results of absorbency are given in Tables 13.3 and 13.4 [7, 8]. Considering first the absorbent capacity, it is noted that the fibre type and

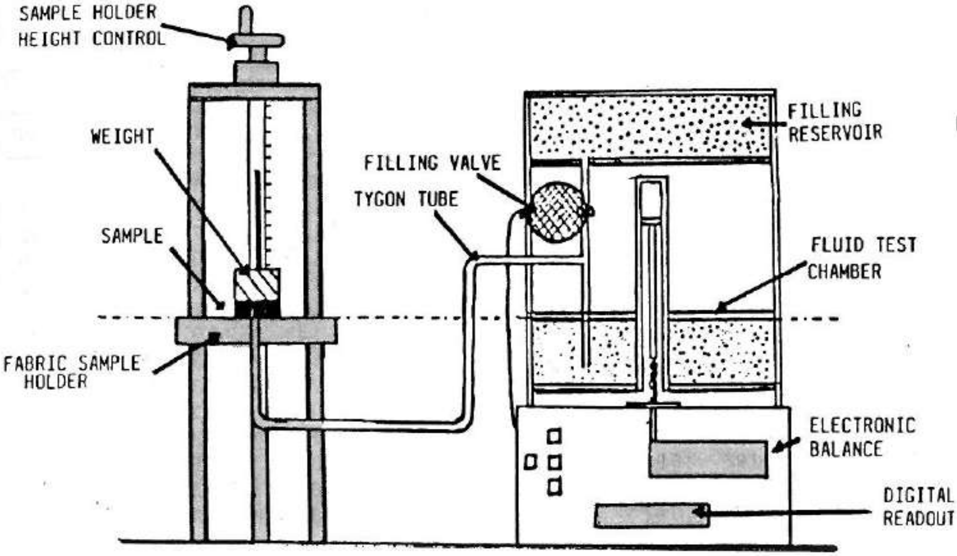

Fig. 13.6 The Gravimetric absorbency testing system apparatus

TABLE 13.3 Absorbent Capacity (g fluid/g fabric) [7, 8]

	ND1, EP22			ND3, EP22			ND3, EP09		
	R	PP	R/PP	R	PP	R/PP	R	PP	R/PP
E	8.2	13.1	10.4	8.8	13.3	11.3	12.3	14.3	15.9
E/W 1 : 3	7.2	12.1	9.8	8.4	12.3	11.0	10.7	12.1	12.1
E/W 2 : 2	7.3	12.6	10.1	8.5	12.4	11.1	10.9	12.4	13.5
E/W 3 : 1	7.6	12.9	10.3	8.7	12.9	11.3	11.9	13.1	13.8
F	9.1	14.6	12.2	10.5	14.7	13.1	13.2	16.6	16.3
F/W 1 : 3	8.2	13.2	10.4	9.6	13.5	12.0	11.6	16.1	15.8
F/W 2 : 2	8.4	13.8	10.7	10.1	13.9	12.4	12.2	16.1	15.9
F/W 3 : 1	8.7	14.1	10.9	10.3	14.2	12.5	12.8	16.2	16.3
W	8.3	13.1	10.6	8.9	13.6	11.5	12.4	15.3	16.3
DMPT	9.6	14.8	12.7	11.3	15.2	13.9	13.3	15.0	16.3
H	8.1	12.9	9.9	8.5	12.9	11.6	12.2	13.9	14.5
S 1%	8.0	12.7	10.9	8.6	13.5	11.4	11.2	15.3	16.2
S 2%	7.8	12.5	10.3	8.5	13.2	11.3	11.1	15.3	15.8
S 3%	7.6	12.3	9.9	8.3	13.0	11.2	11.0	15.2	15.3
S 4%	7.5	12.1	9.9	8.1	12.6	11.2	10.9	14.1	14.2
S 5%	7.4	12.1	9.8	—	—	—	10.5	13.7	13.8
SU	8.0	10.6	9.9	8.1	12.0	11.1	12.0	15.2	15.2
SMF	7.9	9.2	8.0	8.0	9.6	8.9	11.3	12.2	12.5

R—Rayon; PP–Polypropylene; E–Ethanol; W–Water; F–Formamide; DMPT–Dimethyl phthalate; H–Hexadecane; S–Saline; SU–Synthetic urine; SMF–Synthetic menstrual fluid; ND–Needling depth; EP–Environmental pressure (gf/cm^2).

the fabric structure produced significant effects. Polypropylene fibre consistently gave a higher value than rayon. Higher needling depth or lower environmental pressure gave appreciably higher values. Some differences in absorbent capacity are noted among different fluids. Generally, dimethyl

TABLE 13.4 Rate of Absorbency (g/g-sec$^{1/2}$) [7, 8]

	ND1, EP22			ND3, EP22			ND3, EP09		
	R	PP	R/PP	R	PP	R/PP	R	PP	R/PP
E	1.94	1.95	1.93	2.08	2.07	2.06	3.48	3.54	3.62
E/W 1 : 3	1.61	1.56	1.59	1.72	1.75	1.73	2.56	2.59	2.61
E/W 2 : 2	1.73	1.67	1.67	1.86	1.90	1.87	2.71	2.70	3.02
E/W 3 : 1	1.89	1.85	1.87	1.99	1.95	1.95	3.02	3.06	3.26
F	1.72	1.59	1.68	1.83	1.76	1.79	2.49	2.58	2.62
F/W 1 : 3	1.22	1.20	1.23	1.29	1.26	1.24	2.17	2.22	2.22
F/W 2 : 2	1.36	1.36	1.34	1.45	1.40	1.43	2.32	2.34	2.37
F/W 3 : 1	1.53	1.48	1.48	1.71	1.65	1.66	2.37	2.37	2.39
W	1.54	1.53	1.51	1.64	1.59	1.59	2.31	2.33	2.36
DMPT	0.27	0.26	0.19	0.30	0.33	0.32	1.22	1.29	1.32
H	1.25	1.19	1.24	1.25	1.19	1.20	2.35	2.37	2.49
S 1%	0.97	0.90	0.91	1.08	1.02	0.99	1.61	1.67	1.59
S 2%	0.95	0.88	0.91	1.09	1.08	0.93	1.53	1.57	1.59
S 3%	0.90	0.87	0.88	0.95	0.95	0.88	1.44	1.45	1.48
S 4%	0.88	0.85	0.80	0.92	0.85	0.83	1.32	1.35	1.35
S 5%	0.84	0.78	0.80	0.90	0.85	0.80	1.24	1.26	1.27
SU	1.01	0.96	0.99	1.04	1.00	1.01	1.96	2.18	2.20
SMF	0.36	0.32	0.43	0.58	0.51	0.53	1.32	1.16	1.17

For legend, see footnote under Table 13.3.

phthalate and formamide gave the highest values while synthetic menstrual fluid gave the lowest value. The addition of salt to water resulted in a decrease in the value; the greater the salt concentration, the lower the capacity.

Table 13.4 shows that for any given fluid the rate was not much affected by the fibre of the web. The effects of the structural factors, namely the needling depth, the environmental pressure, and the fluid type, are, however, evident. Increasing the needling depth or decreasing the environmental pressure gave a consistent increase in the rate. Generally, a change in the fabric structure produced an enhancement in the rate by 50% or more. However, comparatively the greatest effect on the rate of absorbency was produced by the differences in the properties of the fluids. Irrespective of the fabric structure, ethanol gave the highest value and dimethyl phthalate the lowest. This last fluid reacted poorly to testing in the GATS apparatus as it frequently clogged the fluid valve and caused difficulties in resetting and restarting the apparatus. This behaviour was most certainly due to the viscosity of this fluid which was the highest of all fluids.

As expected, the rate value also showed a dependency on the amount of salt present: as the concentration of the latter increased, the rate decreased. As compared with water, the rate for salines was much lower. Synthetic urine gave a slightly lower rate than did water which could also be due to the presence of salt in the former. The synthetic menstrual fluid gave a low value, the second lowest to that of the dimethyl phthalate. An expected reason for this also was its viscosity which was the second highest to that of dimethyl phthalate.

4. STRUCTURAL MODEL

Two structural factors which directly affected capillary absorption are the capillary size and the pore volume of the fabric. The former could be expected to affect the capillary force and the rate of absorbency [21–23], and the latter, assuming the fluid was mostly absorbed in the interstitial space between the fibres, the total capacity of the structure to imbibe and retain fluid. A model was developed which predicted the values of these two parameters. These, when used in conjunction with classical theories, provided a means for predicting the absorbent characteristics of fabrics. While the detailed treatment of the model is published elsewhere [20], the necessary features are reviewed below.

4.1 Pore Volume

This is given by the difference between the volume of a fabric sample and the volume occupied by the fibres. If a web of dry mass M is made up of two different fibres of mass fractions m_1 and m_2, and densities ρ_1 and ρ_2, then the volume V_f occupied by the fibres in the web would be given by

$$V_f = M\left[\frac{m_1}{\rho_1} + \frac{m_2}{\rho_2}\right] \tag{1}$$

Total air volume (interstitial space) in a web of area A and thickness L (Fig. 13.7) is given by

$$V_a = AL - V_f$$

In absorbency tests, one is normally concerned with the amount of fluid absorbed per unit mass of the fabric. A parameter, called specific air volume, V_s, is defined as the volume of interstitial space per unit mass of the fabric:

$$V_s = \frac{V_a}{M} = \frac{AL - V_f}{M} \tag{2}$$

If, on the other hand, absorbent capacity is characterized in units of mass of fluid absorbed per unit mass of the fabric, as done in the results of this paper, an estimate of it can be obtained by taking the product of V_s with the density of the fluid ρ_l absorbed, or

$$C' = V_s \cdot \rho_l = \left[\frac{AL - V_f}{M}\right]\rho_l \tag{3}$$

In absorbency tests, normally, a fabric sample is die-cut to the desired size and tested under some environmental pressure P using a specific fluid. Estimation of the value of C' thus requires a measurement of the value of fabric thickness, L, under the environmental pressure P (Fig. 13.7). It is understood that if during absorption any of the parameters of Eq. (3) change, such as due to swelling of fibres, which could be expected from fabrics containing hydrophilic fibres, the estimate of the value of C' will also change.

If a fabric is not a blend but consists of a single fibre of density ρ, then Eq. (3) reduces to

$$C' = \left[\frac{AL}{M} - \frac{1}{\rho}\right]\rho_l$$

4.2 Pore Size

In estimating this quantity, it is assumed that a capillary is bounded by three fibres, oriented parallel or randomly. Out of the three fibres, n_1 come from type 1 and n_2 from type 2 of the blend. The treatments involving the parallel or the random assumptions led to exactly the same estimate of the capillary size [20]. The procedure involving the former is briefly reviewed. The fibres are assumed to be distributed uniformly throughout the structure, they lie at the apexes of equilateral triangles of length Y (Fig. 13.8), and contribute 1/6th of their areas to those of the triangles. The unoccupied areas of the triangles

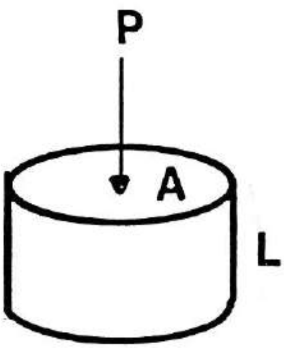

Fig. 13.7 Fabric element

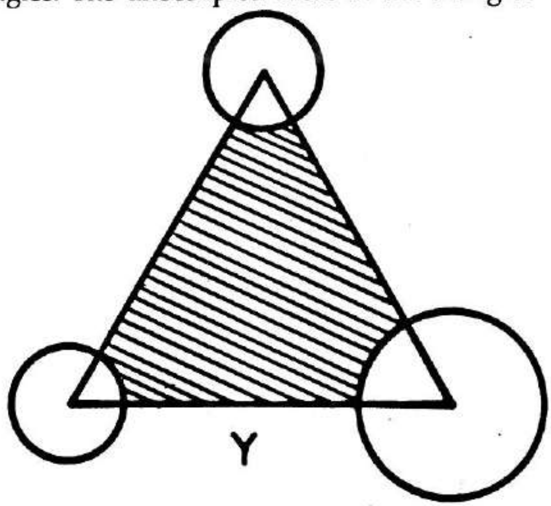

Fig. 13.8 Hypothetical capillary bounded by three fibres

form the capillaries. The average value of this area, when equated with that of a circle, provides the average value of the capillary radius for the fabric which is as follows:

$$R = \left[\frac{S}{\pi}\left(\frac{AL}{V_f} - 1\right)\right]^{1/2} \tag{4}$$

where,

$$S = \frac{1}{6K}\left[\frac{n_1 d_1}{\rho_1} + \frac{n_2 d_2}{\rho_2}\right]$$

$$n_2 = \frac{3m_2 d_1}{m_1 d_2 + m_2 d_1}$$

and

$$n_1 = 3 - n_2$$
$$K = 9 \times 10^5$$

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The above estimate of the capillary radius is strongly validated by the fact that the model based on the random arrangement of fibres led to exactly the same value [20]. The assumptions made in that treatment are that each fibre is surrounded by free volume proportional to its own volume, an interstitial space is still bounded at each point by three fibres, and each fibre contributes 1/6th of its free volume to interstitial space at each point along the length.

An experiment was conducted to determine the manner in which the values of V_s and R change with the environmental pressure and the structure of the fabric [20]. The webs containing blends of rayon (3.3 denier, 1.56") and polypropylene (1.5 denier, 1.5", and 6.0 denier and 1.875") were prepared. The webs produced on the air laying equipment were needled to 244 needles/in.^{2} and depth of 1 and 3 barbs. The samples were die-cut and weighted. Their thicknesses were measured on Instron with compression all under different pressures.

Selected results are illustrated in Figs. 13.9 and 13.10, respectively, for V_s and R. These illustrate the effects of environmental pressure, needling depth, fibre denier and fibre type. As expected from the results of the study discussed earlier, the value of V_s is greatly affected by the pressure under which tests

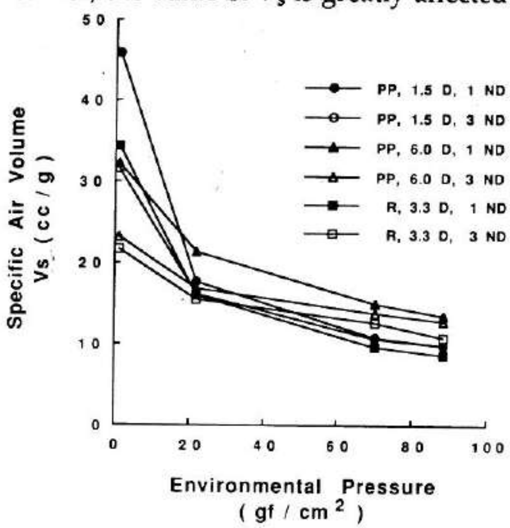

Fig. 13.9 Effect of environmental pressure on computed values of specific air volume

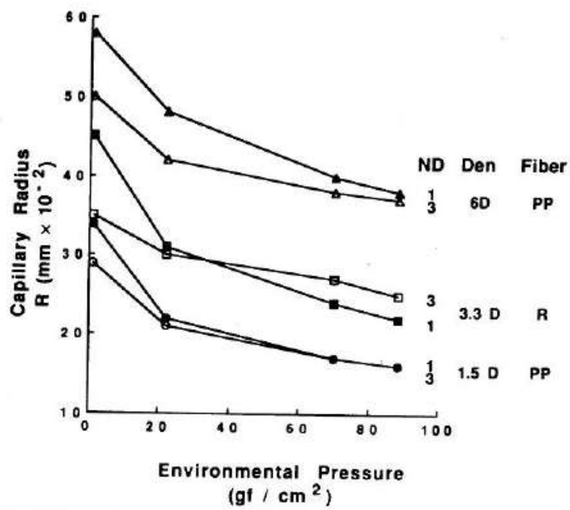

Fig. 13.10 Effect of environmental pressure on computed values of capillary radius

are conducted—an increase in the latter causes a decrease in the former, the rate depending upon the properties of the fibre and the structure of the fabric. The spread in values resulting from the differences in the fibre types and the fabric structure greatly decreased as pressure increased from 1.2 (essentially none) to 22 gf/cm^2. Increase in pressure beyond this level produced relatively little additional change. Effects of fibre denier in polypropylene web and of needling in rayon web are interesting. Polypropylene web with higher denier as compared to lower denier and rayon web with larger needling level as compared to smaller needling level gave V_s values which were lower at low pressure and higher at high pressure. These differences in behaviour indicate that the use of higher denier fibre and/or higher needling intensity in the web produced a structure which was relatively more entangled and consolidated and, therefore, was more effective in resisting collapse when subjected to pressure.

More or less the same effects as above are noted of EP and ND on the value of R, illustrated in Fig. 13.10. The effect of denier of fibres is somewhat different on R than on V_s. Higher denier led to higher value of R, irrespective of EP and fibre type. A major and obvious reason for this is the number of fibres per unit mass making up the web decreases as denier increases. This leads to an increase in the distance between fibres with increase in denier.

4.3 Comparison with Actual Absorbency Results

Assuming that the fluid absorbed in the internal structure of the fibres was negligible and the fabric specimen was fully saturated in an absorbency test, one could use Eq. (3) to predict the total absorbent capacity. To accomplish this, the thickness, L, of the fabric samples was required. This was measured with a gauge during the absorbency tests. Absorbent capacity was estimated for the web specimens studied with different fluids in the previous section, and the results obtained gave excellent correlations with the measured values [8]. The small differences noted could be ascribed to the difficulties associated with the measurements of fabric thickness and the departure from the validity of the two assumptions mentioned above.

For estimating the value of rate of absorbency, Washburn's equation [21] was used. The rate given by the integrated version of his equation is as follows:

$$\frac{S}{\sqrt{t}} = \left(\frac{R\gamma_{lv}\cos\theta}{2\eta}\right)^{1/2}$$

In this, S is the distance to which the penetration extends in time t, R is the effective radius of the capillaries, γ_{lv} is the liquid-vapour surface, tension, and η is the coefficient of viscosity.

The predicted and the measured values of the rates for selected fluids and web structures are given in Table 13.5. The results showed a qualitative agreement between the two. The most interesting observation, however, was that while the non-aqueous fluids gave numbers which were higher than the predicted, the aqueous fluids (water, salines, synthetic urine and synthetic menstrual fluid) gave numbers which were lower than the predicted. It is suspected that two reasons which may have led to a different trend with the aqueous fluids are the swelling of the fibre structure, and the chemical interaction between the fluid and the fibre material not accounted for in

TABLE 13.5 Comparison of the Measured Rates with the Predicted Rates by the Washburn Equation

Fluid	R/PP; EP 22 gf/cm^2; ND3	
	Theoretical cm/sec$^{1/2}$	Measured cc/g-sec$^{1/2}$
Ethanol	1.61	2.61
Formamide	1.50	1.58
Water	3.06	1.59
Hexadecane	1.00	1.56
Saline 3%	2.59	0.86
S. Urine	1.69	1.00
S. Menstrual Fluid	0.59	0.50

Washburn's equation. The latter assumed ideal capillaries with little chemical interaction between the fluid and the capillary material.

5. DISCUSSION

Presented above were selected results from some of the studies conducted at North Carolina State University on absorbency in nonwovens. The objectives of these studies were to identify the factors which affected absorbency and to understand the nature of their effects. Presented below is a general but brief discussion of the results obtained.

The total absorption in fabrics is made up of the absorptions within the structure of the fibre and in the interstitial space between the fibres. If a web was composed mostly of hydrophilic fibres, absorption should result from both mechanisms. If, on the other hand, it consists mostly of hydrophobic fibres, most of the absorption should take place in the spaces between the fibres. Hydrophobic fibres maintain their resiliency under wet conditions and resist collapse when subjected to pressure. The hydrophilic fibres, in contrast, lose greatly their resiliency when wet, and the webs containing them tend to collapse under pressure and undergo a decrease in interstitial space.

When a small amount of hydrophobic fibre is blended in the web with hydrophilic fibre, it can be expected to bring about a change in the absorbent capacity by causing a change in absorption in both the inter- and the intra-fibre structure. The resultant, thus, depends upon whether the increase in the former is greater or smaller than the decrease in the latter. In the case of the polyester/rayon blends discussed earlier, when the fraction of the former was as little as 20%, the absorbent capacity was higher than that of 100% rayon web at all levels of environmental pressures and depth of needle penetration. At this blend level, the increase in interstitial space clearly overshadowed the decrease in the ability of the fibres to absorb fluid, and gave a definite increase in C. As more hydrophobic fibre was added, absorbent capacity increased further (Fig. 13.2). However, when the fraction of polyester increased to 80% or above, difficulties in fluid uptake were encountered. In some webs, no absorption took place. In some of the others in which absorption did take place, wicking was found difficult and had to be initiated by special means. This showed that at this blend level, the percentage of the hydrophilic fibre was not large enough to attract the fluid to initiate wicking.

Absorbency rate was also affected by blend ratio, but differently. It increased as the percentage of hydrophilic fibre in the web increased (Fig. 13.3). Generally, the maximum value of Q was found in a blend consisting of from 80 to 100% rayon. These results showed that the greater attractive forces present in the hydrophilic fibres were responsible for higher absorbency rate.

Substantial amount of work has been done on the development of hydrophilic finishes for the hydrophobic fibres to make the latter more readily acceptable in those products in which traditionally natural fibres have dominated. These finishes work by reducing the contact angle and increasing the capillary force. The polypropylene fibre used in this investigation contained such a finish. The results (Tables 13.3 and 13.4) showed that the webs containing 100% hydrophobic fibre were effective in attracting and imbibing fluid. The absorbent capacity obtained was significantly higher than those of either the 50/50 rayon/polypropylene blend or the 100% rayon web. The rate of absorbency in the polypropylene web was also not less than those in the other two.

5.1 Fabric Structure Variables

Among fabric structural factors which affect absorbent characteristics are the pore size, pore specific volume, the nature and extent of bonding, and the orientation of the flow channels. If the web is a blend of different fibres, then the nature of the distribution of the fibres should be an additional factor. The effects of some of these variables were investigated and the results were presented above. Pore size, pore specific volume, and the orientation of channels were affected jointly by the needling depth and the environmental pressure. The extent of bonding which imparted structural rigidity to the web was governed by the needling parameters. The nature of the distribution of fibres in blended webs was affected by the uniformity of mixing and layering. Absorbent behaviour was found to be significantly affected by all these structural factors. In some cases, these factors interacted with each other in governing the trends. This was particularly true of needling depth or intensity and environmental pressure in influencing the value of Q.

The general effect of an increase in environmental pressure was to steadily decrease absorbent capacity (Fig. 13.4). This was expectedly due to a decrease in the interstitial space between the fibres. It also generally caused a decrease in the value of Q (Fig. 13.5, Table 13.4), which could be speculated as being due to, (1) the capillaries becoming blocked or distorted with an increase in pressure which was expected to slow down the absorption process, and (2) a decrease in the pore size which, according to Washburn's equation, had a direct effect on the rate. The exception to this general trend was observed at needling level of 1 (Fig. 13.5), in which case there was no change in Q in going from EP of 22 to 170 gf/cm^2. This suggests that pore size, which varied with

EP at ND of 1, had a limit on the effect it could exert on absorbency rate. Pore size falling in a certain range and the degree to which the flow channels are undistorted and oriented are important factors in governing rate.

As needling depth increased from 1 to 2, only a slight and irregular change took place in the value of C. However, as it increased to 3, a definite increase occurred in absorbent capacity (Fig. 13.4, Table 13.3). The rate of absorption also increased with ND in more or less a similar manner (Fig. 13.5, Table 13.4). An increase of ND was expected to produce three structural changes: (1) more fibres aligning in the direction of the thickness; (2) more rigid channels forming; and (3) the web becoming denser, thereby giving a decrease in the available free space for absorbency. At needling levels of 1 and 2, the webs were relatively bulkier and were easily compressed by external pressure. This distorted the channels and reduced interstitial space. At ND level of 3, the webs were much denser and flow channels more rigid. These resisted collapse and distortion when subjected to pressure.

If the web is a blend of two fibres, the nature of the distribution should affect the results. In one experiment the effect of the uniformity of blending was examined. The webs in which the fibres were more uniformly distributed showed less sample-to-sample variation in C and Q values—an expected result—and a significantly higher value of Q. The latter was expected to be due to a more homogeneous network of channels. Randomly dispersed pockets of hydrophobic and hydrophilic fibres could be expected to retard the flow. When the web consisted of layers of hydrophobic and hydrophilic fibres needled together, the rate was twice as much if the polyester layer was next to the fluid source. This showed that the polyester layer acted as an efficient fluid transport medium for the absorbent layer of rayon—the fluid was sucked through the channels created by needling and absorbed into the rayon matrix. Interestingly, if the layered webs were not needled, then absorbency only occurred when the rayon layer was next to the fluid source.

The above discussion, thus, shows that structural factors play an important role in influencing absorbent characteristics of fabrics. A thorough understanding of the effects of these factors should be expected to provide an effective tool for optimizing the performance of a given structure.

5.2 End-use Related Variables

While several variables may fall in this category, two most important are the environmental pressure and the nature of the fluid absorbed. Comments concerning the former have been given above. Absorbent structures for personal hygiene and medical applications are expected to handle a variety of fluids—from fluids as simple as water to as complex as menstrual. Body fluids such as menstrual, urine, and blood vary greatly among people, some contributing factors being the differences in age, general health, and the dietary habits of the individuals. No systematic studies have been available in the scientific literature which shed light on the effect the fluid properties produce on the absorbent characteristics of nonwovens. The study described in this paper and published recently [8] closed a part of this gap. Fluids varying in surface tension, pH, density, viscosity, and contact angle were examined as absorbates. Results showed that absorbency was greatly affected by the properties of the fluid. While the effect of the latter on total absorbent capacity was limited, that on the rate was substantial, varying over half an order of magnitude. Synthetic menstrual fluid, synthetic urine, salines, and water differed greatly in their interaction as absorbates. Some causes for the differences in values obtained could easily be identified, however, there were some others which were not yet known. This became quite clear when one substituted the properties of the fluids along with the pore characteristics of the structure in classical equations and predicted the absorbent behaviour of a fabric [Table 13.5].

The above results show that gaps still exist in our understanding of the absorbency phenomena and, thus, in our ability to optimize the performance of a product. Some of the reasons for these are that the models and the equations used currently assume ideal capillaries and little or no absorption and swelling by the fibres. The real products, in contrast, contain capillaries which come in different shapes, sizes and orientations, and fibres which absorb large amounts of fluids and swell. What effects these factors have on absorbency and how they can be accounted for by modifications of existing theories are areas in which fundamental work would be most useful.

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14

Effect of Web Weight, Needling Density and Depth of Needle Penetration on Fabric Mechanical Properties

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In this paper, the central compound rotatable design of Box and Hunter has been used to study the individual and interactive effects of web weight (WW), depth of needle penetration (DNP) and needling density (ND) on some of the fabric mechanical properties. The results show that these types of multivariable statistical techniques can be used to predict the trend of the mechanical properties.

1. INTRODUCTION

From a detailed survey of literature on the effect of processing parameters, on the mechanical properties of the needle-punched nonwoven fabrics, following conclusions have emerged.

- The parameters like ND, DNP and WW individually and collectively affect the fabric tensile properties, and the trend observed at one set of conditions may not be the same at another set of conditions.
- For a given WW, the increase in ND and DNP increases the tenacity and initial modulus. But at very high DNP or ND, the tenacity and initial modulus decrease; the breaking elongation decreases with the increase in DNP and ND.
- For a given DNP and ND, an increase in WW has led to an increase in the tenacity up to an optimum WW. Thereafter the tenacity decreases with the increase in WW. With the increase in WW, the breaking elongation reduces, but the initial modulus increases.
- The air flow through the needle-punched fabric depends mainly on the processing parameters like ND and DNP and web characteristics like WW. An increase in ND or DNP first reduces the flow of air through the fabric, and subsequently it increases the amount of air that can pass through the fabric. An increase in WW results in a decrease in air permeability value.

From the foregoing, it is clear that fabric mechanical properties depend on WW, ND and DNP, and the interaction between these parameters. By using an experimental design technique like the Box and Hunter central rotatable design [2], it is possible to study the individual and interactive effects of the chosen variables with very little experimentation. This type of multivariable studies has been carried out by a number of researchers [1, 17, 21, 22]. But so far no work has been reported in the application of this type of multivariable studies on needle-punched nonwoven fabrics.

2. EXPERIMENTAL

To study the individual and interactive effects of WW, ND and DNP, needled fabrics were produced according to the Box and Hunter central compound rotatable design for three variables [2]. In Table 14.1 the coded and actual levels of the three parameters considered are listed along with the twenty sets of experimental combinations performed.

TABLE 14.1 Coded and Actual Levels of Web Weight, Needling Density and Depth of Needle Penetration

Sl. No.	x_1		x_2		x_3	
	Coded Level	Actual Level	Coded Level	Actual Level	Coded Level	Actual Level
1	− 1.000	281	− 1.000	42.0	− 1.000	11.4
2	+ 1.000	519	− 1.000	42.0	− 1.000	11.4
3	− 1.000	281	+ 1.000	74.2	− 1.000	11.4
4	+ 1.000	519	+ 1.000	74.2	− 1.000	11.4
5	− 1.000	281	− 1.000	42.0	+ 1.000	17.0
6	+ 1.000	519	− 1.000	42.0	+ 1.000	17.0
7	− 1.000	281	+ 1.000	74.2	+ 1.000	17.0
8	+ 1.000	519	+ 1.000	74.2	+ 1.000	17.0
9	− 1.682	200	0.000	58.1	0.000	14.2
10	+ 1.682	600	0.000	58.1	0.000	14.2
11	0.000	400	− 1.682	31.0	0.000	14.2
12	0.000	400	+ 1.682	85.3	0.000	14.2
13	0.000	400	0.000	58.1	− 1.682	9.5
14	0.000	400	0.000	58.1	+ 1.682	19.0
15	0.000	400	0.000	58.1	0.000	14.2
16	0.000	400	0.000	58.1	0.000	14.2
17	0.000	400	0.000	58.1	0.000	14.2
18	0.000	400	0.000	58.1	0.000	14.2
19	0.000	400	0.000	58.1	0.000	14.2
20	0.000	400	0.000	58.1	0.000	14.2

x_1 —Web weight, g/m^2
x_2 —Needling density, punches/cm^2
x_3 —Depth of needle penetration, mm

For this study, 51 mm acrylic fibre of 3 denier was used. Parallel laid webs were produced in a miniature card. Needle-punched fabrics were produced from these webs in a lab model James Hunter needle loom. For all webs a

15 × 18 × 36. R/SP × 3 1/2, 1/4, 9 needle was used for producing needled fabrics. Twenty different fabrics were produced as per Table 14.1.

All tests were carried out in the standard atmosphere of 65 ± 2% RH and 20 ± 2°C. The fabrics were conditioned for twentyfour hours in the standard atmosphere before testing.

The tenacity, elongation, initial modulus, Poisson's ratio and tensile resilience were measured in machine direction using an Instron tensile tester. For testing tenacity, breaking elongation and initial modulus, the sample size and rate of straining were chosen according to ASTM standard D 1117-80 (Sample size 7.6 cm × 2.5 cm, cross-head traverse speed 300 mm/min). The initial modulus was calculated from the load elongation curve. For each sample, the mean of fifteen readings was considered. The CV % was less than 9% for all the fabric samples.

Poisson's ratio is measured by extending a fabric sample of 10 cm × 5 cm to 10% of its gauge length. The extension rate used was 1 cm/min. After extending, the width of the fabric sample was measured using a travelling microscope equipped with a vernier. The Poisson's ratio was expressed as a ratio of change in width and change in length. For each sample, the average of fifteen readings was taken. The CV % was less than 11 % in all the cases.

The air permeability measurements were made on the Metafem air permeability tester. For each sample the mean of fifteen readings was considered. The CV % was less than 10% in all the cases.

Fabric samples of the dimensions, 7.6 cm × 2.5 cm were used for measuring the tensile resilience. The fabric samples were extended till a load of 500 g/cm was reached, and immediately the cross-head movement was reversed at the same speed. The cross-head was moved at 0.76 cm/min. From the plot the tensile energy during extension, WT, and during retraction, WT^1, were calculated and the tensile resilience was calculated using the formula:

$$RT = WT^1/WT \times 100$$

For each sample ten tests were carried out. The coefficient of variation was in the range of 7 to 12%.

The compressional resilience of the fabric samples was measured on a Kawabata KES-FB3 compression tester. A maximum pressure of 50 g/sq. cm was applied. The plunger was moved at a speed of 1 mm for 50 sec. The work done for compression WC and the work done in the recovery process WC^1 were measured by the instrument itself. The compressional resilience (RC) was calculated from this using the formula:

$$RC = WC^1 /WC \times 100$$

For each fabric sample, ten readings were taken. The coefficient of variation was in the range of 7 to 10%.

3. RESULTS AND DISCUSSION

Table 14.2 shows the values of fabric properties considered. Table 14.3 gives

TABLE 14.2 Properties of Needle Punched Nonwoven Fabrics

Sl. No.	Tenacity (g/tex)	Breaking Elongation (%)	Initial Modulus (g/tex)	Poisson's Ratio	Air Permeability ($m^3/m^2/s$)	Tensile Resilience (%)	Compressional Resilience (%)
1	2.686	77.16	2.257	1.188	1.015	17.85	41.17
2	3.484	70.19	2.826	1.632	0.519	23.51	44.01
3	3.334	61.54	2.848	1.420	0.804	18.77	44.01
4	5.146	51.05	5.059	2.414	0.436	26.74	44.01
5	3.649	41.15	2.630	2.235	0.635	20.14	46.73
6	4.196	37.34	5.195	2.722	0.365	24.31	48.75
7	4.575	37.03	4.717	2.405	0.750	23.20	47.66
8	4.895	30.72	5.543	2.741	0.441	28.81	50.63
9	2.507	63.13	2.542	2.234	1.482	14.89	42.43
10	4.621	44.91	5.328	2.746	0.375	25.31	49.71
11	3.719	57.72	2.412	1.845	0.778	20.99	42.45
12	4.646	41.08	4.553	2.876	0.596	26.51	47.92
13	3.079	70.74	1.606	1.522	0.769	18.83	41.26
14	4.942	30.20	5.561	2.987	0.606	24.83	47.08
15	4.392	48.04	3.226	2.837	0.690	23.21	45.85
16	4.299	49.35	3.517	2.904	0.644	22.77	46.04
17	4.365	47.50	3.885	2.781	0.649	23.34	44.48
18	4.356	45.99	3.367	2.722	0.678	23.01	46.74
19	4.472	53.70	3.381	2.831	0.607	22.96	45.85
20	4.182	51.55	3.831	2.883	0.664	23.91	43.12

TABLE 14.3 Response Surface Equation for Various Fabric Characteristics

Response	Response Surface Equation	Correlation Coefficient
Tenacity (g/tex)	$4.312 + 0.52x_1 + 0.41x_2 + 0.43x_1x_2 + 0.1x_1x_3 - 0.22x_2x_3 - 0.25x_1^2 - 0.09x_3^2$	0.96
Breaking elongation (%)	$50.50 - 4.26x_1 - 5.38x_2 - 13.32x_3 + 3x_2x_3$	0.98
Initial modulus (g/tex)	$3.59 + 0.80x_1 + 0.65x_2 + 0.86x_3 + 0.18x_1^2 - 0.24x_2^2 - 0.09x_1x_2$	0.94
Poisson's ratio	$2.83 + 0.23x_1 + 0.22x_2 + 0.43x_3 - 0.08x_1x_3 - 0.11x_2x_3 - 0.22x_2^2 - 0.25x_3^2$	0.96
Air permeability ($m^3/m^2/sec$)	$0.660 - 0.242x_1 - 0.030x_2 - 0.060x_3 + 0.036x_1x_3 + 0.061x_2x_3 + 0.064x_1^2 - 0.021x_2^2 - 0.021x_3^2$	0. 92
Tensile resilience (%)	$22.96 + 2.99x_1 + 1.54x_2 + 1.44x_3 + 0.47x_1x_2 - 0.48x_1x_3 + 0.43x_2x_3 - 0.84x_1^2 + 0.45x_2^2$	0.93
Compressional resilience (%)	$45.56 + 1.71x_1 + 1.15x_2 + 2.15x_3$	0.90

x_1—Web weight in coded form
x_2—Needling density in coded form
x_3—Depth of needle penetration in coded form

the response surface equations derived from these data, and the coefficient of multiple correlation between the data and the predicted equation. From the response surface equations two and three dimensional graphs were constructed to study the effect of variables on the properties.

3.1 Tenacity

Figures 14.1 and 14.2 show the effect of WW and DNP on the tenacity of the fabrics at different needling densities. It has been reported in the literature that with the increase in DNP for a given WW and ND, the tenacity increases, reaches a maximum and then decreases [3–8, 14–16, 18]. In the present study at low WW no such trend is observed at any ND. At lower WW and ND (Fig. 14.1),

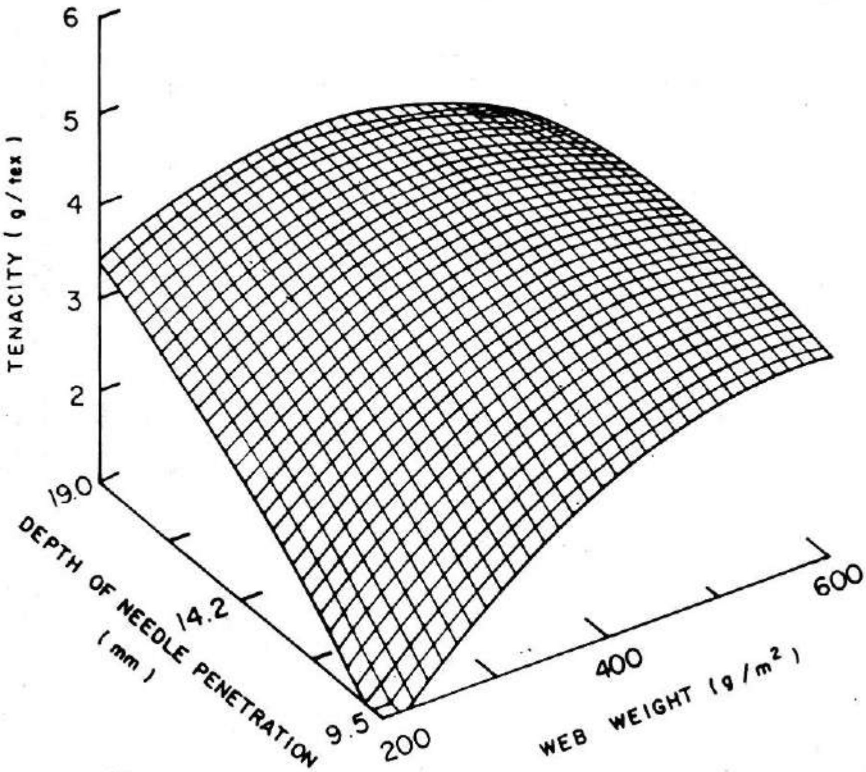

Fig. 14.1 Effect of web weight and depth of needle penetration on tenacity when the needling density is 31.0 punches/cm^2

when the DNP is increased, the number of fibres caught by the barbs and reoriented into the vertical structure will increase and the fibre breakage will also be not very high because the lighter web will not offer greater resistance to the passage of the needle. This can be substantiated by the findings of Hearle and his co-workers [9, 10] who have shown that for a lighter web even at relatively high penetration there is no drop in punching force, which suggests that fibre breakage is less in these conditions. The consolidation of the web will not be very high for each needle insertion as the acrylic fibres generally have good recovery properties. The poorly consolidated structure offers lower resistance to the passage of subsequent needles so the fibre breakage will also be less. Due to the above reasons, namely, the increased entanglement and lower fibre breakage, the tenacity increases with increased DNP at lower WW and ND. At higher ND (Fig. 14.2) and at lower WW, when the

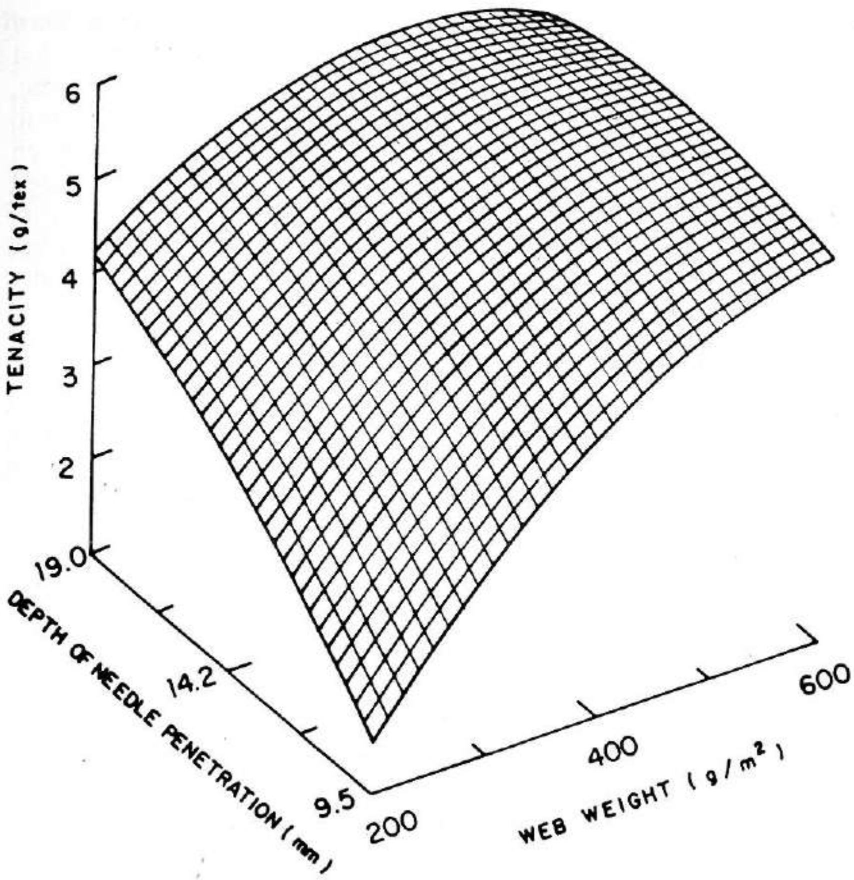

Fig. 14.2 Effect of web weight and depth of needle penetration on tenacity when the needling density is 85.3 punches/cm^2

DNP is increased, the fibre breakage will increase (compared to the earlier case). Even in this condition, the tenacity increases. This can be observed from Fig. 14.2. This suggests that the increased fibre entanglement achieved at higher ND and DNP is able to overcome the reduction caused by the increased fibre damage.

At higher WW and at any ND (Figs. 14.1 and 14.2) with the increase in DNP the tenacity first increases and reaches a maximum value and then decreases. The increase in tenacity can be attributed to better entanglement and consolidation of the structure, and the fall in tenacity to excessive fibre breakage and reduced contact between horizontal and vertical structure that take place at higher DNP. This agrees with the results reported by other workers [3, 5–7, 14, 16, 18, 20].

From Figs. 14.1 and 14.2 it is observed that for a given DNP, when the WW is increased, the tenacity first increases, reaches a maximum and then with further increase in WW the tenacity falls. Similar findings have been reported by other workers [3, 5, 16]. For a given DNP when the WW is increased, more barbs will enter the web and the first few barbs will travel a greater distance through the web. This results in greater number of fibres being reoriented into the vertical structure and at the same time fibre breakage will also increase. Due to the increase in number of fibres in a vertical peg, the tenacity tends to increase and due to fibre breakage the tenacity tends to decrease. Up to an optimum WW for a given DNP the contribution to tenacity by the increased number of fibres in a vertical peg is able to outweigh the reduction in tenacity caused by the increased fibre breakage. Beyond this optimum WW the fibre breakage is probably excessive and it is the dominating factor that decides the final fabric tenacity. This results in a drop in tenacity.

From Fig. 14.3 it can be observed that with the increase in ND for a given WW and DNP the tenacity increases. A similar trend is observed at other ND also. But, it has been reported in the literature [3, 5, 6, 11, 14, 16, 18, 20] that with the increase in ND the tenacity increases and then decreases. The fall in tenacity at high ND is attributed to excessive fibre breakage. In the present study no such reduction is observed at any given WW or DNP; this is probably due to the fact that the ND is not high enough to cause fibre breakage.

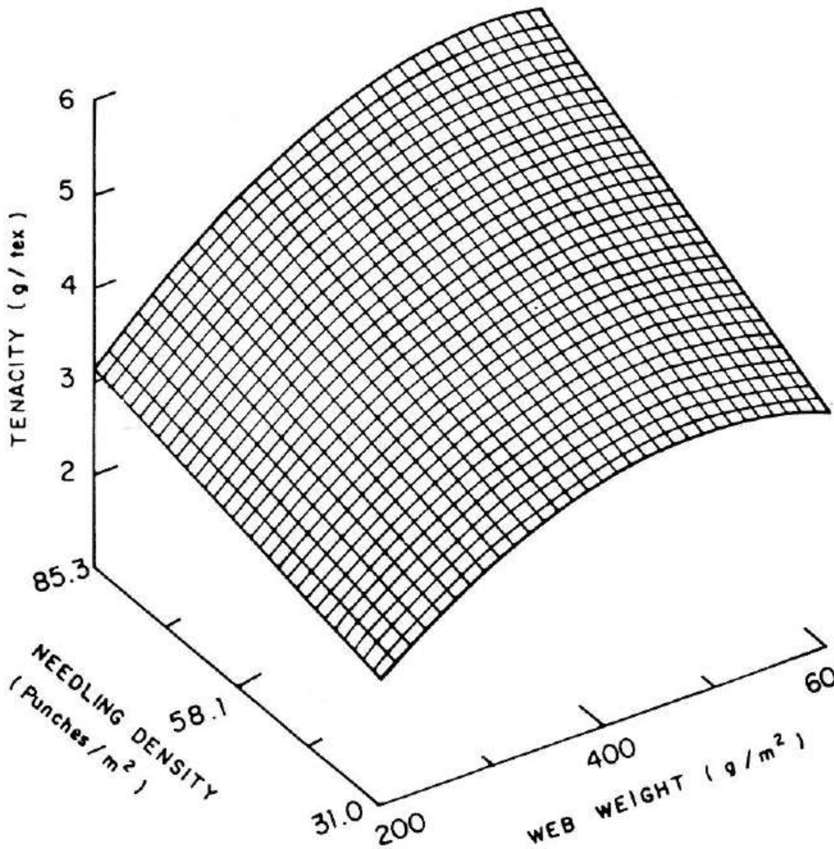

Fig. 14.3 Effect of web weight and needling density on tenacity when the depth of needle penetration is 14.2 mm

3.2 Breaking Elongation

Figure 14.4 shows the effect of ND and DNP on the breaking elongation of the fabrics at 400 g/sq. cm ww. It can be seen that with the increase in DNP or ND, the breaking elongation decreases. With the increase in DNP and ND, the consolidation of the structure improves, and this restricts fibre movement and results in lower breaking elongation. These are consistent with the results reported in the literature [3-5, 11, 14, 16, 18]. The change in ww also produced similar results.

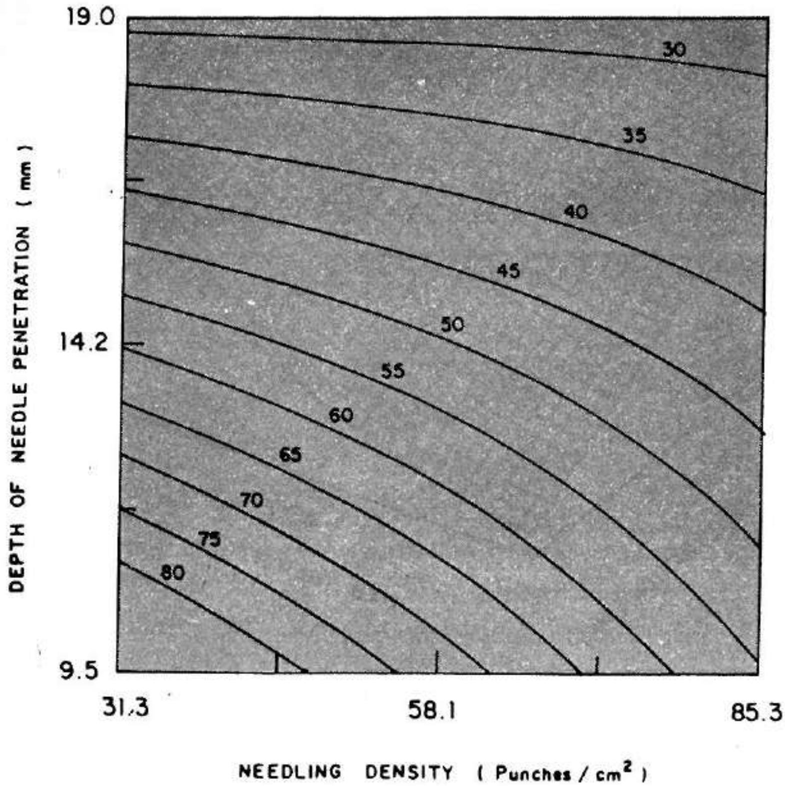

Fig. 14.4 Effect of needling density and depth of needle penetration on breaking elongation when the web weight is 400 g/m^2

3.3 Modulus

Figure 14.5 shows the effect of DNP and ww on the initial modulus of the fabric at 58.1 punches/sq. cm ND. It can be seen from Fig. 14.5 that with the increase in DNP and ww the initial modulus of the fabric increases. With the increase in DNP or ww for a given ND, the number of fibres which are reoriented into the vertical structure increases. These larger vertical tufts resist fibre movement during initial fabric extension and this results in a higher load, and consequently higher initial modulus. This agrees with the results reported by other workers [4, 5,14]. At other needling densities also a similar trend is

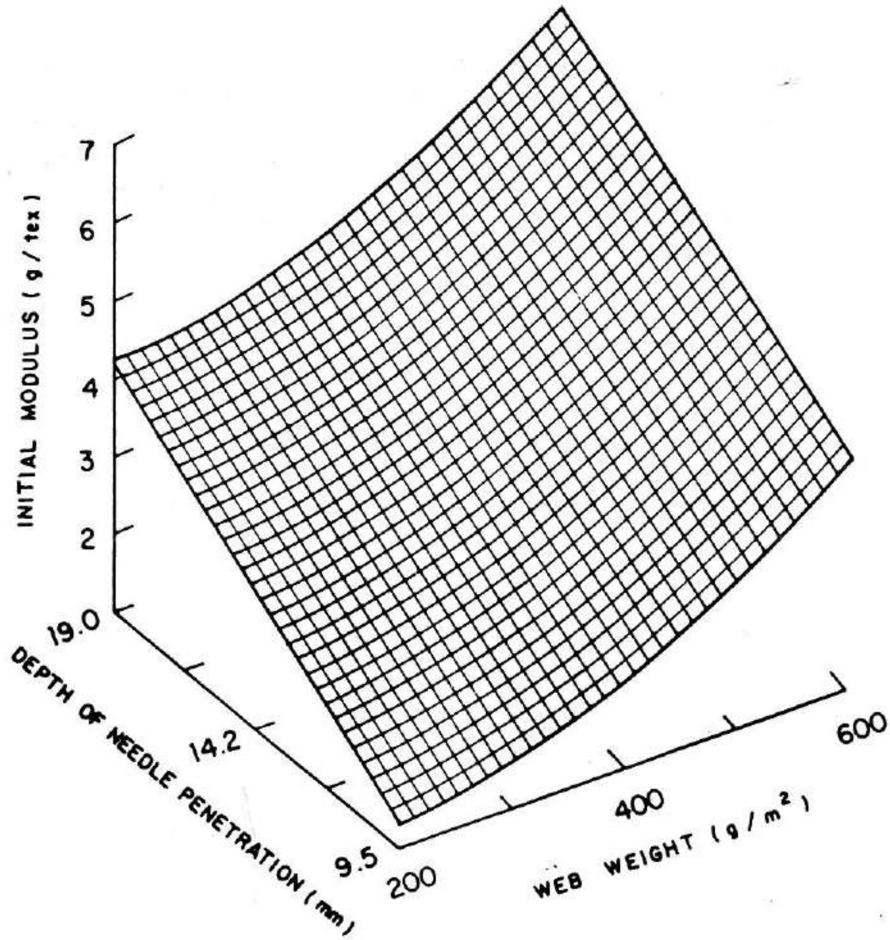

Fig. 14.5 Effect of web weight and depth of needle penetration on initial modulus when the needling density is 58.1 punches/cm^2

observed. With the increase in ND for a given DNP and WW also, the initial modulus is found to increase. With the increase in ND the number of pegs per unit area increases. This increases the number of vertical pegs and restricts the fibre movement during extension resulting in higher load being developed in the fabric. It has been reported in the literature that with the increase in DNP or ND the initial modulus increases and then decreases [5, 14]. The fall in initial modulus at higher ND or DNP is attributed to fibre breakage. In the present study no such reduction in initial modulus was observed.

3.4 Poisson's Ratio

Figure 14.6 shows the effect of DNP and WW on the fabric Poisson's ratio for 85.3 punches/sq. cm ND. It can be concluded that with the increase in WW or DNP the Poisson's ratio first increases, reaches a maximum value and then decreases. This trend can be explained in the following way, with the increase in WW or

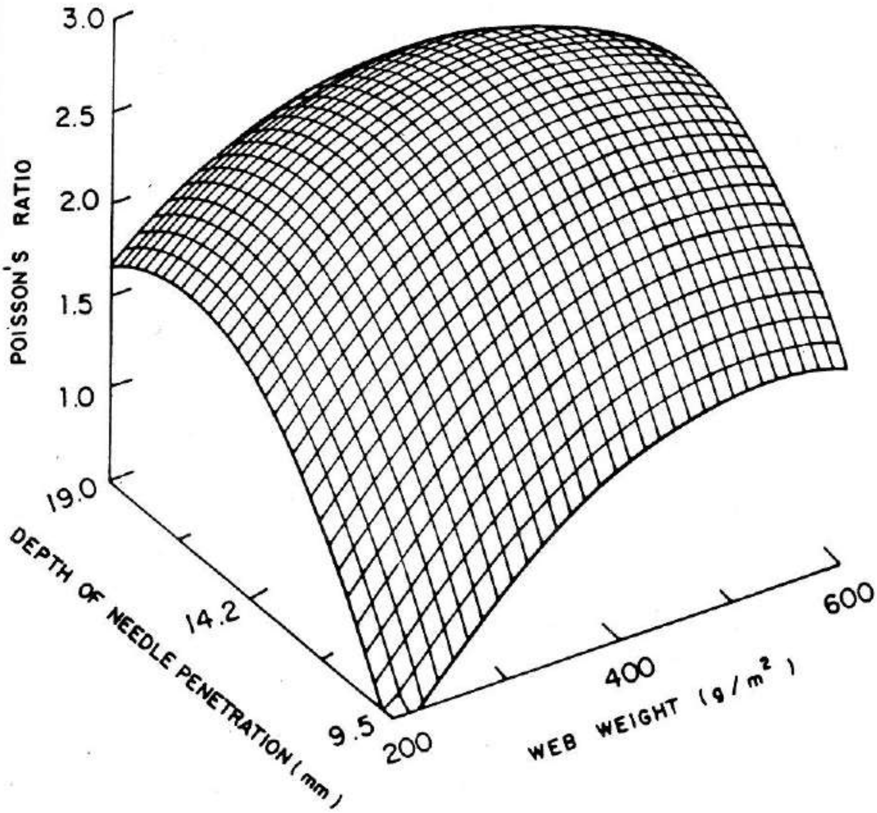

Fig. 14.6 Effect of web weight and depth of needle penetration on Poisson's ratio when the needling density is 85.3 punches/cm^2

DNP, a coherent structure will be produced, and due to this for a given extension the load developed in the fabric in the direction of extension will increase considerably. Due to this the forces acting in the transverse direction will increase resulting in greater width-wise contraction. At higher DNP or WW the forces developed will be very high, but due to the higher density of the fabric, the fabric width-wise contraction will be less. A similar trend is observed at other ND also. The increase in ND also produced similar results.

3.5 Air Permeability

Figures 14.7 and 14.8 show the effect of WW and DNP on the air permeability of the fabrics at two levels of ND (31 punches/sq. cm and 85.3 punches/sq. cm, respectively). It can be observed from the Figs. 14.7 and 14.8 that at any level of DNP and ND when the WW is increased the air permeability decreases. At 31 punches/sq. cm needling density (Fig. 14.7) for any level of WW, the increase in DNP causes a decrease in air permeability. These trends can be attributed to the fact that at these conditions the consolidation of the web is greater and the density of the web also increases.

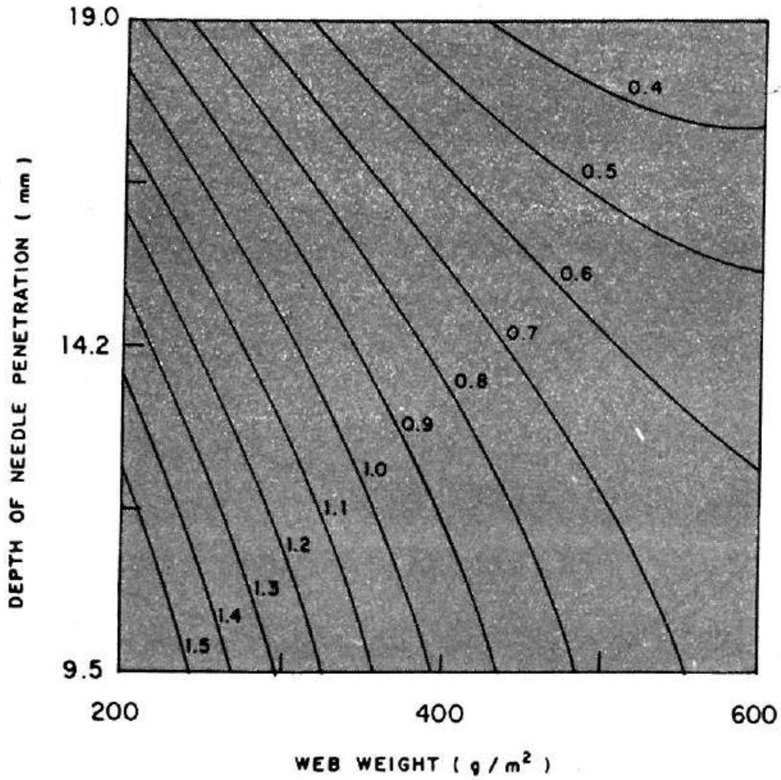

Fig. 14.7 Effect of web weight and depth of needle penetration on air permeability when the needling density is 31.0 punches/cm^2

At 85.3 punches/sq. cm ND at lower levels of WW with the increase in DNP the air permeability value first slightly increases and then decreases slightly. At higher levels of WW with the increase in DNP the air permeability value increases. This trend has been reported earlier by different workers also [12, 13, 19]. The channels created in the fabric due to the passage of needle is attributed as one of the reasons for this behaviour. If channels created in the fabric is one of the main reasons for the rise in air permeability value, a similar trend with much pronounced effect should occur at lower WW also. But at lower WW the air permeability value does not change much. This suggests more than the channels created in the fabric the fibre breakage and fabric spreading which is inevitable at high levels of DNP, ND and WW seems to affect significantly the air permeability of the fabric.

3.6 Resilience

The effect of DNP and WW on the tensile resilience of the fabric samples at 31 punches/sq. cm are given in Fig. 14.9, from which it can be observed that with the increase in DNP or WW, the tensile resilience increases. With the increase in DNP or WW, the interlocking of fibres in the fabric increases. Due to this when the tensile load is removed the fabric is able to recover well. At higher levels of ND also a similar trend was observed.

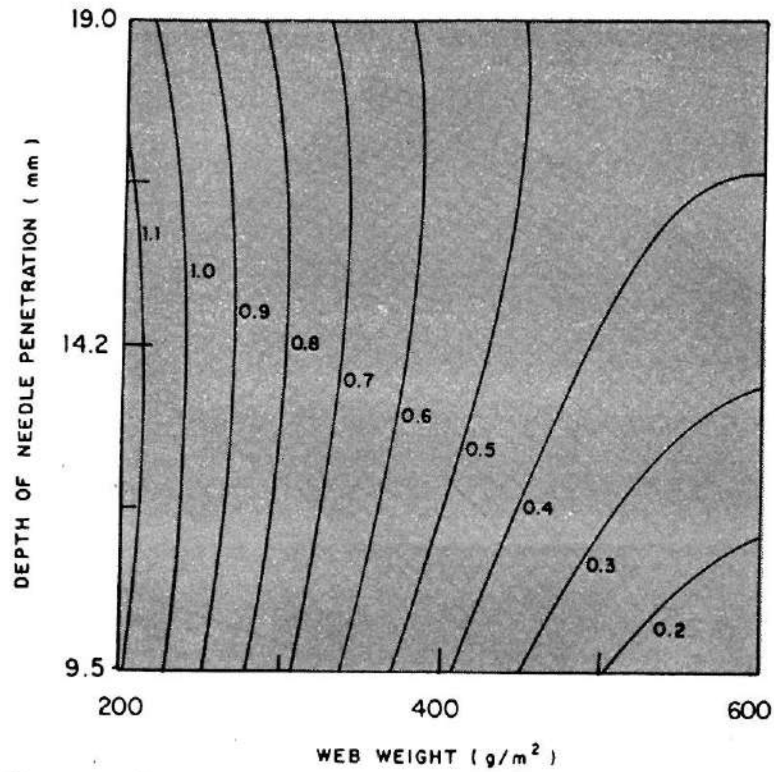

Fig. 14.8 Effect of web weight and depth of needle penetration on air permeability when the needling density is 85.3 punches/cm^2

Figure 14.10 shows the effect of WW and DNP on the compressional resilience of the fabric at 85.3 punches/sq. cm ND. It can be seen that with the increase in WW and DNP, the compressive resilience increases. With the increase in WW and DNP the fabric becomes more consolidated, and due to this the compressional resilience of the fabric improves. At other needling densities also similar trends are observed. It is also observed that with the increase in ND, the compressional resilience increases.

4. CONCLUSIONS

The predicted equations for various responses agree well with the experimental data, as can be seen by the high coefficient of multiple correlations.

At lower WW, an increase in DNP or ND causes an increase in tenacity, but with heavier webs, at any ND, an increase in DNP first increase the tenacity and then decreases it. For a given DNP, an increase in WW first increases and then decreases the tenacity. The WW at which the maximum tenacity occurs reduces, as the DNP increases.

With the increase in WW, ND or DNP, the fabric breaking elongation decreases while the initial modulus increases.

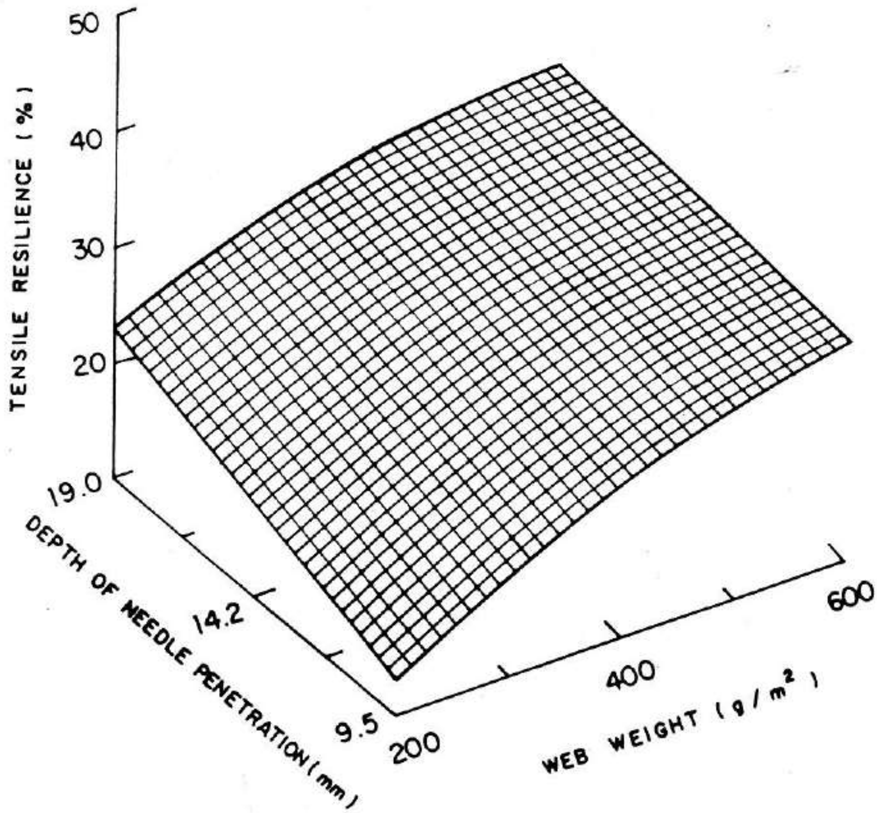

Fig. 14.9 Effect of web weight and depth of needle penetration on tensile resilience when the needling density is 85.3 punches/cm^2

With the increase in ww, ND and DNP, the Poisson's ratio first increases and then decreases.

At higher levels of ND, at lower ww, an increase in needle penetration depth does not cause much change in air permeability value, but at higher ww, an increase in DNP causes an increase in air permeability value. At lower levels of ND, at any level of ww, an increase in needle penetration depth, lowers the air permeability of the fabric. The increase in ww at all levels of DNP and ND results in a decrease in air permeability.

The compressive and tensile resilience increase with the increase in ND, DNP and ww.

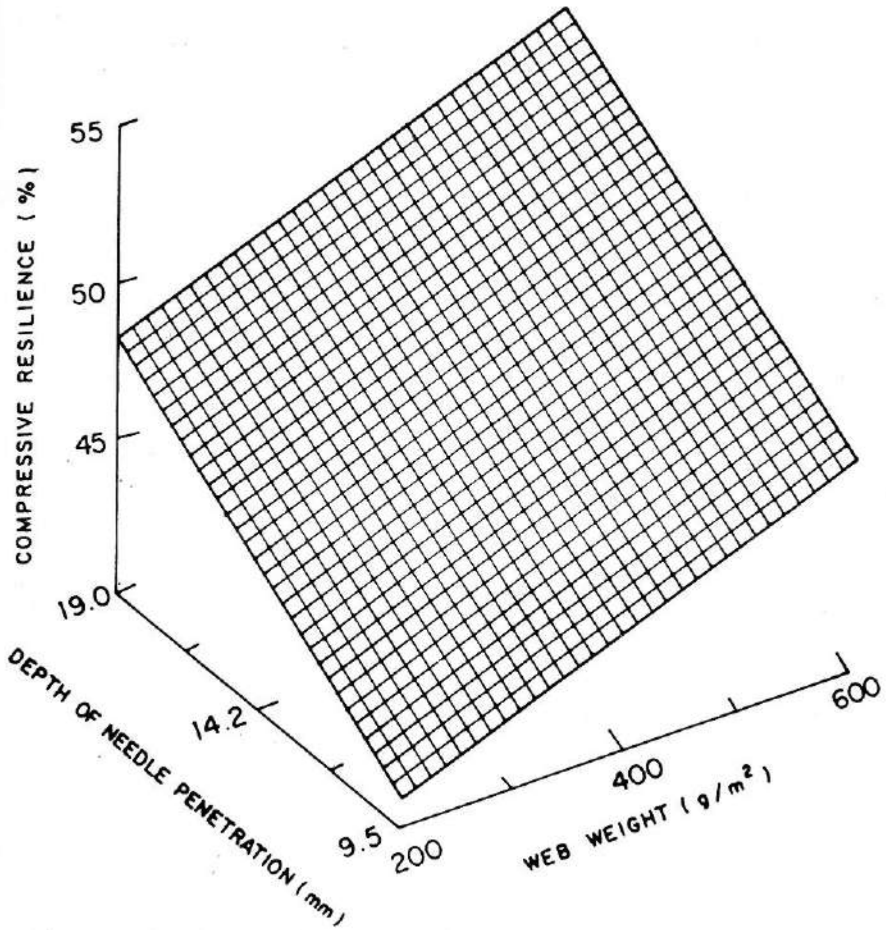

Fig. 14.10 Effect of web weight and depth of needle penetration on compressive resilience when the needling density is 85.3 punches/cm^2

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15

Comparative Performance of Woven and Warp Knitted Fabrics

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Fabrics produced by different methods of manufacture are marketed and often successfully compete with similar products and outlets. This is often aimed at either improving the performance of the product or gaining a price advantage. Good examples of this are the increasing use of warp knitted weft insertion fabric for raised bed-linen, and the increasing commercial interest in warp knitted double-sided terry for gowns, bath robes, beach-wear, curtains and towels.

The main objective of this paper is to compare commercially available woven and warp knitted fabrics with regard to their structure, performance and economics when tested using standard test methods and fabric costing procedures.

A number of fabrics used for similar products are fully analysed to determine the structural/constructional parameters and tested for a number of appropriate properties to relate them to the fabric structure. The raw material and production costs are also computed and compared.

1. INTRODUCTION

In today's consumer-orientated environment, manufacturers are in constant pursuit of higher quality products at more competitive prices in order to develop and maintain a commercial 'edge'. In certain product areas, this has led to manufacturers considering the possibilities of using fabrics produced by alternative methods in an attempt to enhance performance or to gain a price advantage. A good example of this is the increasing use of warp knitted weft insertion fabric for flannelette bed-linen. This fabric has made substantial inroads into a market which was thought of as very much the domain of the weaver. This is particularly true in West Germany.

Warp knitting has been around for over 200 years but it is only recently that the principle has been used to produce towelling with any degree of success. As in many areas warp knitted fabrics are being widely used to compete with conventional woven fabrics due to the numerous advantages they can offer. Towelling is one of these product areas and warp knitted towelling has many advantages such as increased slip resistance of the pile yarns, high loop strength, the ability to produce lighter or more open structures, and good fray-proof properties which facilitate easier making-up. A wide range of products are produced from these fabrics for example bath robes, beach gowns, towels and curtains for wet rooms.

The main objective of this study was to compare commercially available woven and warp knitted flannelette and woven and warp knitted terry towelling fabrics with regard to their structrure, constructional parameters, performance and production costs. A number of properties were investigated using standard test methods, which included tensile properties, tear resistance, abrasion resistance, fabric handle and drape, crease recovery, dimensional stability to washing, seam slippage, pile retention and flammability characteristics. The raw material and conversion costs were also compared.

When considering the use of alternative fabric types in industry, certain technical and commercial questions are often posed. It is hoped that this investigation will help to answer many of these questions.

2. EXPERIMENTAL

2.1 Fabric Details

The woven flannelette fabric was a plain weave, 100 per cent cotton fabric with an area density of 130 g/m^2 in the finished and raised state. The fabric had been produced on a projectile weaving machine. The warp knitted raised fabric was a weft insertion type produced with a polyester warp and a cotton weft having an area density of 127 g/m^2 in the finished and raised state. The fibre content in the fabric was 78% cotton 22% polyester, which had been produced on a Karl Mayer tricot machine type HKS2 MSU with a gauge of E24.

The woven terry fabric was a 100% cotton 3-pick terry having an area density of 460 g/m^2 and a pile ratio of 6.8 : 1 in the finished state. The warp knitted terry was a double-sided 90% cotton, 10% polyamide fabric somewhat lighter at a finished area density of 360 g/m^2. Both fabrics are readily available in the UK and Europe and used to produce bath robes/gowns.

2.2 Test Methods

The following tests were carried out on flannelette and towelling fabrics:

TENSILE TESTING

The tensile tests were carried out on an Instron model 1026, which is a constant rate of extension tensile testing instrument. The test method used was ASTM D-1682-67 (1" grab test). A 500N load cell was used. Five warp-wise and five weft-wise samples were taken from each fabric and the individual load-elongation curves were produced. From these the mean breaking load in Newtons and percentage extension-at-break were calculated.

TEAR RESISTANCE

The tear resistance tests were also carried out on the Instron model 1026. The test method used was BS 4304: 1968 wing rip tear test. Five warp and five weft specimens were taken from each fabric, and using the median method the tear resistance results were determined. Warp tear strength in this paper refers to the resistance to tearing through warp yarns, whilst the weft tear strength means the tearing force required to tear through weft threads.

ABRASION RESISTANCE

The abrasion resistance of the fabrics was investigated using the Martindale wear and abrasion tester. The test method employed was BS 5690: 1970 in which four specimens are abraded simultaneously on the Martindale tester. A 12 kPa load was used on each of the specimens which were subjected to 12000 rubs in case of the two flannelette fabrics or 15000 rubs in case of the two towelling fabrics, after which the damage was assessed. In addition to this visual assessment, an alternative method was also employed. This involved the determination of the mass of fibre lost at various stages of the 15000 rubs, i.e. at 3000, 6000, 9000, 12000, 15000 rubs. The relationship between the fabric area density and number of rubs was then plotted graphically for comparison.

DIMENSIONAL STABILITY TO WASHING

The dimensional stability was evaluated in accordance with BS 4923: 1973 using process B, which stipulates washing at 60°C for 30 minutes with 3 rinse cycles in the Wascator. After washing the samples were dried flat. Three warp-wise and three weft-wise specimens were tested and the percentage change in dimensions was calculated.

LIMITING OXYGEN INDEX

The Limiting Oxygen Index (LOI) tests were carried out in accordance with ASTM D 2863-77. The Oxygen Index is expressed as: The minimum percentage concentration of oxygen in a mixture of oxygen and nitrogen that will just support flaming combustion of a material initially at room temperature under the conditions of the test method. The rate of air flow through the test column was maintained at 18 mm/minute. This test method gives a measure of the flammability of a yarn, fibre or fabric.

The following tests were carried out on flannelette fabrics only:

FLEXURAL RIGIDITY (FABRIC STIFFNESS)

The flexural rigidity was determined on a Shirley Stiffness Tester in accordance with BS 3356: 1961. This tester measures the bending length, that is, the length in cm that will bend under its own weight through a fixed angle of 41.5°. The flexural rigidity can be calculated by using the following expression:

$$G = 0.1 \times m \times c^3$$

where G = flexural rigidity (mg cm)
m = area density (g/m^2)
c = bending length (cm).

CREASE RECOVERY

The crease recovery was determined using the Shirley Combined Stiffness and Crease Recovery Tester. The test method employed was BS 3086: 1972. Ten warp wise and ten weftwise specimens were tested from each fabric and the mean results were calculated.

The following tests were carried out on towelling fabrics only:

FABRIC DRAPE

The drape coefficient for each fabric was determined on the Cusick Drape Tester. The test method used was BS 5058: 1973. In this method the fabrics deform multidirectionally, therefore the shearing stiffness in addition to the bending stiffness has an effect on the drapeability of a fabric. The fabric drape coefficient is expressed as a percentage between zero and 100. The higher the figure the stiffer the fabric.

SEAM SLIPPAGE

The seam slippage of the fabrics was assessed using the Instron model 1026. The test method used was BS 3320: 1970. Five warp-wise and five weft-wise specimens were seamed using a lockstitch type machine capable of producing stitch type 301 (BS 3870). Each specimen was subjected to a 12 kg load and the width of the seam opening was measured. The load was then reduced to 0.25 kg and the seam opening remeasured. The two seam opening measurements were recorded for each specimen and the mean values calculated for each fabric type.

PILE RETENTION

The pile retention, or the force required to extract a pile yarn from a 10 cm strip of fabric, was determined on the Instron model 1026. Unlike the other tests carried out in this investigation, no standard test method exists, therefore, a method was devised specifically for this work. A rectangular specimen was wrapped around a cylindrical tube so that the trailing edges of fabric could be trapped in the lower jaws of the machine with the cylinder, wrapped in fabric sitting on top of the lower jaws. A knitting machine needle was then placed in the top jaws so that one pile loop could be hooked onto the needle and slowly removed from the fabric. The test was repeated a total of twelve times in each fabric and the median method was used to calculate the mean pile retention values.

2.3 Fabric Specification

FLANNELETTE FABRICS

Woven Fabric

Fibre content	100% cotton
Ends per cm	19.3
Picks per cm	13.0
Warp linear density	27.68 tex (21.3 cc)

Weft linear density	57.18 tex (10.3 cc)
Warp crimp	3.03%
Weft crimp	8.7%
Actual area density	130 g/m^2
Calculated area density	135.92 g/m^2
Difference	4.55%
Warp cover factor	10.15
Weft cover	9.82
Fabric cover factor	19.97

Warp Knitted Fabric

Fibre content	78% cotton, 22% polyester
Courses per cm	16.9
Wales per cm	9.8
Warp linear density	76 dtex polyesters dull
Weft linear density	R59 tex/2 (2/20s) cotton
Run-in per rack	119 cm
Actual area density	127 g/m^2
Calculated area density	131.17 g/m^2
Difference	3.18%

TOWELLING FABRICS

Woven Towelling

Fibre content	100% cotton
Construction	Three-pick terry
Ends per cm	27.6 (ground and pile)
Picks per cm	16.5
Warp linear density	R49 tex/2 (2/24s cc), ring spun yarn
Weft linear density	49 tex (12s cc), rotor spun yarn
Pile linear density	33 tex (18s cc), pima cotton ring spun yarn
Actual area density	459.4 g/m^2
Terry ratio	6.8 : 1

Warp Knitted Towelling

Fibre content	90% cotton, 10% polyamide
Construction	Double-sided terry
Courses per cm	12.5
Wales per cm	10.2 (ground and pile)
Ground yarn linear density (both pillar and laid-in threads)	78 dtex, 20 filament polyamide type 66
Pile yarn linear density	35.7 tex (16.5s cc) rotor spun cotton
Actual area density	356.5 g/m^2
Pile height	
technical face	5 mm
technical back	6 mm

Yarn, threading and structure:

Guide Bar	Yarn	Threading	Pattern Chains
1 (back)	35.7 tex cotton	1 in, 1 out	3-2-4, 6-6-0
2	78 dtex polyamide	1 in, 1 out	5-5-5, 0-0-0
3	78 dtex polyamide	1 in, 1 out	0-1-1, 1-0-0
4 (front)	35.7 tex cotton	1 in, 1 out	1-0-0, 3-4-4

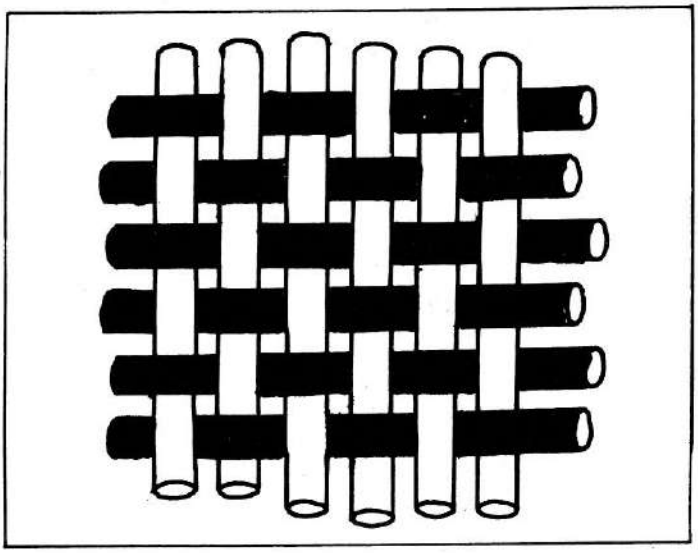


Fig. 15.1 Woven flannelette

The structure of the two flannelette fabrics are shown in Figs. 15.1 and 15.2, and the two towelling fabrics evaluated and compared in this work are illustrated in Figs. 15.3 and 15.4.

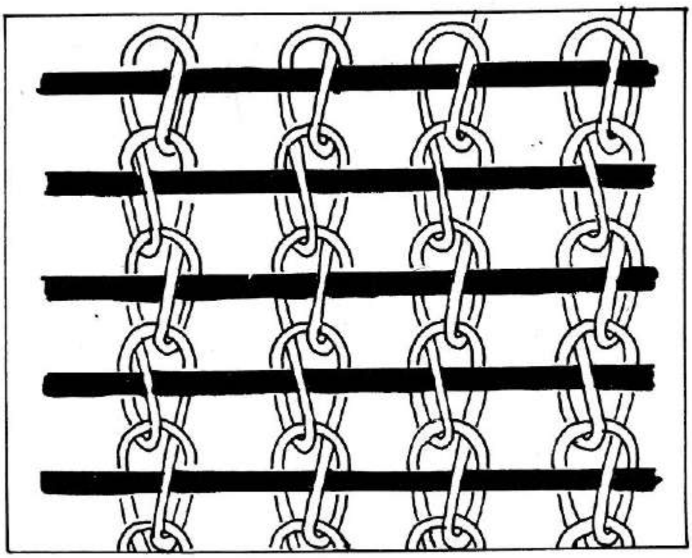


Fig. 15.2 Warp knitted flannelette

3. DISCUSSION OF RESULTS

The mean results of the various physical properties determined for woven and warp knitted flannelette and towelling fabrics are presented in Tables 15.1 and 15.2, respectively.

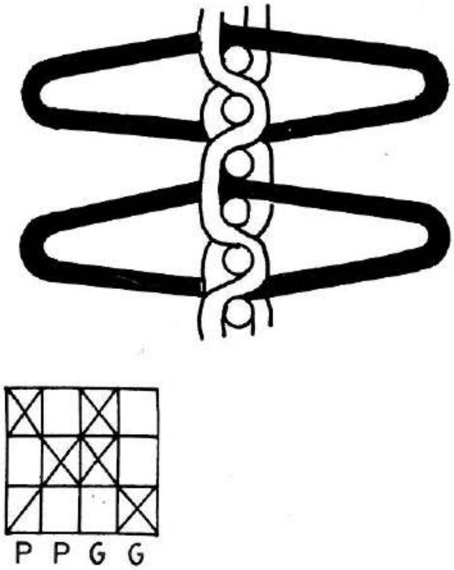


Fig. 15.3 Woven terry

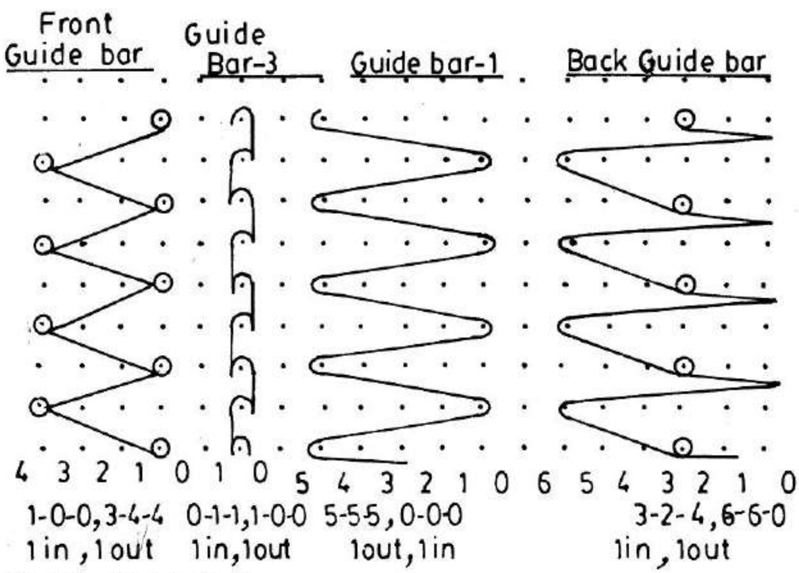


Fig. 15.4 Warp knitted terry

3.1 Tensile Properties

It can be seen from Table 15.1 that the warp breaking load is quite similar for both fabrics, the woven fabric being marginally higher. Both fabrics showed a higher breaking load in the weft direction than in the warp; this is obviously due to the heavier weft component in both cases. The weft breaking load in the knitted fabric was significantly higher than the woven fabric, although the resultant weft yarn linear densities were very similar. The breaking

TABLE 15.1 Summary of Properties of Flannelette Fabrics

	Woven Fabric		Warp Knitted Fabric	
	Warp-wise	Weft-wise	Warp-wise	Weft-Wise
Breaking load (N)	276.0	304.8	265.7	476.0
Extension-at-break (%)	6.88	16.85	21.0	6.45
Tear resistance (N)	10.25	15.31	8.8	22.12
Flexural rigidity (mg. cm)	108.1	80.2	62.4	87.2
Dimensional stability to washing (%)	10.5	4.7	3.1	3.9
Crease recovery (deg)	86	97	138	99
LOI (%)	17.6	17.6	17.8	18.2

extension results in both fabrics were also interesting. In the warp direction, the knitted fabric exhibited a much higher extension: this was due to the geometry of the open pillar stitch and the fact that a filament yarn was used as against a staple-fibre yarn in the woven fabric. In the weft direction, the opposite was true, the warp knitted fabric having a much lower extension-at-break. This was mainly due to the following reasons:

(i) the weft yarn is 'locked' into the structure being trapped between the underlaps and overlaps; and
(ii) the weft component is incorporated into the structure absolutely straight and crimp-free.

The results in Table 15.2 show that the woven towelling had a much higher breaking load in the warp direction than the warp knitted towelling. This is not really surprising since it is from the ground yarns that a woven pile fabric derives its tensile strength, and in the warp direction the ground yarn is much heavier in the woven fabric than in the warp knitted. In addition to this, the number of threads per cm is higher in the woven fabric.

TABLE 15.2 Summary of Properties of Towelling Fabrics

	Woven Fabric		Warp Knitted Fabric	
	Warp-wise	Weft-wise	Warp-wise	Weft-wise
Breaking load (N)	218.0	236.7	136.1	247.7
Extension-at-break (%)	8.2	25.3	72.3	84.0
Tear resistance (N)	47.4	27.7	16.5	37.3
Dimensional stability to washing (%)	6.0	+1.3*	1.2	+ 2.2*
Fabric drape (%)	53.23		41.97	
Seam slippage (mm) 12 kg	6	16.4	10.2	6.8
0.25 kg	5.4	15.4	8.2	4.6
Pile retention (N)	2.22		4.59†	
LOI (%)	19.0	19.0	17.1	17.1

*(+) Denotes an extension
†Denotes a pile loop breakage

In the weft direction however, the warp knitted fabric has the higher tensile strength, although the difference is not as great as in the warp direction. The reason for this is that in the weft direction, the lapped-in cotton pile yarn also contributes to the tensile strength along with the continuous-filament yarn which is laid-in via guide bar No 2. Therefore both ground and pile yarns play a part in the weft tensile strength.

The results also reveal that the knitted towelling has a significantly higher extension-at-break, over 72% in the warp direction and 84% in the weft. The woven towelling has much lower values, just over 8% in the warp and 25.3% in the weft. A very high breaking extension is not uncommon in warp knitted fabrics. A combination of knitted loops within the structure and the use of continuous-filament yarns are the reasons for these high extensibility values. Cotton yarns in woven towelling are intrinsically much less extensible than continuous-filament yarns.

3.2 Tear Resistance

The results were calculated using the 'median' method for tear resistance. This may be defined as the median of the individual values of tear resistance in tearing through a prescribed length of fabric.

Similar to the tensile test results, the weft tear resistance in both fabric types was markedly higher than the warp tear resistance, again due to a heavier weft yarn used in each case. The woven fabric showed a slightly higher tear resistance in the warp direction than the knitted fabric, however, in the weft direction the warp knitted fabric had a significantly higher value. It appears that the use of two threads of 30 tex (1/20s cc each yarn was more advantageous in terms of tear resistance than a single pick of 59 tex as in the woven fabric, although the resultant yarn linear densities in both cases are the same.

From the results in Table 15.2 it can be seen that the warp tear resistance in the woven towelling was significantly higher than the warp knitted towelling. However, the weft tear resistance was higher for the warp knitted towelling. In fact the results are very similar in magnitude to the tensile strength test results. This is once again related to the differences in fabric structure. The warp tear resistance, i.e. the resistance to tearing through the warp yarns, is higher in the woven towelling due to the fact that the ends per cm were much higher and also the linear densities of both pile and ground warp yarns were much higher than the 78 dtex open pillar stitch yarn used in the warp direction of the knitted towelling. The weft tear resistance in the knitted towelling i.e. the resistance to tearing through the weft yarns, has the advantage because both ground and pile yarns contribute to the tear resistance, whereas the woven towelling only has the 49 tex rotor spun yarn contributing to the tear resistance.

3.3 Abrasion Resistance

Generally speaking, plain woven polyester/cotton unraised bed-linen fabrics have to achieve a level of 15000 rubs to the first thread breakage in order to meet the requirements of most high street store groups. As part of the finishing process, a flannelette fabric is raised. This process enhances the aesthetic appeal of the product in terms of its handle and comfort, as well as improves its thermal properties, but as a result causes considerable fibre loss from the yarns—predominantly the weft. This fibre loss can also mean that minimum target of 15000 rubs would be difficult to attain in most cases, therefore it is generally accepted that a lower level of abrasion resistance is acceptable for most raised fabrics, for example, 10000 or 12000 rubs.

At 12000 rubs the woven flannelette had a number of broken threads and appeared to be beginning to disintegrate. Both warp and weft components appeared to have suffered some fibre loss. The warp knitted fabric has obviously lost its raised finish or nap and some laddering had occured. However, there were no signs of disintegration and the specimens appeared to have performed somewhat better. The higher resistance was mainly due to the polyester pillar stitch construction in the warp of the fabric. Once the fabric's nap had been abraded away, the polyester pillar stitches were exposed on the fabric surface, offering further abrasion or wear protection for the softer spun weft yarns.

Figure 15.5 illustrates the behaviour of both fabric types during abrasion testing from the start to 12000 rubs in each case. It can be observed that in the warp knitted fabric the weight loss occured at a constant rate, thus producing an almost linear relationship between the two variables. The woven fabric

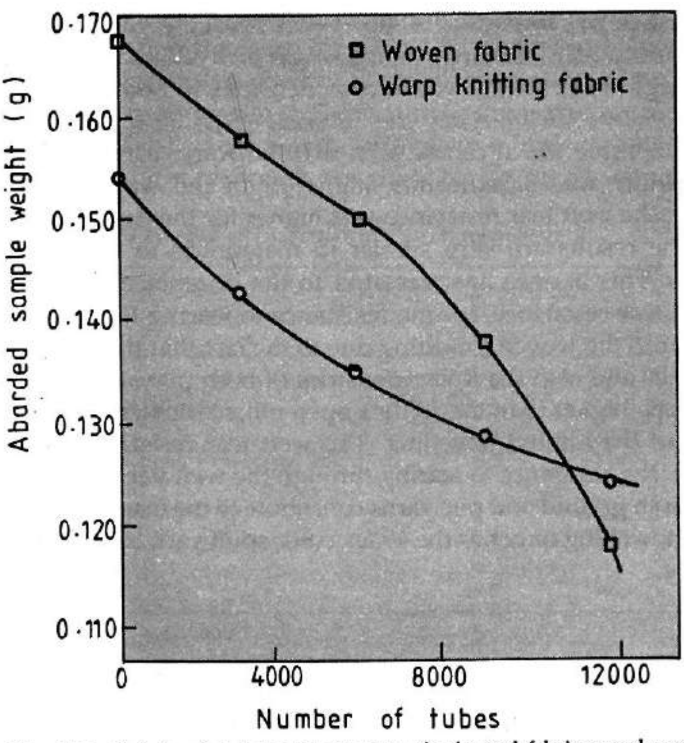


Fig. 15.5 Relacionship between number of rubs and fabric sample weight

behaved in a similar fashion up to 9000 rubs after which it suffered weight loss at a higher rate. It has been mentioned earlier that the continuous-filament pillar stitches protect the softer-spun cotton weft to a certain degree. This is not the case in the woven fabric, in which both warp and weft components suffer similar damage during wear.

The specimens were subjected to 15000 rubs using a 12 kPa load on the Martindale wear and abrasion tester. They were visually assessed at 3000 rub intervals. Although both fabrics suffered flattening and some damage to the pile there was no significant difference in appearance of the two. The ground structures, although exposed in places, remained intact even at 15000 rubs. In addition to this visual assessment, the rate of fibre loss of the abraded specimens was investigated. Figure 15.6 illustrates the relationship between the rate of fibre loss and the number of rubs for each fabric.

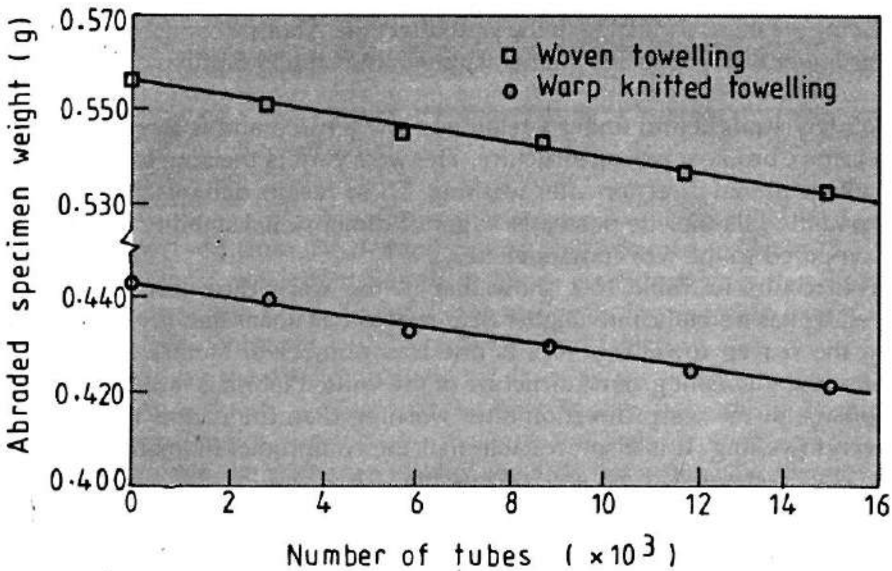


Fig. 15.6 Relationship between number of rubs and abraded sample weight

The weight loss was calculated at 3000 rub intervals up to 15000 rubs. It can be seen from Fig. 15.6 that although initially the woven fabric specimen is heavier, the slopes of the two lines are almost identical, i.e. the fabrics suffer roughly the same rate of fibre loss from the pile yarns. These results would therefore suggest that the wear performance during use of these two fabrics would be very similar.

3.4 Dimensional Stability to Washing

The results in Table 15.1 show that the warp knitted fabric was far more dimensionally stable to washing than the woven fabric, especially in the warp direction.

The comparatively low warp shrinkage in the warp knitted fabric is mainly due to the fact that the polyester yarns are heat-set during wet processing, thus reducing the level of further shrinkage. The warp yarns in the woven fabric on the other hand are subjected to high tensions throughout the warping, sizing, weaving and finishing processes. These tensions are then relieved during the washing process, therefore causing a higher shrinkage. This has the obvious disadvantage in that allowances have to be made for shrinkage which decreases the fabric utilisation. It is also interesting to observe from the results given in Table 15.1 that the weft washing shrinkage in the warp knitted flannelette fabric is also lower than the corresponding value for the woven flannelette, despite the weft yarns used in both fabrics being 100 per cent cotton and of similar linear densities; 57.2 tex in the woven fabric an R59 tex/2 in the warp knitted.

This can be explained by the fact that the weft yarn in the warp knitted fabric is firmly bound in-between the needle loops and the underlaps, thus reducing washing shrinkage in the weft direction. Another contributing factor to the lower weft shrinkage after washing in the knitted fabric is the fact that, as mentioned previously, the weft component is incorporated into the structure absolutely straight and under a relatively low tension and is therfore free of any crimp, unlike a woven structure. The weft yarn is therfore less prone to shrinkage in that direction after washing. These results demonstrate that the warp knitted flannelette possesses superior dimensional stability to washing as compared to the woven flannelette.

The results in Table 15.2 show that in the warp direction the knitted towelling has a significantly higher degree of dimensional stability to washing than the woven towelling. This is due to a number of factors. Firstly, the continuous-filament ground structure of the knitted fabric is far less prone to shrinkage in the warp direction after washing than the cotton warp in the woven towelling. It is also probable that the continuous-filament yarns are partially heat-set during wet processing. This would obviously have a favourable effect on final washing shrinkage. Another factor which is likely to affect the dimensional stability would be the high stresses encountered by the warp yarns of the woven fabric, especially during warp preparation and weaving, but also during subsequent processing as a fabric. These stresses are often partially relieved during wet processing but subsequent laundering almost inevitably causes further shrinkage.

In the weft direction the results for the two fabrics were very similar, in fact a small extension occured in each case. An extension in the weft direction is often the case when a shrinkage has taken place in the warp direction. This slight extension would be irrelevant to the finished garment.

3.5 Limiting Oxygen Index

The flammability characteristics of the two fabrics were investigated by determining the Limiting Oxygen Index (LOI) values in order to highlight any differences in terms of the ease with which the two fabrics would burn. The tests were carried out in accordance with ASTM 2863-1977. This standard was used since it is generally accepted as the most relevant test method for testing the Limiting Oxygen Index of textile fibres and fabrics. The results in Table 15.1 are the mean values of a series of tests and show very little difference between the two fabrics. The combustion characteristics of the two fabrics therefore are quite similar.

It can be seen in Table 15.2 that the warp knitted towelling burned more readily, that is it will continue to burn after the external ignition source is removed with almost 2% less oxygen present then the woven towelling.

On a close examination of the burning specimens, in particular the warp knitted ones, an unusual effect could be observed at the base of the pile loops. The polyamide in the ground structure, once in a liquid state, appeared to be flowing through the structure thus fuelling the cotton component and propagating the flame. This mechanism was also assisted by gravity, as the test specimen is suspended vertically in the chamber and ignited at the top, therefore helping the molten polyamide to flow downwards through the fabric.

For all practical purposes it is suggested that this small difference in the LOI values between the two fabric types would not be sufficiently significant to cause concern.

3.6 Flexural Rigidity

It can be observed from the flexural rigitity results given in Table 15.1 that the woven fabric was stiffer overall. It had a considerably higher flexural rigidity value in the warp direction but a slightly lower value in the weft direction, when compared with the warp knitted fabric.

The reason for the considerably better drape in the warp direction of the knitted fabric is due to the fact that the finer 76 dtex polyester continuous-filament yarn cannot support the mass of the heavier weft component, therefore causing the specimen to 'dip' towards the pointer on the stiffness tester far more readily than is the case with the woven fabric. The flexural rigidity of the woven fabric is lower than that of the knitted fabric in the weft direction. This is mainly due to the fact that during testing on the stiffness tester, the picks in the woven fabric have to support a higher warp mass of 28 tex, whereas the weft yarns of the knitted fabric only have to support a 7.6 tex yarn.

3.7 Crease Recovery

From the results presented in Table 15.1 it can be seen that the warp knitted fabric had a higher crease recovery value. A figure of 180° would mean a complete recovery from creasing. The weft components in the two fabrics showed a similar recovery from creasing, but the warp components behaved completely differently. This is mainly due to the continuous-filament polyester pillar stitches in the warp knitted fabric being far more resistant to creasing than a staple-fibre cotton yarn as in the woven fabric.

Another interesting point to note from the results was the significant improvement in crease recovery when testing the warp knitted fabric face to face in the warp direction. This is due to the nature of the overlaps and underlaps. The fabric is more resistant to creasing when the loops are folded inward i. e. technical face to technical face.

3.8 Fabric Drape

The results in Table 15.2 show that the warp knitted towelling has the superior drape characteristics when tested on the Cusick Drape Tester. This ability to drape more readily is mainly due to the type of yarns used in the ground structure itself. The woven terry ground structure consists of 49 tex yarns in both directions whereas the knitted terry has a ground structure with a yarn linear density of approximately 8 tex (78 dtex). This obviously enables the weight of the pile yarns in the knitted towelling to bend or flex the ground yarns more easily than is the case in the woven towelling. Although knitted stuctures can be designed to give very firm, stiff fabrics using certain yarns and constructions,(for example monofilament yarns), in general they have superior drape characteristics to woven fabrics. This is because the normal loop shape in a knitted structure can be deformed more readily during the application of stress therefore enhancing the drape characteristics of the fabric. This particular property makes the knitted fabrics more suitable for robes or gowns. On the other hand, drape characteristics are not as important for towels, an area in which the woven terry fabrics have almost entire domination.

3.9 Seam Slippage

Table 15.2 shows that in the warp direction, the woven towelling has a lower seam slippage. This is due to two main factors. Firstly, the number of warp and pile yarns per unit length is higher in the woven fabric, therefore the inter-fibre or inter-yarn friction is much higher for any given area. Secondly, the warp knitted fabric has open pillar stitches in the warp direction and these tend to slide more readily over the laid-in yarn in the weft direction resulting in a higher warp-way seam slippage. In the weft direction, however, the knitted fabric has a significantly lower seam slippage than the woven fabric. The reason for this is the fact that the yarns running in the weft derection are 'locked' into the structure by being trapped between the loops and the underlaps formed by the pillar threads therefore restricting the amount of yarn movement or slippage.

3.10 Pile Retention

The results in Table 15.2 represent the force in Newtons required to extract pile threads from 10 cm of fabric length. The results in Table 15.2 depict perhaps the most significant difference between woven and warp knitted towelling in terms of its performance in use. From the test results it can be seen that the force required to remove pile yarns or to break the loop was significantly higher for the warp knitted towelling. The behaviour of each fabric was also completely different during the tests.

The pile loop in the woven fabric could be removed completely from the 10 cm strip of fabric, see Figs. 15.7(a) and 15.7(b). During the pile yarn removal, the woven fabric gave a trace on the graph similar to that recorded in the tear test. From these traces the median values were established and the mean force required to pull out the pile from 10 cm fabric length was found to be 2.22 Newtons.

The pile yarn in the knitted fabric, however, was unable to be removed fully from the surface of the fabric. In fact the loop broke after being pulled 5 to 10 mm only from its original length. This is illustrated in Figs. 15.8(a) and 15.8(b). The load at which each loop broke was recorded and the mean force was found to be 4.59 Newton. The reason for this inability to remove the pile yarn in the warp knitted fabric is because the pile loops are firmly locked into the ground structure between the overlaps and the underlaps formed by the pillar stitches of the warp threads. This only allows the pile to be removed as far as the next wale and then the structure tightens up allowing no further yarn slippage. Inevitably the pile loop then breaks.

The warp knitted towelling is therefore much more resistant to plucking and snagging than the woven towelling, and high street stores and other retailers who sell products such as bath robes often market the warp knitted garments as 'snag-resistant which is an obvious advantage with this type of garment.

4. ECONOMICS OF PRODUCTION

It was found that the material cost in the woven flannelette was 38.7 P/m^2 as against 39.5 P/m^2 in the warp knitted flannelette fabric. The conversion cost, that is the cost of producing each fabric, was quite dissimilar in the two cases. The production costs included capital, labour, floor space and energy costs and the machines were operated on a multishift basis, and were depreciated in five years in both cases. It was revealed that the production costs for warp knitted flannelette fabric were significantly lower than the woven fabric. It must be stressed that the actual figures for production costs have been excluded here intentionally, because they were computed for a specific production level and set of conditions, and were kept constant in each case. The finishing cost will be similar for the two fabric types.

The raw material costs in the two towelling fabric types studied revealed that they were substantially lower for the warp knitted fabric. However, this is somewhat misleading because the woven fabric is over 30% heavier than the knitted, although both are used for exactly the same end-product. The conversion cost determination for each fabric showed again that it was significantly lower for the warp knitted fabric. It is less than half that of the woven fabric mainly because of the very high production rates of the warp knitting terry towelling machines.

5. SUMMARY AND CONCLUSIONS

Table 15.3 and 15.4 summarise the comparison of the results of the various tests performed on flannelette and towelling fabrics, respectively.

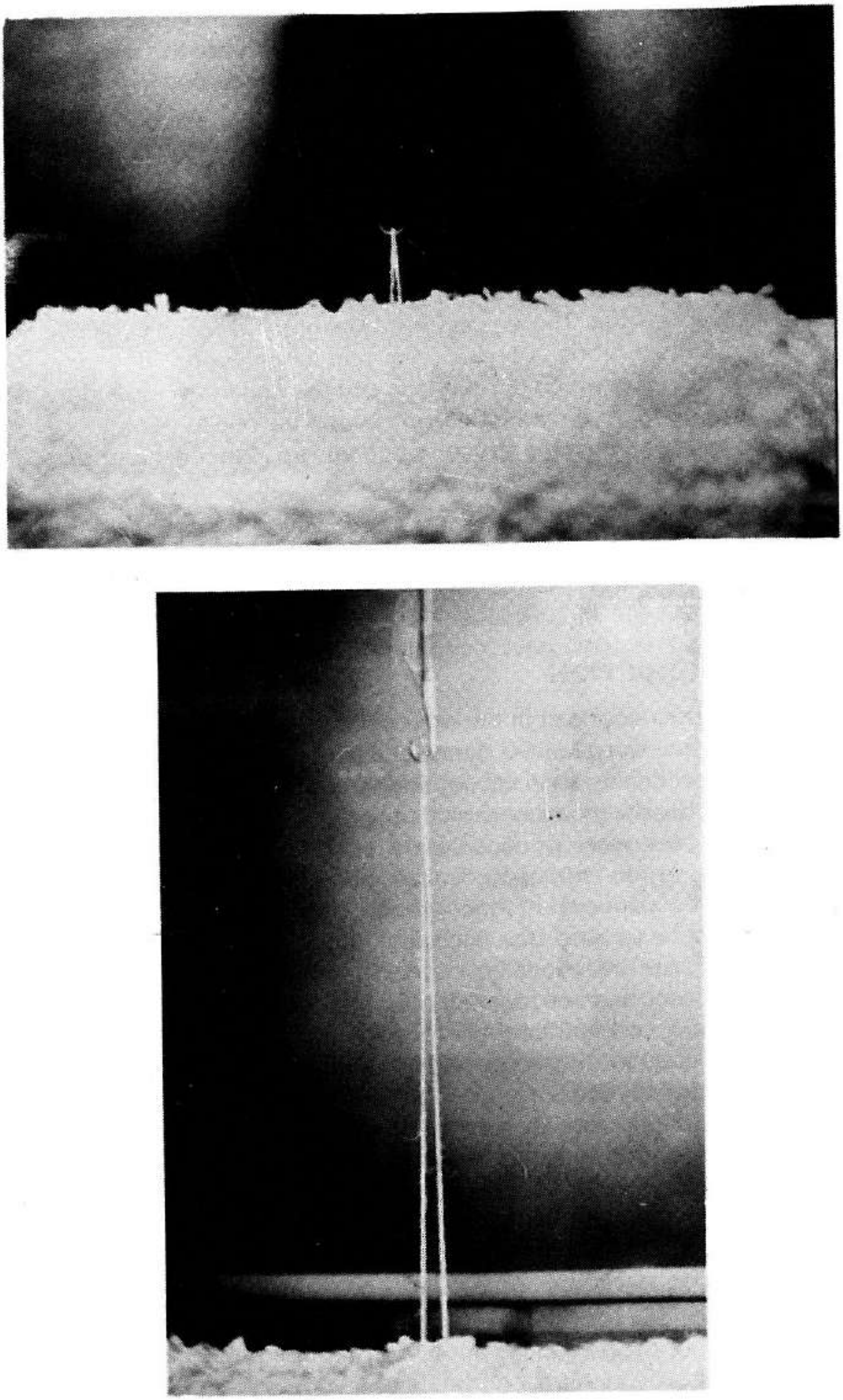
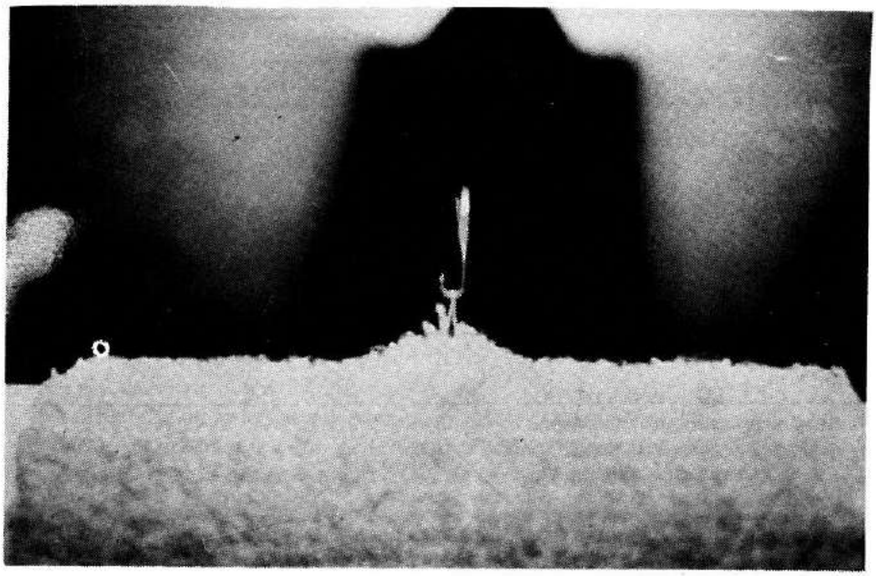
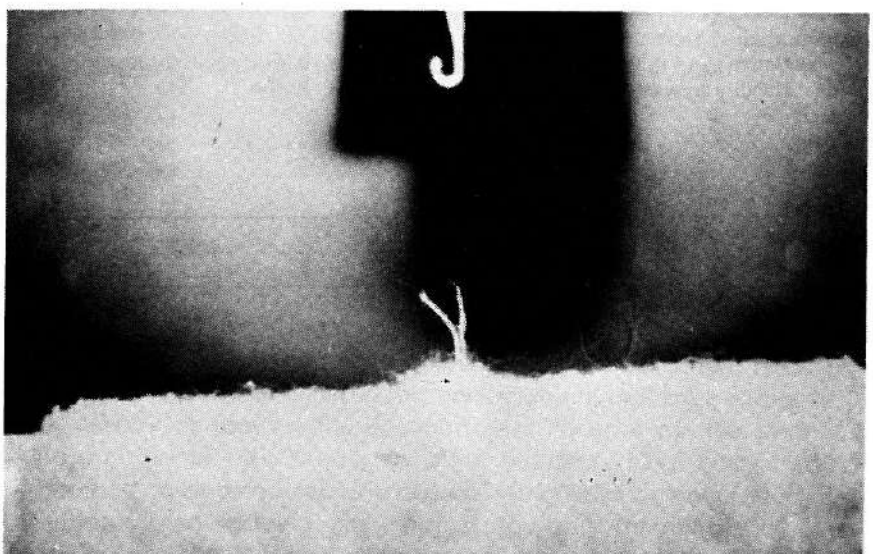


Fig. 15.7 Pile retention test on woven towelling



(a)



(b)

Fig. 15.8 Pile retention tests on warp knitted towelling

TABLE 15.3 Comparison of Performance of Woven and Warp Knitted Flannelette Fabrics

Property	Woven Fabric		Warp Knitted Fabric	
	Warp	Weft	Warp	Weft
Tensile strength	+			+
Extension-at-break	++			++
Tear resistance	+			++
Abrasion resistance			++	++
Flexural rigidity		+	++	
Dimensional stability to washing			++	+
Crease recovery	0	++	0	
LOI	0	0	0	0
Materials costs	+			
Production costs	++			

Key: ++ Denotes significantly superior
+ Denotes slightly superior
0 Denotes negligible difference

Table 15.4 Comparison of Performance of Woven and Warp Knitted Towelling

Property	Woven Fabric		Warp Knitted Fabric	
	Warp	Weft	Warp	Weft
Tensile strength	++			+
Extension-at-break	++	+		+
Tear resistance	++		+	
Abrasion resistance	0	0	0	0
Dimensional stability to washing		0	++	0
Fabric drape			++	
Seam slippage		++		++
Pile retention			++	
LOI	+	+		
Materials costs			+	
Production costs			++	

Key: ++ Denotes significantly superior
+ Denotes slightly superior
0 Denotes negligible difference

BIHE
Bolton
UK

16

Production and Application of Geotextiles in India

P.K. DEY, G.V. RAO and P.K. BANERJEE

India is a vast country with diverse climatic and terrain conditions. These factors pose a great challenge to the construction engineers. Geotextiles are being extensively used the world over as one of the construction materials in solution of such problems. Keeping this in view in India too, geotextiles have begun to be used in various projects, either on trial basis or as an effective, alternative economical solution. Their popular applications are in river embankments, canals, roads, railways, airports, earthen dams, slopes, etc. In such applications geotextiles made of both natural and synthetic fibres have been used. In most cases indigenously manufactured geotextiles have been used with encouraging results. This paper has reviewed the different types of geotextiles being manufactured in India along with their typical properties. Case histories of different projects executed with geotextiles have been brought out. Specifications and properties of geotextiles used in these projects are also detailed. The paper thus reviews the current Indian scenario covering geotextiles and also focuses attention on the potential future applications.

1. INTRODUCTION

India is a vast country with widely varying climatic and terrain conditions. The resulting diverse nature of sub-soil conditions creates a spectrum of problems for the construction engineers. During the last two decades, there has been an increase in demand for construction of civil engineering structures in a variety of topographical conditions. To improve the poor sub-soil conditions in adverse locations, civil engineers have been traditionally depending on conventional raw materials (like bricks, cement, steel, etc.). But situations arise where there may be non-uniform quality or/and non-availability at and around the construction site leading to high material transportation cost. These and other associated technical limitations of building conventional structures on weak soils lead the civil engineers to search for alternate solutions. One such alternative which has emerged as a popular material/technique in recent years is geotextiles. They are being extensively used in various civil engineering projects to facilitate construction, ensure better performance of the structures and reduce maintenance in long run.

They have wide applications in almost all geotechnical and hydraulic engineering projects. Typically such projects include airports, canals, railways, coastal erosion works, dams, embankments, pavements, etc.

During the last decade, there has been a phenomenal growth in use of geotextiles in civil engineering projects all over the world. The growth in consumption of geotextiles in North America is shown in Fig. 16.1 and the

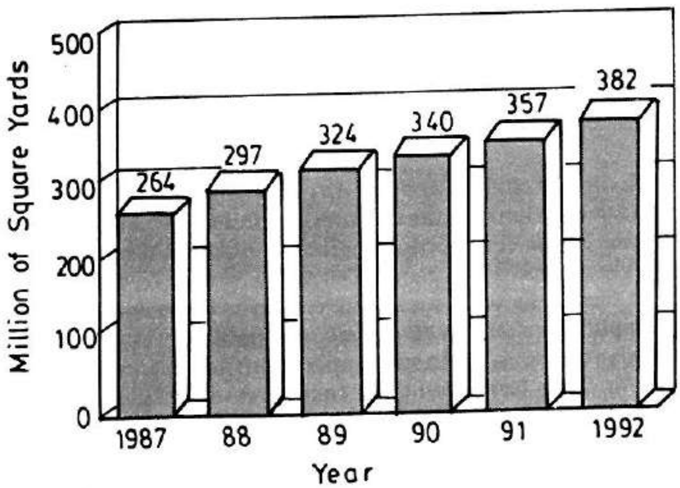


Fig. 16.1

projected geotextile market upto year 2000 is shown in Fig. 16.2. Though the data presented is only for North America, it is indicative of the general worldwide pattern [1]. The Indian engineering community is however still in the process of getting acquainted with this family of new materials through laboratory and field research works, field trials, conferences and workshops.

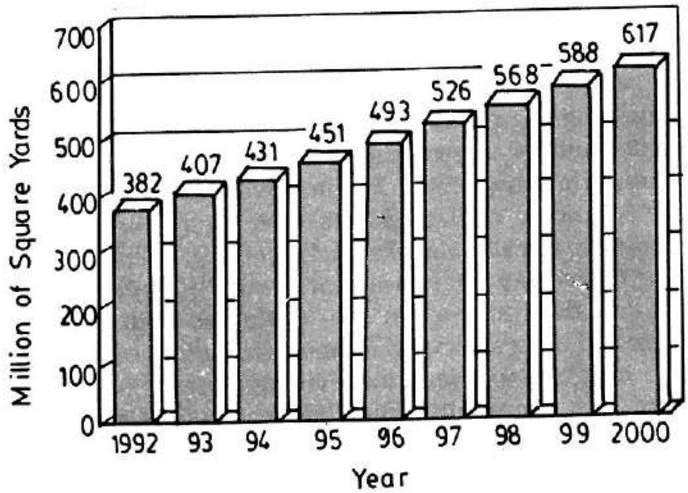


Fig. 16.2

Viewed against the potential and size of our country the application of geotextiles in India has indeed been very marginal as compared to that of certain developed countries. In this paper an attempt has been made to present the Indian scenario in proper perspective by closely examining the prevalent manufacturing processes, properties, applications and potential.

2. PRODUCTION OF GEOTEXTILES

2.1 Manufacturing Processes

Presently there are quite a few units in India where geotextiles and related products can be manufactured. Both woven and nonwoven geotextiles are produced. No report is available about the manufacture of knitted geotextiles.

Woven geotextiles produced in India are mostly made of multifilament polypropylene, having either plain or twill construction.

The indigenously manufactured nonwoven geotextiles are essentially made of synthetic staple fibres and they are either mechanically and/or chemically bonded. The clear advantage of staple fibre as raw material for nonwoven geotextiles is the greater latitude and flexibility to change the denier and the polymer type [2]. It is also known to yield higher tear resistance under impact load because of their greater extensibility [3].

2.2 Raw Material

Though geotextiles made of both synthetic and natural fibres are produced in India, the share of natural fibres has been very small. Among all the synthetic fibres polypropylene enjoys the lion's share followed by polyester, whereas jute and coir are the most commonly used natural fibres. The inertness towards chemicals, low specific gravity, lower cost to volume ratio and easy processibility of the polypropylene fibre are probably the main reasons behind its popularity. Only in certain applications needing low creep, high thermal resistance, or even high specific gravity polyester is preferred [2]. Besides these, use of nylon filament, polyethylene slit film, etc. have also been reported for production of geotextiles.

2.3 Product Profile

An analysis of the product particulars published by different geotextile manufacturers, viz. Bombay Dyeing, Gujarat Filaments Ltd., Hitkari Fibres, Sri Dinesh Mills, Supreme Nonwovens, Tata Mills, published literatures as well as work done at IIT, Delhi leads to the following observations:

WEIGHT

The heaviest mass per unit area belongs to a needle punched polypropylene fabric of 535 gsm, whereas the heaviest polyester nonwoven fabric is of 400 gsm. They are claimed to be multipurpose products, meant for erosion control, separation, drainage and filtration. A double layered woven geotextile made of 100% nylon multifilament of 475 gsm is available for canal lining (grouted mattress) and erosion control. Besides these a range of woven geotextiles upto 400 gsm made of polypropylene multifilament yarns are also produced. They are stated to be meant for reinforcement application.

The lighest fabric is of 180 gsm, a nonwoven made of polypropylene staple fibre.

THICKNESS

Nonwoven fabrics, particularly the needle punched ones, are eminently suitable for fluid transportation along the fabric plane (i.e. drainage). Thickness is one of the important fabric parameters governing this property. Available indigenously made nonwoven geotextiles exhibit thickness ranging between 0.61 mm to 5.3 mm measured at 2 kPa.

STRENGTH

The strongest nonwoven fabric of 535 gsm and made of polypropylene has a strength of 40 kN/m in the cross machine direction and 24 kN/m in the machine direction. The strongest woven fabric of 290 gsm made of polypropylene has a strength of 80 kN/m in the machine direction and 61 kN/m in the cross machine direction. The best combination of strength (strength in the machine direction and the cross machine directions) of 78 kN/m in the machine direction and 67 kN/m in the cross machine direction is exhibited by a woven fabric of 400 gsm made of polypropylene.

The weakest among the lot has strength of 2.5 kN/m in the machine direction and 4.0 kN/m in the cross machine direction. They are polypropylene needle punched nonwovens of 180 gsm.

ELONGATION

In general, the needle punched nonwoven geotextiles exhibit very high elongation-at-break ranging from 60% to 110% in the machine direction and 40% to 85% in the cross machine direction. A 100% polypropylene needle punched nonwoven fabric of 250 gsm reinforced with woven scrim shows comparatively low elongation-at-break of 40% in both the machine and the cross machine directions. This fabric is claimed to be suitable for reinforcement application. In case of woven geotextiles this elongation-at-break varies from 25% to 50%. However, the lowest elongation-at-break of 6.4% is reported for a fabric of 250 gsm made of polypropylene multifilaments and specially made for reinforcement application.

OTHER PROPERTIES

Typical properties which are important for drainage applications exhibit the following ranges.

Property	Nonwovens	Wovens
Width of fabric	upto 4.5 m	upto 3.3 m
Pore size in microns	63 to 130	25 to 175
Water permeability ($1/m^2/s$ at 50 mm water head)	39 to 105	4 to 55

A large number of geotextiles were evaluated with respect to their physical, mechanical, hydraulic, survivability and endurance properties at the Indian Institute of Technology, Delhi for various experimental projects. Some of the typical survivability properties of Indian geotextiles reported therein are listed below [4].

Properties	Nonwovens	Wovens
Puncture resistance (kg/cm^2)	—	73.3 – 114.0
CBR push through (kg/cm^2)	9.47 – 14.92	8.48 – 92.5
Cone drop (cm)	0.396 – 0.717	0.53 – 1.613

Their micro-structures were also studied through scanning electron microscope and projection microscope photographs. Figure 16.3 shows some of the typical photomicrographs.

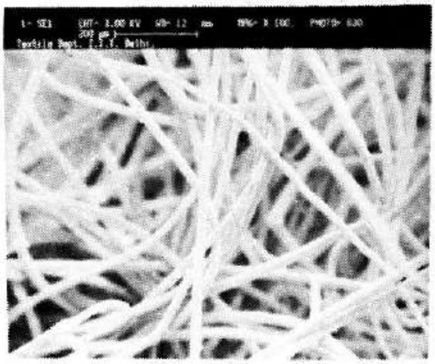
Geotextiles made of natural fibres are also marketed by indigenous manufacturers. They are mostly available in the form of plain or twill woven fabrics or open mesh net. Nonwoven geotextiles made of natural fibres have not been reported so far as a regular product. However, research in product diversification incorporating natural fibres has resulted in the development of coir and jute needle felts which have potential in varied applications, especially in land drainage, slope protection, etc. [5].

As of today, spun bonded geotextiles, one of the most popular geotextiles for separation function, and knitted geotextiles are not manufactured in India.

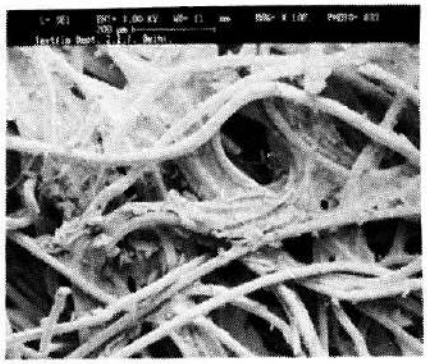
3. APPLICATION OF GEOTEXTILES IN INDIA

During the last 10 to 15 years, geotextiles have been successfully used in quite a few Civil engineering projects, viz., earthen dams, roads, railways, airports, river banks, canal lining, etc. for the following primary applications [6].

* Subgrade Stabilization
* Railroad Track-bed Stabilization
* Sedimentation Control; Silt Fence
* Asphalt Overlay
* Soil Reinforcement
* Erosion Control Filter

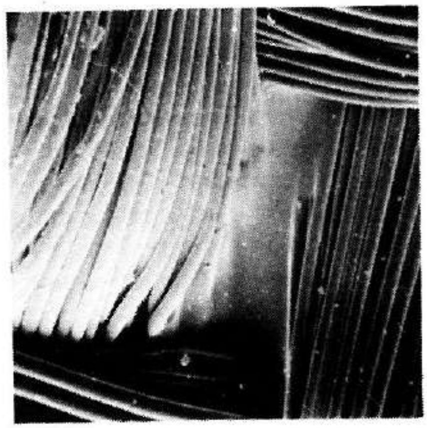


Needle Punched Nonwoven Geotextile



Adhesive Bonded Nonwoven Geotextile

Multifilament Woven Geotextile



Interlacement Point of Woven Multifilament Geotextile

Fig. 16.3 Scanning electron microscope photographs of typical Indian geotextiles

- ✶ Subsurface Drainage Filter
- ✶ Geomembrane Protection
- ✶ Subsurface Drainage
- ✶ Surfacial Erosion Control

Applications have been reported in new construction works and also in repair works. They have also provided instant solution under distress situations [7]. The primary use geotextiles have been put to in India is for erosion control.

This is followed by application in roads and railways for separation, filtration, drainage and rarely for reinforcement functions.

On the other hand a comparison of strength data presented in Table 16.1 for some of the typical reinforcement fabrics available in India with those made in other countries clearly reveals that the strength of Indian woven

TABLE 16.1 Typical Woven and Nonwoven Geotextiles—A Comparison Chart

Product	Polymer	Material	Mass (g/m^2)	Wide width Tensile Strength (kN/m)		Extension = at-break (%)	
				m/c	× m/c	m/c	× m/c
WOVEN							
Mirafi, U.S.A. 2500 HP	PET	Multi-filament	810	175.1	175.1	15	15
Nicolon, Netherland Geolon 1500	PP/PET	Multi-filament	—	192.6	262.7	15	12
Nicolon New Test fabric Netherland	PET	Multi-filament	2370	663.7	206.6	11	11
Geolon (Bombay Dyeing)							
Style 499	PP	Multi-filament	270	31	—	28	—
Style 500	PP	Multi-filament	200	22	—	22	—
Style 501	PP	Multi-filament	306	42	—	32	—
NONWOVEN							
Supac 8NP, U.S.A	PP	Staple	223	15.17	—	60	100
Supac 9NP, U.S.A	PP	Staple	280	19.64	—	65	90
Dinesh Mills							
GPB–132	PP	Staple	276	19.0	—	58	90
IPB–128	PP	Staple	220	13.0	—	85	100

geotextiles are significantly low and their elongation is quite high. However, the tensile properties of typical Indian nonwoven geotextiles appear to be in the same range as their counterparts available in the world market. When viewed against the requirement suggested in Table 16.2 (After Hausman, 1987) for reinforcement, it is evident that their tensile properties make them suitable for retaining structures of low height, slope stabilisation (with close spacing), unpaved roads and also to a limited extent in foundations. However, as of today even this use has been limited to laboratory trials [4]. Various model tests on geotextile reinforced retaining walls, conducted at the Indian Institute of Technology, Delhi have revealed that the locally made geotextiles may be safely used for reinforcement functions in low height retaining walls (2 to 3 m high) with a surcharge of 2 t/m^2. For other applications the fabrics need to be much stronger (say by 5 to 10 times). Unless and until this

Table 16.2 Strength Requirements of Geotextiles for Soil Reinforement (after Koerner and Hausman, 1987)

S. No	Application area description	Tensile strength kN/m	Modulus kN/m
1	Retaining structures		
	(a) Low height (< 3 m)	13.1–17.5	35.0–52.4
	(b) Moderate height (3–7 m)	17.5–21.9	43.7–87.4
	(c) High height (> 7 m)	21.9–26.2	61.2–175.0
2	Slope stabilization		
	(a) Close spacing (< 0.9 m)	13.1–21.9	26.2–61.2
	(b) Moderate spacing (0.9 – 3 m)	17.5–26.2	35.0–70.0
	(c) Wide spacing (> 3.0 m)	26.2–52.4	43.7–175.0
3	Unpaved roads		
	(a) CBR ≤ 4	13.1–21.9	52.4–87.4
	(b) CBR ≤ 2	17.5–26.2	87.4–175
	(c) CBR ≤ 1	21.9–52.4	175.0–525
4	Foundations		
	(a) Nominal improvement in BC	26.2–69.9	175–350
	(b) Moderate improvement in BC	43.7–87.4	350–874
	(c) Large improvement in BC	69.9–175	700–1750
5	Embankment over soft soil		
	(a) Strength > 9.6 kPa	87.4–262	874–1750
	(b) Strength > 4.8 kPa	175–350	1750–3500
	(c) Strength > 2.4 kPa	262–524	3500–6120

development is carried out, the entire range of applications in reinforcement cannot be met [8].

One of the common phenomena with all the natural fibres is their biodegradability. In the early stages of geotextiles application, natural fibres were considered unsuitable. With increasing application of geotextiles, biodegradability is being used to advantage. There are several geotechnical application areas where expected life span of a geotextile is very small. Erosion control is one such application. In developed countries like USA, UK, France etc. use of natural fibre like jute is gradually increasing in recent years due to its being nature friendly. In India geotextiles made from natural fibres have been employed in quite a few experimental projects with encouraging results.

In the following various field trials and field applications of geotextiles in India are briefly summarised, critically highlighting the necessity and improvement effected. Also brought forth are the potential applications which have great scope.

3.1 Erosion Control

Erosion of river banks, canals or shore lines of sea is a common phenomenon due to the action of the flowing water. Sometimes the rate of erosion is so fast that it endangers the survivability of the near shore structures. Soil erosion may also be caused by rain water and strong wind on steep ground, hill slopes and even on the plain land with little or no vegetation cover. Energy of splash of rain drops loosens the soil particles and carries them down the slope thus resulting in the erosion of the land. Such lands, susceptible to surface erosion could be effectively protected from erosion with proper vegetation cover. In such situations biodegradable geotextiles not only protect the slopes from erosion but also provide an acceptable protection to the seeds until they germinate and take roots deep into the soil. Moreover, after biodegradation these geotextiles act as manure and help in the speedy growth of the plants by providing nutrition.

Due to the action of flowing water, tidal waves, etc. water may flow within the soil of the embankment or bank through the gaps between the individual members of the bank lining, stone pitching, etc. While it comes out, it may carry the fine soil particles from within the embankment. In course of time this creates voids in the embankment thereby causing the failure of coastal defence system. Application of a suitable geotextile between the embankment soil and lining helps to eliminate the movement of soil particles from the embankment. In such situations geotextiles act as a filter as well as separating medium (Fig. 16.4).

In India, erosion of embankment is a very common problem for the geotechnical engineer. In fact various type of geotextiles have been successfully used in different erosion control and embankment protection projects. Table 16.3 presents a list of the various projects implemented successfully for erosion control works with geotextiles. In the following a few typical case histories are brought out.

RIVER BED/BANK PROTECTION

In Hooghly river at Nayachara island near Haldia port, a guide wall (embankment) of about 2.8 km has been constructed on the soft river bed for overcoming the siltation problems in the river channel [9]. Geomattresses made of a grid of fascine wieps over geotextiles was used in this project for river bed protection (Fig. 16.5). Fascine wieps were made of locally available needs wrapped over the split bamboo core. A grid of 1 m × 1 m aperture was made by placing one layer of these wieps (10 cm dia. and 11 m length) over an identical layer at right angle to each other. The composite geotextile made of woven and nonwoven fabrics was fastened to the wieps by means of a polypropylene—sisal rope, having a tearing strength of 2 kN, through the loops inbuilt within the woven fabric.

The specifications of the imported geotextiles used in this project are listed below:

(a)	Woven type:		
	Tensile strength	Machine direction	80 kN/m
		Cross machine direction	50 kN/m
	Water permeability	At 100 mm water head	35 $l/m^2/sec$
	EOS	O_{90}	150 microns
(b)	Nonwoven type:		
	Tensile strength	Machine direction	15 kN/m
	Area density		250 g/m^2
	Water permeability	At 100 mm water head	80 $l/m^2/sec$
	EOS	O_{90}	60 microns

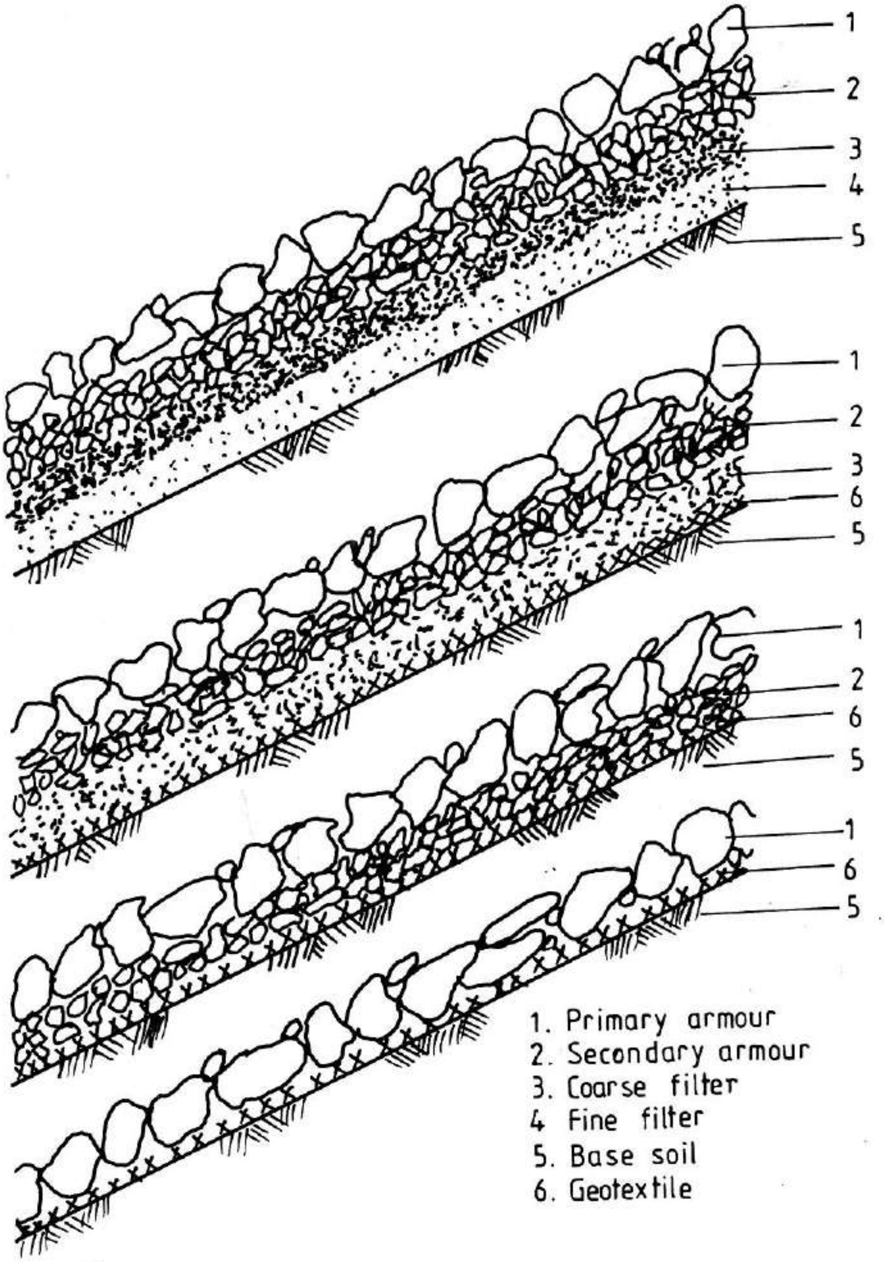


Fig. 16.4

About 2 km of embankment of Hooghly river near Nayachara island, above the low water level was protected with concrete blocks placed on layers of brick and filter cloth. Specifications of the filter cloth used in this project are as follows [10].

Tensile strength	:	15 kN/m
Area density	:	250 g/m^2
O_{90}	:	60 microns

TABLE 16.3 Summary of the Various Projects Carried out in India Using Geotextiles in Erosion Control Works

Slope stabilization, drainage control in embankments and dams using synthetic geotextiles	1. Kakrapara canal system near Surat, Gujarat	Grouted geotextile mattress to facilitate concrete lining work
	2. Bardoli branch canal of Ukai canal, Surat, Gujarat	Grouted geotextile mattress to facilitate concrete lining work
	3. Left bank of Dadhar river, near Gandhar Gujarat	Stone gabion caged in geogrids over geotextiles for bank protection
	4. Loktak hydro-electricity electricity project West Bengal	Erosion control (bank erosion)
	5. Farakka Barrage project, West Bengal	River bed/slope protection with grouted mattress
	6. Dharoi earth dam, Gujarat	Envelope toe drain bank protection
	7. Nayachara island near Haldia Port, West Bengal	River bed protection with geomattress
	8. Mahi canal, Gujarat	Embankment protection with geotextile
	9. Nayachara island near Hooghly estuary, West Bengal	Bank protection with bitumen coated geojute and Mangrove plants
	10. Nayachara island near Hooghly estuary, West Bengal	River bank and bed protection with geojute

At the estuary of river Dadhar (Gujarat) the embankment was eroding very fast due to the action of tidal water. It was observed that the rate of erosion was as high as 10 m per month and endangered the survivability of an active oil well of ONGC (Fig. 16.6a). An indigenously made nonwoven geotextile along with gabions filled with rip-rap was used for controlling the embankment erosion. After one year it was observed that the erosion over this area had completely stopped (Fig. 16.6b) and natural sedimentation had started. It was also found that the fabric had remained intact without any damage [11].

The fabric specifications are as follows:

Material composition	Polypropylene	100%
Type	Needle punched nonwoven	
Area density		400 g/m^2
Thickness		3.2 mm
Breaking strength	Machine direction	20 kN/m
	Cross machine direction	20 kN/m
AOS	O_{95}	75 microns
Water permeability	At 100 mm water head	75 $l/m^2/sec$
Air permeability	At 12.5 mm water head	85 cu. m/sq. ft

In 1986, the Calcutta Port Trust had successfully used jute netting to arrest erosion of river Hooghly near Haldia Port, at Kulpi. The work was carried

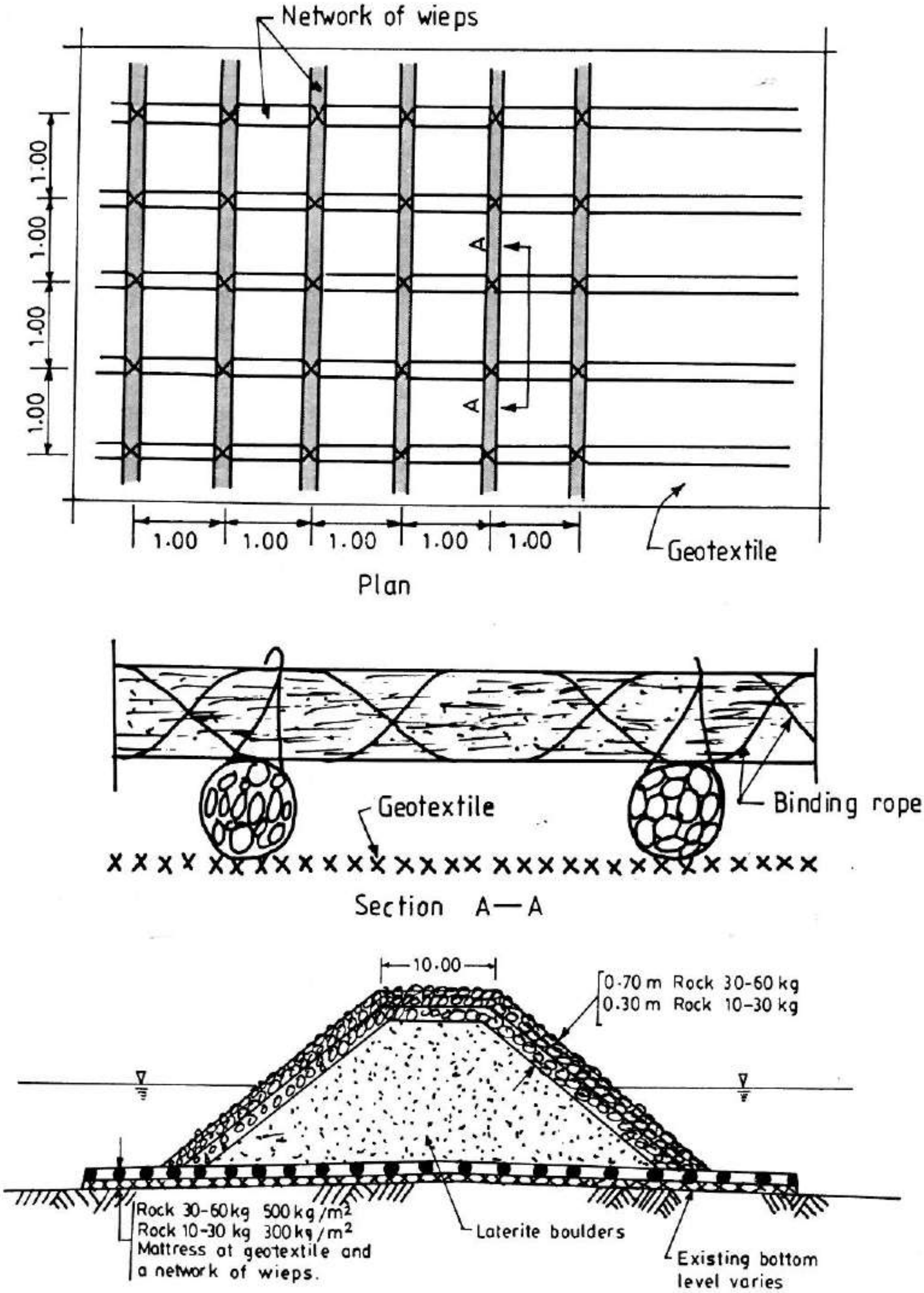


Fig. 16.5

out in river bed during low tide. On the surface, jute geotextile was laid within a framed bamboo structure to help minimize the creep during weighing

Fig. 16.6 (a) Erosion of Dhadhar Estaury

Fig. 16.6 (b) Protection work at Dadhar Estaury

down stage. Encouraged with its success at Nayachara, 3000 m^2 of similar fabric was used in 1990 (Fig. 16.7a and 16.7b) [12].

In another project near Nayachara, geo-jute coated with Bitumen was successfully used for control of river bank erosion [13].

Fabric specifications:

Material	Jute	
Type	Coated woven (D.W. Twill)	
Area density		1538 gsm
Thickness	At 10 kPa	2.83 mm
Breaking strength	Machine direction	33.2 kN/m
	Cross machine direction	28.2 kN/m
Elongation-at-break	Machine direction	11.8%
	Cross machine direction	13.5%
Puncture resistance		37.9 kgf/cm^2
Air permeability		16.2 $m^3/m^2/min$
Water permeability	At 100 mm water head	20.4 $l/m^2/sec$
Pore size		150 microns

CANAL LINING

It is estimated that about 70% water is lost in an unlined canal, mostly due to seepage and rest in radiation and distribution losses. Excess seepage of water

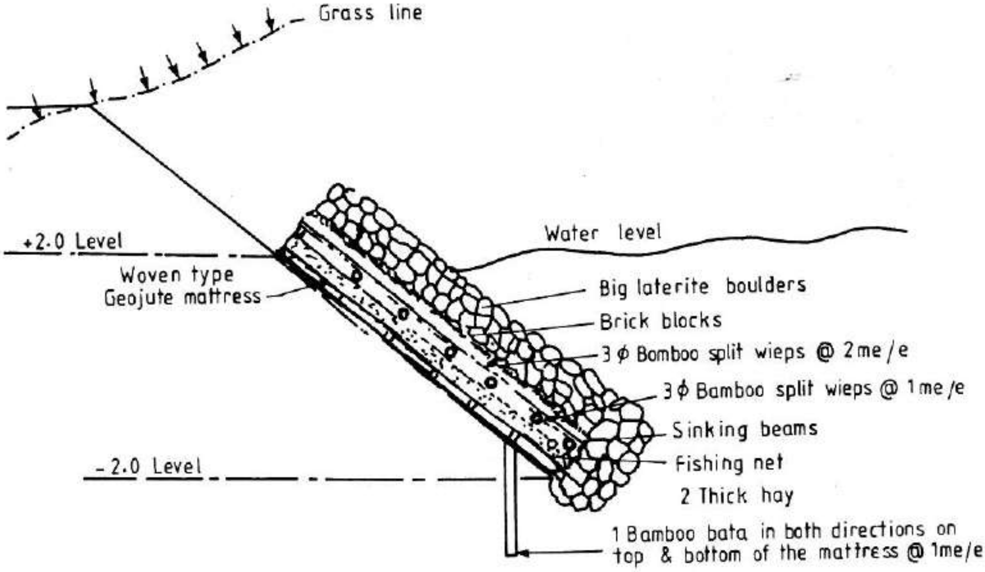


Fig. 16.7 (a) Use of woven jute mattress for erosion control Port Trust

not only makes the adjacent land unsuitable for agriculture but may also reduce the stability of side slope and may ultimately bring it to the point of breach.

In India, most of the irrigation canals are unlined and suffer from the above problems. Conventional methods of lining the canal with impervious concrete slabs, tiles or bricks are generally effective, but they cannot be used in canals under flowing condition. These limitations have been overcome by using a specially designed geotextile mattress in a small stretch of the Ukai canal (Gujarat). A specially designed nylon double layered woven fabric, interconnected at frequent intervals with spacer thread was used as fabric form to facilitate concrete lining grouting in running water condition (Fig. 16.8a and 16.8b) [11].

The specifications of the fabric used are as below:

Material composition	Nylon	100%
Type	Double layered woven cloth	
Area density		475 g/m^2
Breaking strength	Machine direction	40 kN/m
	Cross machine direction	50 kN/m
Bursting strength		> 25 kg/cm^2
Elongation-at-break	Machine direction	30%
	Cross machine direction	25%
Water permeability	At 50 mm water head	45 $l/m^2/sec$
Air permeability	At 12.5 mm water head	80 cf m/sq. ft

The same technique has been applied for canal lining and embankment protection in the Farakka barage project, West Bengal [14] and Kakrapar canal, Gujarat [15].

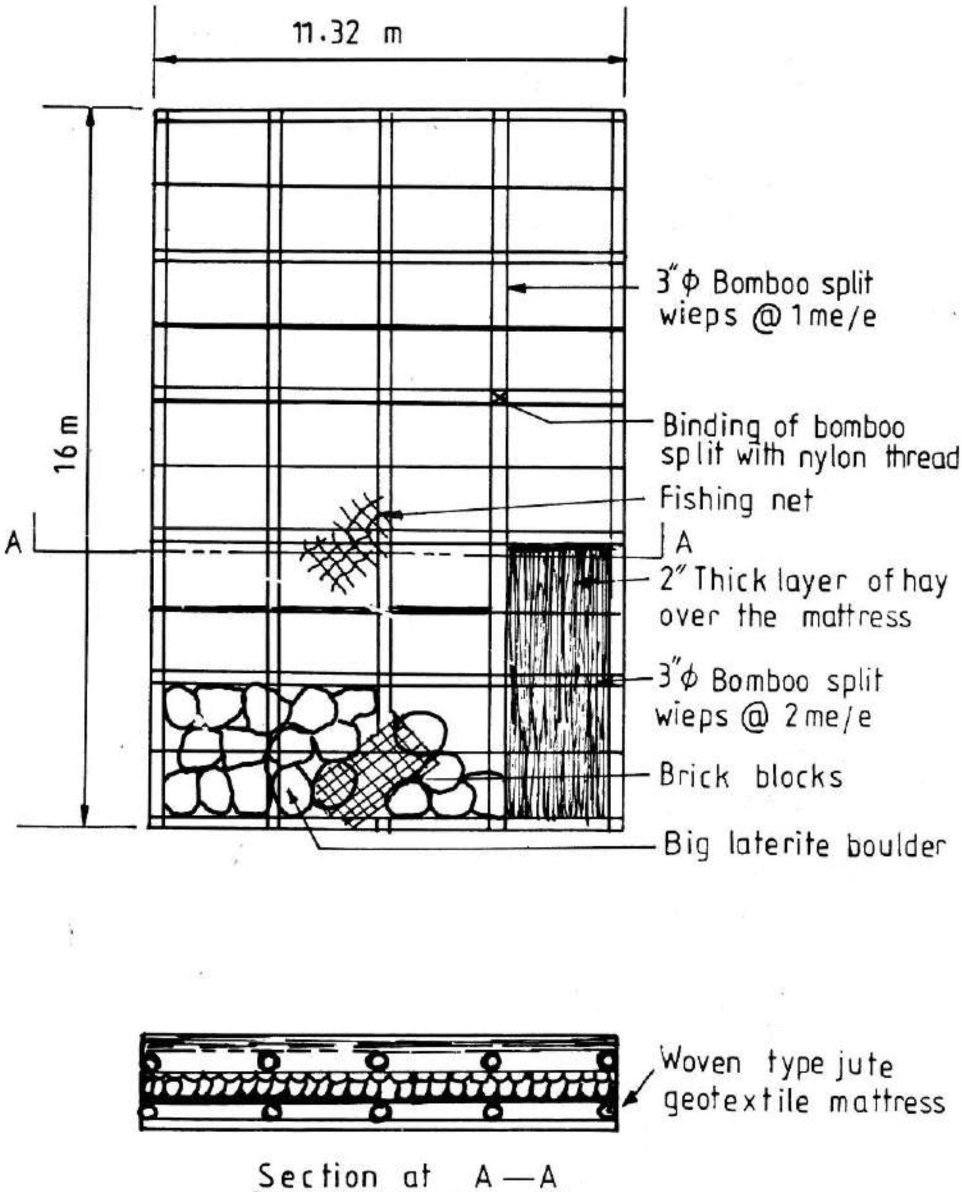


Fig. 16.7 (b)

PROTECTION OF NATURAL SLOPES

In a tropical country like India, hill slopes, embankment slopes and even the planes experience surface erosion due to rain water and wind. Such erosion causes loss of huge amount of top soil every year. This results in land slides along hill slope, loss in fertility of agricultural land and flooding of a huge area in every rainy season. Such land erosions can be very effectively controlled by simple and inexpensive techniques involving the use of geotextiles in

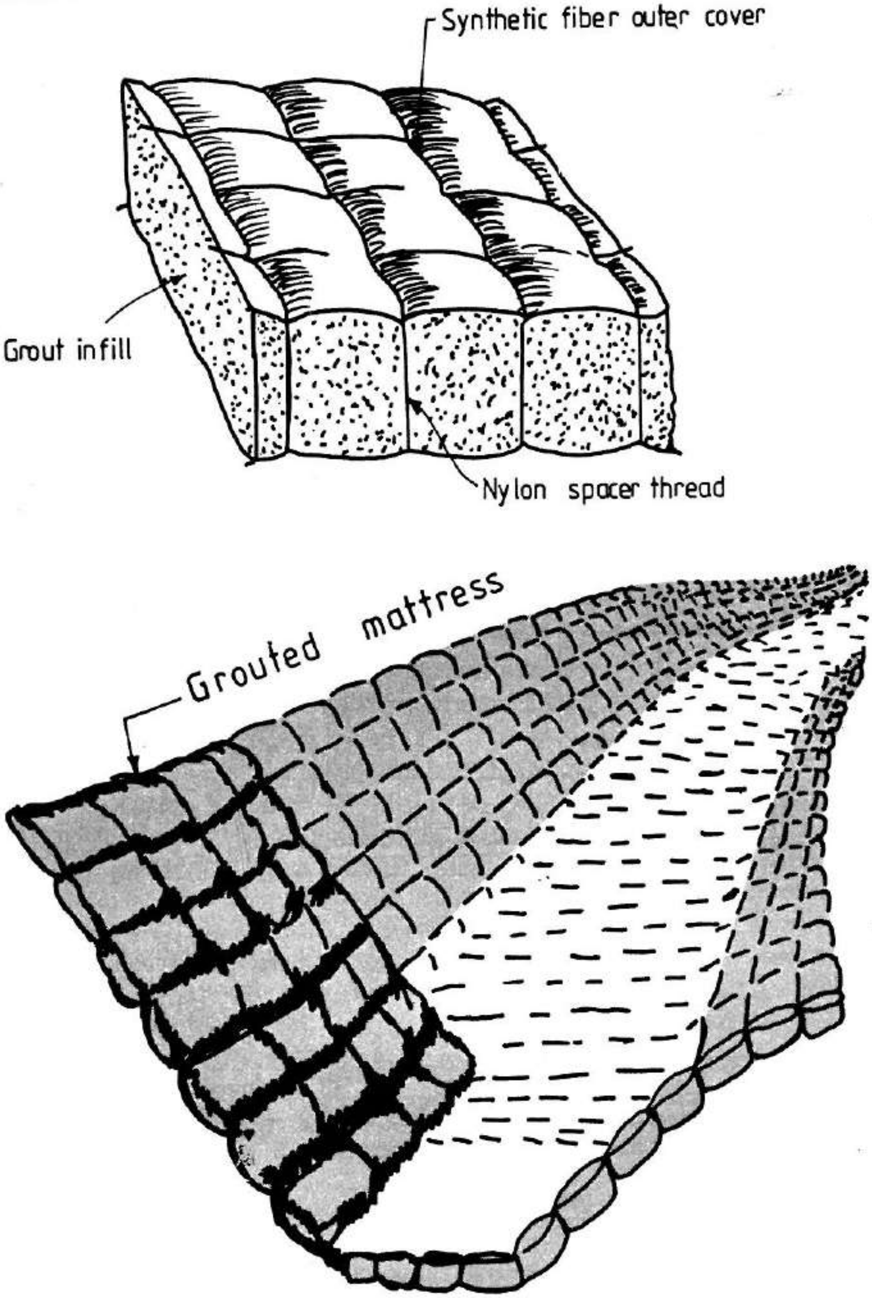


Fig. 16.8 (a) and (b)

conjunction with the promotion of the growth or re-establishment of vegetation cover.

Full scale field experiments using coir netting for control of erosion of slopes were carried out at the following locations highly susceptible to erosion.

TABLE 16.4 Summary of the Various Projects Carried out in India for Erosion Control of Slopes and Embankments Using Geojute and Coir Geogrid

1	Kathgodam—Almora State Highway	Slope protection
2	Lambidhar Mines Area Mussoorie	Wind erosion control
3	Meerapur—Dewal Road, Muzaffarnagar	Surface erosion control
4	Nagapattinam—Gudalore—Mysore	Surface erosion control
5	Coonoor—Kundha Road	Surface erosion control

About 6000 sq m of coir netting was used successfully for controlling the land erosion [16]. Figures 16.9a and 16.9b depict an embankment before and after it is protected with coir netting.

For prevention of the slide in the forebay area of the Ramman hydroelectric

Fig. 16.9a Stretch of embankment prior to the laying of coir-netting

Fig. 16.9b Embankment slope covered with vegetation after protected with coir-netting

project, West Bengal, an extensive network of drainages, both surface and subsurface has been planned. Subsurface drainages consist of a series of 100 mm diameter perforated polyethylene pipes filled with gravel. For efficient functioning of the pipe drainage systems, geotextile filters have been proposed around the perforated pipes.

3.2 Land Reclamation and Improvement

On occasions, construction of structures becomes essential over a very soft ground like reclaimed land near coastal planes or on swamp land. But the heterogeneous nature of the fill material as well as the varying loads over it, generate varying vertical resistance and ultimately causes differential vertical soil movement. This deleterious soil movement poses substantial problem to the civil engineers. Application of geotextiles in such areas helps in redistributing these varying vertical forces over a large area. Due to its continuity and high strength, differential movement of soil causes strains in the textiles which resists the movement and thereby provides support, as well as exerts a tensional effect on adjacent areas, thus redistributing stresses [17].

In India, vast area of swamp land and potentially huge reclaimed land near the long coastal lines have remained unexplored due to the poor bearing capacity of the soil. In such areas geotextiles could be used as relatively inexpensive, time saving and technically viable alternative to the conventional civil engineering solutions.

IMPROVEMENT OF RECLAIMED LAND

An offshore fabrication yard spread over about 100 acres land has been established in eastern India, about 16 km down stream of Haldia Port, where huge cranes of 250 t capacity and weighing upto 200 t are used to carry out the fabrication work. The fully assembled weight of the fabricated structure was about 5,000 t. The site had been reclaimed by dredged silt from the river Hooghly. The ground was very soft and was unsuitable for movement of any heavy equipment. A cross-section of the yard with aggregate fill and geotextiles is shown in Fig. 16.10. A number of soil stabilization techniques were considered for the development of the fabrication yard including pile foundations, pre-loading with sand drain and geotextiles. The first two techniques had been discarded due to the large cost involvement, long execution time and other technical difficulties. The application of geotextiles was found to be the most suitable alternative. Accordingly a spun-bonded nonwoven geotextile had been used as reinforcing and separating element and for the improvement of the bearing capacity of the soil. During more than three years of full operation the yard is performing consistently, barring a few cases of isolated local settlement [18].

The specifications of the fabrics used are as follows:

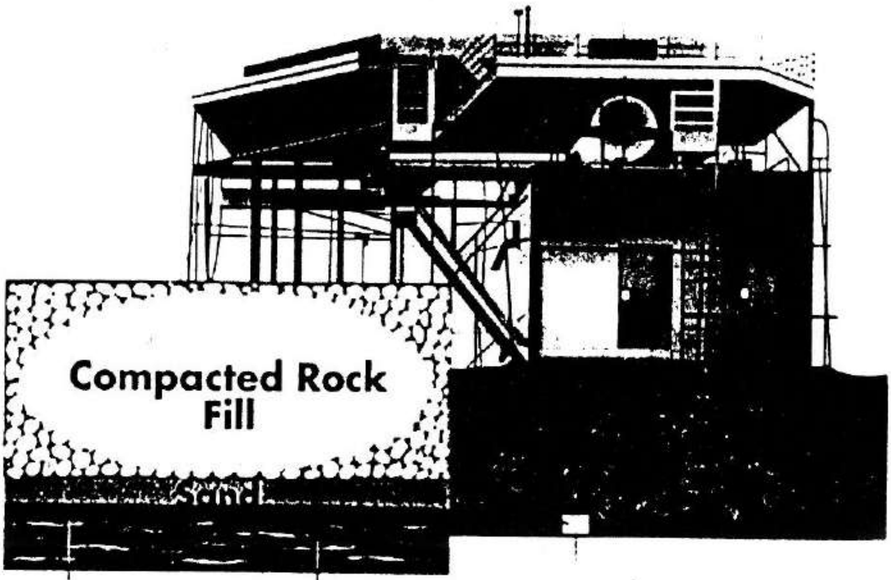


Fig. 16.10 Cross-section of heavy duty fabrication yard over soft-reclaimed land near Haldia Port

Raw material	Polypropylene 100%
Type	Spun bonded nonwoven
Thickness	0.46 mm
Weight	170 g/m^2
Elongation at break	63%
Modulus	400 kN/m
Puncture strength	35 kg
Air permeability	1.8×10^{-2} cm/sec
AOS	80 microns

HARBOURS, DOCKS AND PORTS CONSTRUCTION

One of the potential application areas of geotextiles is in the construction of major harbours, docks and ports in deep water tidal areas. By permitting a staged construction sequence and separating dredged sand from the rock protective layers, the geotextiles provide the means for constructing steep sand filled slope of gradient upto 1 : 1.5, whereas sand will only normally stand at a gradient of 1 : 20 in tidal water with moving current [17]. It may also help in the construction of structures on soft marine clays (Fig. 16.11). On the long coast line in India, in some locations presently it is nearly impossible to construct much needed near-shore/off-shore structures due to the fast moving water and non-availability of proper sand fill. In such locations geotextiles could offer a cost effective solution. Figure 16.12 shows the typical use of geotextile in land reclamation.

The largest ever project which has been executed with geotextiles so far in

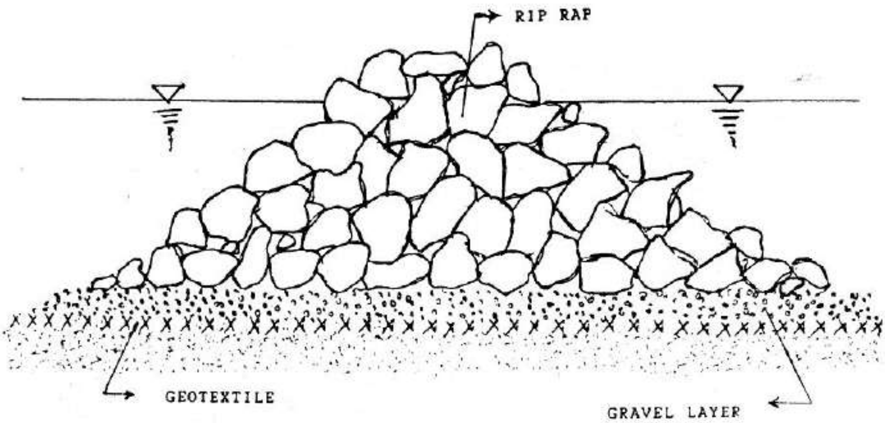


Fig. 16.11 Use of geotextiles for construction of structures on soft sea/river bed

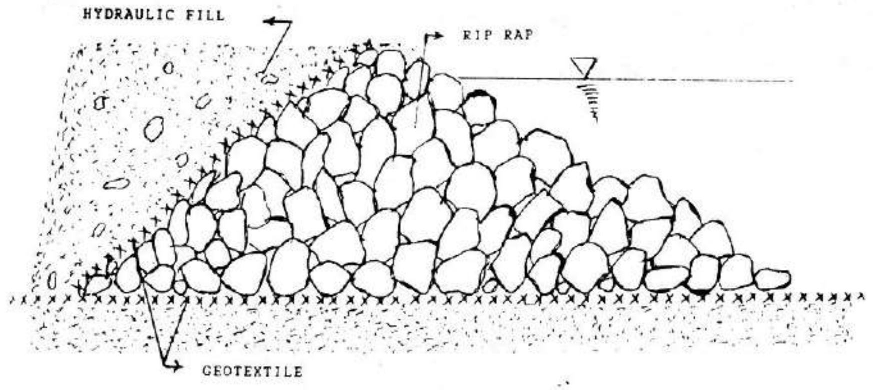


Fig. 16.12 Use of geotextiles in land reclamation

India is the *Nhava Sheva* port project near Bombay. The project, since completed, envisaged construction of deep water bulk and container berths, roads, reclamation of large area and reclamation bunds. The bunds as well as reclamation was done on very soft marine clays. The traditional method would have necessitated flatter side slopes, long rest periods for sufficient consolidation to occur. Such method of construction not only takes a very long time but also use considerably more fill and, therefore, can prove to be more expensive as well. Therefore, as a suitable alternative, polypropylene and polyester geotextiles of varying strength have been used for separation, filtration and reinforcement functions. About one million m^2 of imported woven polyester geotextiles and 20,000 m^2 of woven polypropylene geotextiles were consumed in this project [19]. The strength of the geotextiles used in this project are as follows.

Function		Strength
Separation, filtration	Both machine and cross machine directions	27.5 kN/m
Reinforcement	Both machine and cross machine directions	400 kN/m (Polyester)

To overcome water logging and salinity problems in Mahi command (Gujarat), French drain system has been installed in 50 hectres of agricultural land. Different types of filter systems in the form of envelopes around perforated PVC pipes (Fig. 16.13a and 16.13b) were provided. The media used for envelopes are gravel sand, plastic wire net, coconut fibre, coir mat and geotextiles. The drainage system became operative in May 1988 and since then it is reported to be working satisfactorily. By judging the turbidity of the discharged drain water it is found that the performance of geotextiles envelope is the best so far [20]. The water level thereby has remained below 1.5 m depth and the salinity of the soil has reduced considerably.

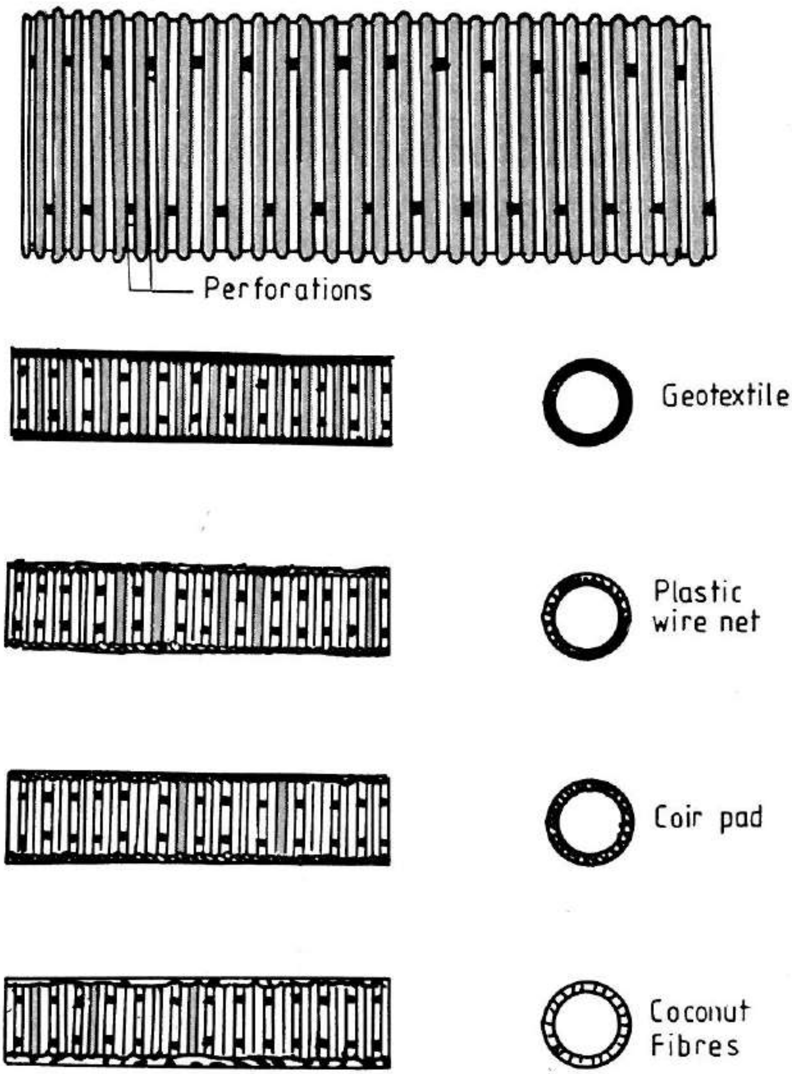


Fig. 16.13a and b

3.3 Stabilization and Improvement of Bearing Capacity of Subgrade

Geotextiles are nowadays widely used for stabilization and bearing capacity improvement of the subgrade specially below the roads and railway tracks. When constructed over the poor load bearing soil, these roads, particularly the unpaved roads, are subjected to severe rutting and aggregate loss resulting in costly maintenance. This phenomenon is more apparent in rainy seasons when rainfall is heavy, water table is high and ingress of water through the pavement crust is common.

Application of a suitable geotextile between the sub-base and subgrade as shown in Fig. 16.14 helps in distributing the normal stresses over the subgrade thereby improving the load bearing capacity of the system. In such

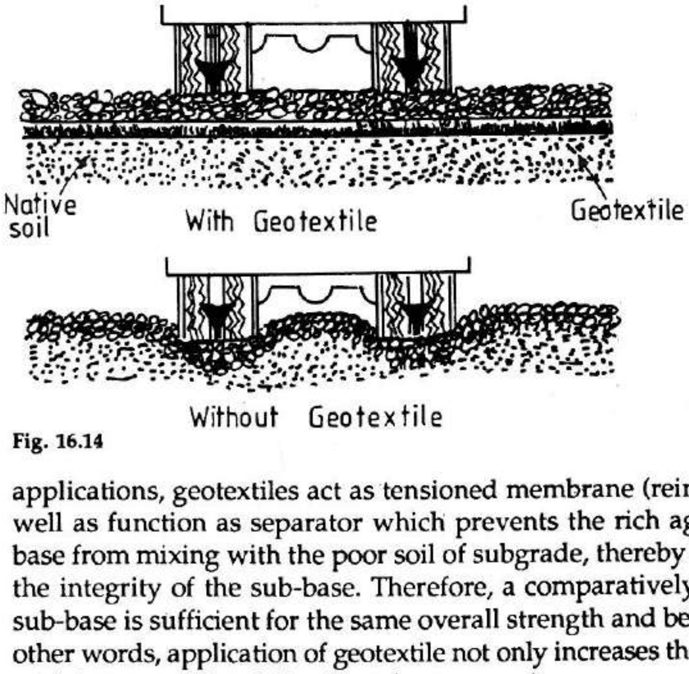


Fig. 16.14

applications, geotextiles act as tensioned membrane (reinforcing element) as well as function as separator which prevents the rich aggregate of the sub-base from mixing with the poor soil of subgrade, thereby helping in retaining the integrity of the sub-base. Therefore, a comparatively lower thickness of sub-base is sufficient for the same overall strength and better performance. In other words, application of geotextile not only increases the life of the structure with better serviceability but also generates an economy equivalent to the cost of sub-base material saved including the labour and transportation cost for the same.

ROAD CONSTRUCTION

One of the most common uses of geotextile has been in the construction and/or rehabilitation of both permanent and temporary roadways. Geotextiles are particularly effective where roads have been constructed over fairly weak subgrade soils. A large percentage of roads in India have been constructed over such soils. Roads of this kind include urban roads within quarries, roads to borrow-pits for transportation of excavated raw material, roads within industrial development area, project roads, forest roads, etc. Table 16.5, shows the list of various instances where geotextiles have been incorporated.

TABLE 16.5 Summary of the Various Projects Carried Out in India Using Geotextiles in Pavements

(a) pavement overlay to prevent reflection cracks	1. Ahmedabad airport main runway, Gujarat
(b) Separator	1. Erumbur-Nellikollai round branching at km 22/8 at Portanava—Vridhachalam road
	2. Command area development of Gujarat and Maharashtra partly funded by World Bank
	3. Tapi command road near Surat, Gujarat
(c) French Drains	1. Harsoan village under Ghaziabad Development Authority, Uttar Pradesh

The Central Road Research Institute, Delhi in collaboration with the Gujarat Engineering Research Institute, Vadodara and the Maharashtra Engineering Research Institute, Nasik have successfully installed geotextiles in high-way construction. In an experimental stretch of 14.0 km on black cotton soil, geotextiles, both imported and indigenously made, have been laid on the subgrade for separation, filtration and drainage function. Both woven and nonwoven geotextiles with the following specifications have been used [21, 22].

Composition	Polypropylene	100%
Thickness		0.3 to 0.7 mm
Tensile strength	Machine direction	9 kN/m
	Cross machine direction	9 kN/m
Elongation-at-break	Machine direction	15%
	Cross machine direction	15%
Area density		120 g/m^2
Width	Imported	5 m to 6 m
	Indigenous	≤ 2 m
Water permeability	50 mm water head	6 to 40 $l/m^2/sec$

RURAL ROAD EDGE DRAINS

During the monsoon months, in general, Indian rural roads become impassable to vehicular traffic due to the failure of the open trench drains. This problem becomes more aggravated due to choking of these drains with the household sewage. To improve the performance of these roads, a field trial sponsored by the Department of Science and Technology, Goverment of India was undertaken by the Indian Institute of Technology, Delhi in collaboration with CARTE, Ghaziabad. Under this project geotextile wrapped French drain have been constructed in a village road near Ghaziabad, U.P. An indigenously made nonwoven geotextile had been used for this project. After one year of construction the performance of the drain is satisfactory and now is under the observation for its long-term filtration and drainage efficiency [23].

PREVENTION OF REFLECTION CRACKING

Formation of cracks on a pavement structure is a natural phenomenon. If preventive measures are neglected in design and/or care is not taken against their formation during construction/repair, they would re-appear even on overlaying. In case treatment is delayed or neglected, their growth takes place phenomenally leading to premature collapse of pavement [24]. These cracks reappear mainly due to the relative vertical and horizontal movements between the original pavement and overlays. Such cracks are often very difficult to prevent because the original source of the cracks is usually beneath the pavement either in the stone base or in the soil subgrade. Available conventional methods for prevention of these cracks are mostly ineffective.

Application of suitable geotextile on the pavement before resurfacing has proved to be an economical method to reduce or even eliminate cracking from occurring (Fig. 16.15).

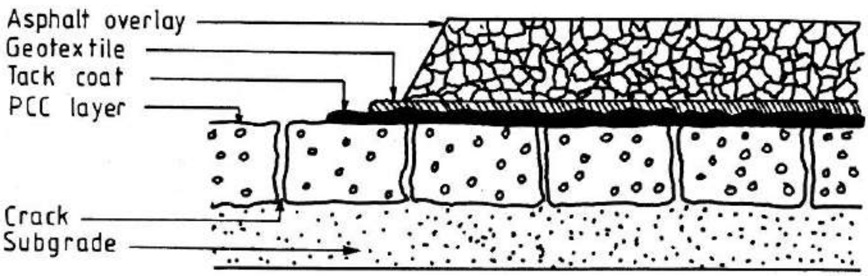


Fig. 16.15 (a)

Fig. 16.15 (b) Application of geotextile in the main runway of the ahmedabad airport for prevention of reflection cracking

In Ahmedabad and Madurai airports, geotextiles have been successfuly used in reducing the cracking of the main runway. Strips of indigenously made needle punched nonwoven geotextile have been placed on existing cracks/joints before flexible overlay. After three years of treatment, it was observed that fine hair line cracks reappeared on the treated surface, whereas the same reappeared on untreated surface only after six months of operation [25].

APPLICATION IN RAILWAYS

Maintenance of proper gauge and level of railway track laid over the weak formation is the key problem facing all railway engineers around the world with increasing truck load and traffic volumes. This in turn causes speed restrictions, train delays, accelerated operating cost and more significantly may also lead to safety hazards.

Due to the dynamic nature of the loading on the railway track the fine soil particles from the subgrade attempt to enter into the voids of stone ballast and thus reduces its drainage capability. On the other hand, the stone ballast attempts to intrude in the soil. This action commonly known as pumping or fouling the ballast reduces the stability of the railway track considerably.

Several techniques are available for tackling this problem. Placement of geotextile between subgrade and ballast as a separator has been used successfully during past 15 to 20 years. Geotextile in rail track may perform the functions of separation, filtration, containment/reinforcement drainage [26].

In India out of 62,000 km (B.G. and M.G.) track, 13,000 km needs renewal [27] and 24,000 km track is installed over weak subgrade formations [28] Indigenously made woven and nonwoven geotextiles have been successfully employed at different experimental stretches on Indian railway tracks. This has helped in lowering track attention in some cases from 50 per year to 5 per year. Moreover, no fabric damage has been observed even after four years of use [29]. Figure 16.16 shows typical application of nonwoven geotextile beneath the railway track.

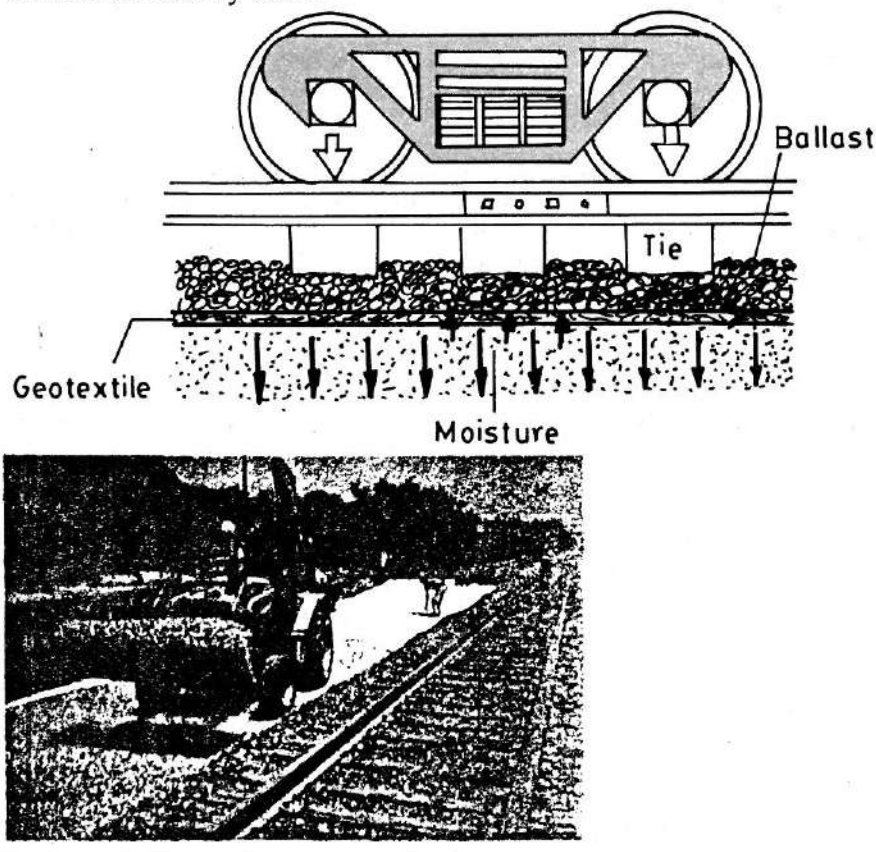


Fig. 16.16 Application of geotextile in railroad stabilization

3.4 Application in Dams

Erosion control of water retaining embankment, i.e. dam is one of the many problems facing the civil engineers. The upstream slope of a dam is continuously exposed to the wave action and fluctuating water level, which can cause erosion. Dumping of stone rip rap over the natural graded filter is the conventional way of slope erosion control. In many cases natural filter materials available near the construction site either do not conform to the required quality or are not available in sufficient quantities. In such situations, instead of transporting suitable natural filter material from a distant place, use of geotextile as filter medium has proved viable both technically as well as economically. Figure 16.17 shows the various possible applications of geotextiles in dams.

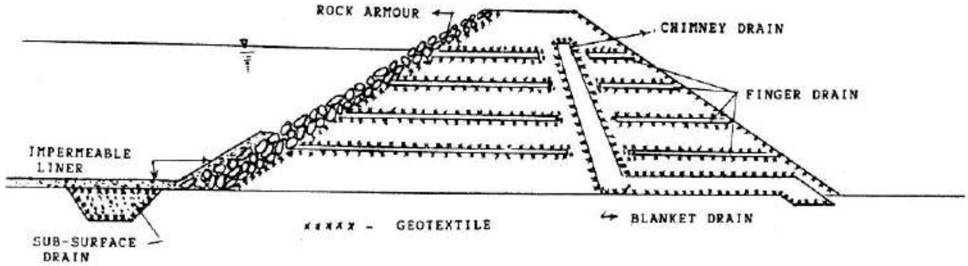


Fig. 16.17 Schematic diagram of different applications of geotextiles in dam construction

In India, there exists a large number of dams of varying age. Besides these, a large number of dams are either in construction or in planning stage. Documented case histories depict that the failure of deterioration of a number of the earthen dams in India is due to inadequate drainage and filtration. In such areas, there exists a wide scope of geotextile applications [30] for slope protection (separation, filtration, drainage), interface filter, internal drain, foundation mattress, etc.

Indigenously made geotextiles have been used in a number of dams for control of erosion and slope protection. Table 16.6 gives the listing of different dams where geotextiles have been used in India.

TABLE 16.6 Summary of the Various Projects Carried Out in India Using Geotextiles as Filter in Earth Fill Dams

1. Medha Creek Dam, Gujarat	Filter layer
2. Hiran Dam–II, Gujarat	Filter layer
3. Ramman Hydroelectricity project, West Bengal	Filter layer
4. Dharoi Earth Dam, Gujarat	Upstream and Downstream Protection
5. Salal Hydroelectric project, Jammu	Filter layer around the relief well

Nonwoven geotextiles suitable for filtration and separation functions have been used successfully for preventing the sinking of the slope of the Hiran dam.

In the Medha creek dam, nonwoven geotextiles have been used for protecting the downstream slope against wave action and fluctuating water level from the sea. This dam is about 513 m long and 8.8 m high.

Indigenously made needle punched nonwoven fabrics used in the above project had the following specifications;

Area density		400 gsm
Thickness	At 4 kPa	2.94 mm
	At 10 kPa	2.58 mm
Strip strength	Machine direction	14 kN/m
	Cross machine direction	16 kN/m
Grab strength	Machine direction	0.9 kN
	Cross machine direction	1.0 kN
Trapezoid tear	Machine direction	0.6 kN
strength	Cross machine direction	0.6 kN
Puncture resistance	Minimum	2.9 kN
EOS	O_{95}	70–80 microns
Water permeability	At 100 mm water head	72 $l/m^2/sec$
Resistance to Chemicals	Excellent	
Biodegradation	Excellent	
UV-light	Good	

In the Dharoi project, geotextiles have been introduced in the downstream of earth dam as a filter between natural soil and loading berm. The performance of the fabric after one year as filter for seepage control system is satisfactory. Although the fabric suffered some loss of strength and elasticity, no sign of fabric rupture was noticed.

Indigenously made needle punched nonwoven fabrics used in the above project had the following specifications.

Type	Nonwoven	
Material	Polypropylene	100%
Thickness		0.61 mm
Area density		179 gsm
EOS	O_{95}	107 microns
Water permeability	At 50 mm water head	27 $l/m^2/sec$
Tensile strength	Machine direction	7.4 kN/m
	Cross machine direction	9.8 kN/m
Elongation-at-break	Machine direction	47%
	Cross machine direction	78%

In the Salal Hydroelectric Project on the river Chenab geotextile filters have been used in place of gannular sand/gravel filter around the perforated polyvinyl pipes in relief wells. The provision of fabric filter has helped in saving costs by way of drilling smaller diameter holes in the rock (Fig. 16.18) [10].

4. DISCUSSION

4.1 Testing, Evaluation and Standardisation

Proper selection of geotextiles for a particular application demands an in–depth knowledge about the geotextile properties relevant to the function,

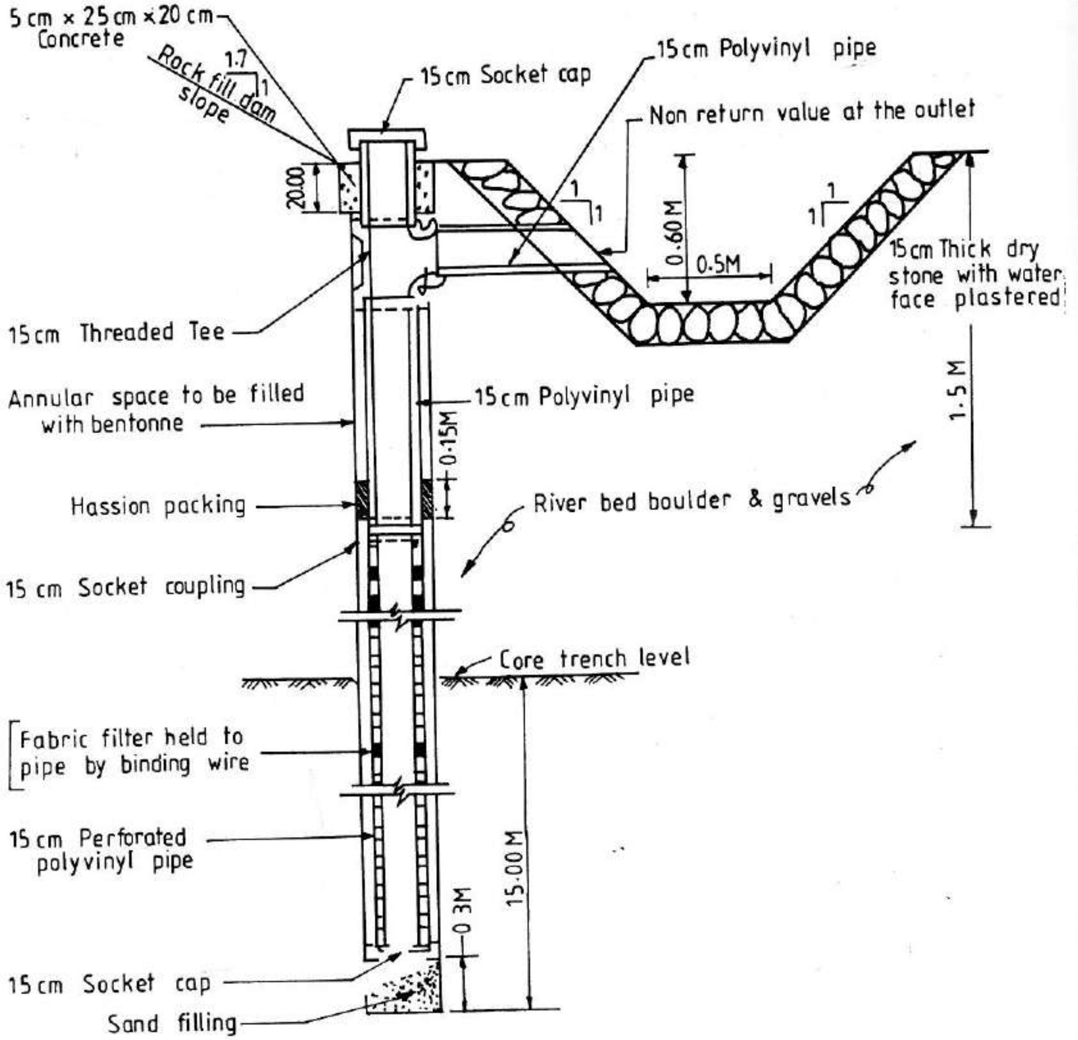


Fig. 16.18

which is only possible if there exists a foolproof testing and evaluation method.

As geotextiles are basically textile materials used in geotechnical applications, except in few instances, the existing testing methods used for general apparel and household textiles cannot directly be used for geotextile evaluation. The properties like strength, thickness, weight, abrasion resistance, etc. are used for quality control and specification purposes of geotextiles and the corresponding tests are termed as index tests. These values can not be used for design purpose. For the purpose of designing, development of new properties relevant to the application functions as well as development of new evaluation techniques of geotextiles in conjunction with geotechnical materials like sand, soil, cement, etc. are called for.

Due to the above reasons alongwith the practical and technical difficulties associated with *in-situ* evaluation, there are as yet no universally accepted test methods. The development of standards for geotextiles has been undertaken in many countries. A first result of this effort is that there is now a general agreement on the types of geotextiles tests that are needed. A list of geotextiles properties and testing methods recommended by Christopher [31] (the chairman of the ASTM Committee D-35 on geotextiles) is reproduced in Table 16.7.

TABLE 16.7 Important Criteria and Principal Properties Required for Geotextile Evaluation (After Christopher 1989)

Criteria	Property	Application			
Design Requirements		Filtration	Drainage	Separation	Reinforcement
Mechanical Strength					
Tensile Strength.	Wide Width Strength	—	—	—	√
Tensile Modulus	Wide Width Modulus	—	—	—	√
Seam Strength	Wide Width	—	—	—	√
Tension Creep	Creep	—	.	—	√
Soil Fabric Friction	Friction Angle	—	—	—	√
Hydraulic					
Flow Capacity	Permeability	√	√	√	√
	Transmissivity	—	√	—	—
Piping Resistance	Apparent Opening Size (AOS)	√	—	√	√
	Porimetry	√	—	—	—
Clogging Resistance	Gradient Ratio	√	. —	—	—
Constructability Requirements					
Tensile Strength	Grab Strength	√	√	√	√
Seam Strength	Grab Strength	√	√	√	—
Bursting Resistance	Mullen Burst	√	√	√	√
Puncture Resistance	Rod Puncture	√	√	√	√
Tear Resistance	Trapezoidal Tear	√	√	√	√
Longevity (Durability)					
Abrasion Resistance ..	Reciprocating Block Abrasion	√	—	—	—
UV Stability ...	UV Resistance	√	—	—	√
Soil Compatibility	Chemical	√	√	?	√
	Biological	√	√	?	√
	Wet–Dry	√	√	—	—
	Freeze Thaw	√	√	—	—

. Compression Creep
. . Erosion control applications where armour stone may move
. . . Exposed fabrics only
. . . . Where required.

In India also work has been initiated in this direction by relevant organisations. The Bureau of Indian Standards (BIS) has taken up this matter on priority basis and set up committees/sub-committees in both Textile Division Council and Building Division Council in order to develop test methods and specifications for use of geotextiles in India (32).BIS, in close liason with different research organisations, has already completed the standardisation work on a number of subjects related to geotextiles. List of upto date Indian standards is given in Table 16.8 [33].

TABLE 16.8 List of Current Indian Standards

IS (CED52)
Glossary of terms for geosynthetics (In print)
IS (CED52)
Method of test for evaluation of interface friction between geosynthetic and soil by the modified direct shear method. (In print)
IS CED52
Test method for determination of tensile properties of extended polymer grids using wide strip method. (In print)
IS 13162 (Part 2)-91
Geotextiles—Methods of test Part 2
Determination of resistance to the exposure of ultraviolet light and water. (Xenon-Arc type apparatus)
IS 13162 (Part 5)-91
Geotextiles—Methods of test Part 5
Determination of tensile properties using a wide width strip.
(TXD 29–1991)
IS TXD 29
Geotextiles—Methods of test Part 6
Determination of seam strength. (Finalised)
IS 1963–81
Methods for determination of threads per unit length of woven fabrics.
IS 1964–70
Methods for determination of weight per square metre and per linear metre of fabrics.
IS 1969–85
Methods for determination of breaking load and elongation of woven textile fabrics.
IS 1969–85
Cut Strip tensile test.
IS 11056–84
Methods for determination of air permeability of fabrics.
IS 6359–71
Method of conditioning of geotextiles.

4.2 Testing Equipment

Acting in this direction a number of testing equipments have been either newly designed according to the requirement or modified for geotextile evaluation by various research organisations and institutions. At present, at least one company is indigenously manufacturing and marketing these specified equipments in India. As of today, no test house is equipped with the complete facilities for geotextile testing. During the last few years different institutions and research organisations have developed facilities for testing geotextiles and related products. Presently some of them have very good testing facilities where almost all the index tests of geotextiles are possible.

4.3 Cost

Today the estimated worldwide consumption of geotextiles is over 1000 million sq m per annum. In contrast, the cumulative Indian consumption of geosynthetics made in India for civil engineering application appears to be only around 0.5 million sq m [34]. It is felt that relatively high cost of geosynthetics is a major limiting factor for the growth of geotextiles in India. In the world market, geotextiles of various types are available at a cost ranging from 0.1 to 20 dollar per sq m whereas in India even the thin to medium type of geotextiles cost from Rs 50 to Rs 100 per sq m and sometimes even more [35]. The basic reasons of the exorbitant cost of Indian geosynthetics are:

(i) Excessive high price of local raw material in comparison to global price.
(ii) High rate of duties lavied at various stages of manufacturing.
(iii) Uneconomic scale of production (due to lack of demand).
(iv) Lack of modernisation of the production unit.
(v) High overhead cost.
(vi) Insignificant R&D effort.

5. CONCLUSIONS

Experience of use of geotextiles in India has demonstrated that it has extensive application potential in various geotechnical engineering works. They could be successfully used in new projects and also in repair works. They are also capable of providing instant solution under distress situations.

Besides the projects detailed in this paper several other experimental projects of diverse nature, employing geotextiles made from both natural and synthetic fibres, have been either successfully executed or are under progress.

The cost of geotextiles in India is a limiting factor for its speedy growth. This situation calls for long term government policy so that geotextiles at reasonable cost could be available for applications in civil engineering works.

Natural fibres are available in abundance in India and they are relatively cheap. There are many applications where the required life span of the geotextile is short. In such cases, geotextiles made from natural fibre could be used as cost effective solution.

Indigenously made geotextiles have a very narrow range and they lack in diversity. Proper attention is needed in R&D effort for improvement of the production quality as well as product diversity.

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17

Development and Evaluation of a Nonwoven Based Geocomposite Canal Liner

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A geocomposite of LDPE/HDPE tape woven fabric with needle punched nonwoven on one or both sides has been developed at the Bombay Textile Research Association (BTRA). This geocomposite has a higher puncture resistance, better friction to sand and superior bond strength to cement mortar than LDPE film. The material is stable at high temperature of upto 50°C under alkaline conditions.

Outdoor laboratory tests and semi-field tests on the project site at Indira Gandhi Nahar Project (IGNP), Bikaner, has revealed that, when the liner is subjected to acceleration subgrade settlement and cracking tests, LDPE film shows microcracks and holes whereas the geocomposite does not exhibit any such defects. The post damage seepage losses in the pond tests were appreciably lower with geocomposite as compared to LDPE film. The geocomposite was also found to be cheaper as compared to imported materials for similar use.

1. INTRODUCTION

Seepage losses in the canals and their distributaries represent a major source of wastage of the water used in irrigation in the country. Seepage losses of the order of 45–60% of the carrying capacity of canals is reported in India [1]. It is estimated that lining of all existing unlined canals in India could save enough water to irrigate an additional 6 million hectares [2]. To prevent seepage losses Low Density Polyethylene (LDPE) membranes have so far been used as canal liners in India.

However, LDPE films when used as a canal liner on slopes of canals and when covered by concrete pose the problem of slippage, due to smooth surface of LDPE film and its low adherence and bonding to the cover material. Friction angles of the order of 18° for LDPE and 22° for PVC are reported [3]. Steep slopes of canals cannot be stable if the cover is placed directly on the film. In addition, LDPE is prone to develop holes and cracks during laying and usage due to its poor puncture resistance, which again leads to seepage losses.

Experience with the fine sands of Indira Gandhi Nahar Project (IGNP) in Rajasthan shows that the conventional plain LDPE film lining has a very low puncturing resistance in addition to inadequate friction and bond strength [4]. Hence the Central Board of Irrigation and Power (CBIP) suggests that the slope should not be steeper than 1.5 : 1.0 (Horizontal : Vertical) [5] and the International Commission on Irrigation and Drainage suggest a cushion layer of 75–150 mm thick sand or a nonwoven geotextile matting on the membrane to protect it from puncture [6].

Further, geotextiles when bonded to geomembranes are very effective in improving puncture resistance [7, 8] and bond strength to concrete [9]. Geotextiles when used in conjunction with a geomembrance such as LDPE is known as a geocomposite. The geomembrane acts as an impermeable barrier and the geotextile ensures its mechanical protection. Use of such a geocomposite where geotextile complements the properties of geomembrane is a relatively new phenomenon. Imported composite liners of this type are found to be very expensive and are therefore not being mush used in India. Though the concept of such a geocomposite exists in the literature, no attempts have been reported about the use of such geocomposites and advan tages gained by the same in India. LDPE continues to be the most widely used membrane for canal liners in India and this has been suffering from many drawbacks mentioned above. It is necessary that experience needs to be gained in the manufacture and application of indigenous geocomposite as substitute to LDPE and carry out critical comparisons of the same. The present work attempts to do the same. Hence the objective of this work is to develop an indigenous geocomposite that overcomes the abovementioned drawbacks of LDPE film and further, is economical in relation to the imported ones.

2. DEVELOPMENT OF A GEOCOMPOSITE CANAL LINER

Keeping in view these objectives, the design considerations involved a combination of a suitable geomembrane and a geotextile to form a geocomposite canal liner. LDPE is already in use as a canal liner and is relatively cheaper than other materials; it has excellent durability and biological resistance. Hence it was retained as a geomembrane.

For the geotextile part, the fibre could be polyester or polypropylene. However, the poor alkali resistance of polyester leaves the field open to polypropylene, as river beds in many of the canals in India are alkaline. Hence three different types of geocomposites made of LDPE/HDPE/polypropylene needle punched nonwoven fabric were developed; two samples with nonwoven on one side and the third with nonwoven on both sides with the impervious membrane, i.e. LDPE/HDPE tape woven material combination sandwiched between them. These materials were bonded together by extrusion coating. After some preliminary experiments, the materials were produced on bulk scale for evaluation. The following are the sample details:

Sample 1:	Nonwoven	80 g/m^2
	HDPE Tape	90 g/m^2
	LDPE	80 g/m^2
Sample 2:	Nonwoven	80 g/m^2 on each side
	HDPE Tape	90 g/m^2
	LDPE	80 g/m^2
Sample 3:	Nonwoven	230 g/m^2
	HDPE Tape	90 g/m^2
	LDPE	100 g/m^2

3. TEST METHODS

The geocomposite canal liners were tested for various properties keeping in mind their end-use requirement. These properties were compared with the properties of LDPE film and also a composite of LDPE and HDPE tape woven material. Breaking strength was tested on a Zwick tensile testing instrument on strips of 20 cm × 5 cm. Heat ageing was done by keeping the specimen in an oven at 50°C for 7 days. Exposure to sodium hydroxide at a pH of 10 for 7 days was carried out for assessing the alkali resistance of the canal liners. The treated strips were later washed, dried and conditioned in the laboratory prior to testing the breaking strength to assess the loss in strength to heat ageing and alkali exposure.

A cone drop testing equipment was fabricated to simulate the kind of damage that may occur to the canal liners during their installation due to sharp stones or other construction material falling on them. The instrument consists of a rod with a cone of 45° totally weighing one kg, falling on the geocomposite material vertically from a height of 50 cm. The diameter of the hole formed as a result of the fall of the cone is an indication of the susceptibility of the material for damage. This test was later extended for 60° cone, and a cone with flat edge in place of sharp edge. Three different testing heights 40, 50 and 55 cm were used for each cone. Puncture test was carried out by another method on a horizontal strength tester where a plunger with a 60° cone traverses at a rate of 100 mm/min and the force required to penetrate the specimen was measured.

In another type of puncture test, the specimen of 15 cm diameter was sandwiched between two layers of stones and the assembly was subjected to horizontal and vertical vibrations for four hours. Afterwards, the specimen was tested for water impermeability in a hydrostatic pressure head tester. Specimens which develop cracks during the test are expected to be inferior and are likely to develop cracks during usage also.

Shear stress of the material to sand was measured in a direct shear Box of 6 cm^2 test area. Normal stresses between 0.7 and 2.9 kg/cm^2 were used; the rate of shear was maintained at 0.25 mm/min. Peak shear stress against normal stress was plotted and the angle of the straight line graph with x-axis was measured and is known as friction angle. The bond strength between the liner and cement mortar was measured by a peeling method. The width of the specimen under the clamp was 2.5 cm and the test was done on a tensile strength tester and the peak strength was noted. A mixture of 50/50 sand/

cement was laid on the liner and watered for two days and dried before testing for bond strength. Thickness was tested on a Hungarian thickness tester used for testing textiles, under a load of 35 g/cm^2. Bursting strength was tested on a hydraulic type of diaphragm bursting strength used for testing of textiles.

4. TEST RESULTS AND DISCUSSION

4.1 Physical Properties

Physical properties of the three types of Bombay Textile Research Association (BTRA) geocomposites, LDPE film and also a composite of LDPE film/HDPE woven tape are given in Table 17.1. It is clear that the geocomposites are superior in physical properties to LDPE film. The combination of LDPE/HDPE also shows a

TABLE 17.1 Comparison of Physical Properties of Geocomposites with Conventional LDPE Film and LDPE Film/HDPE Woven Tape

Property	Sample 1 One Side Nonwoven	Sample 2 Double Side Nonwoven	Sample 3 Thick Nonwoven on One Side	LDPE Film/ HDPE Tape	LDPE Film
Weight (g/m^2)	250	331	416	190	140
Thickness (mm) (at 35 g/m^2 load)	0.9	1.44	1.87	0.4	0.19
Tensile Strength (N) (Elongation %)	794 (20.6)	817 (16.0)	814 @(10.0) 416 * (65.0)	914 (17.9)	113 (414)
Tensile Strength (N) (Elongation %) after heat ageing 50^b C/7 days	784 (21.3)	804 (18.3)	784 @(15.0) 374 *(75.0)	902 (19.4)	106
Tensile Strength (Elongation %) (N) after exposure to pH = 10 for 7 days	853 (20.7)	784 (16.8)	828 (10.0) 432 (70.0)	840 (22.9)	119
Tear Strength (N)	187	156	200	245	32

@—First break *—Second Break

marked improvement over the LDPE film with regard to the physical properties. The tensile properties of the geocomposite made out of LDPE/HDPE nonwoven fabric (Samples 1, 2 and 3) are broadly comparable with that of LDPE/HDPE combination though a marginal reduction in strength is seen which may be because bonding of LDPE/HDPE to nonwoven is done at high temperature. Figures 17.2 to 17.5 show stress-strain behaviour of the various geocomposites. Figure 17.1 shows the stress-strain behaviour for the nonwoven material used for the geocomposite. Nonwoven with 80 g/m^2 was used for samples 1 and 2 and a heavier nonwoven of 230 g/m^2 was used for sample 3. Figure 17.2 shows the stress-strain relation of samples 1 and 2 as also a LDPE/HDPE woven tape,

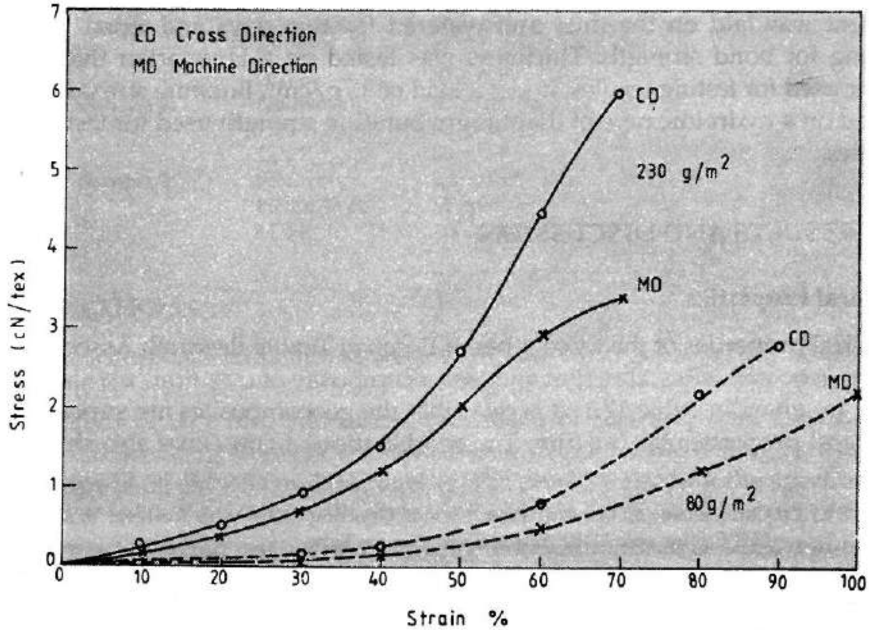

Fig. 17.1 Stress-strain behaviour of nonwovens used for the geocomposites

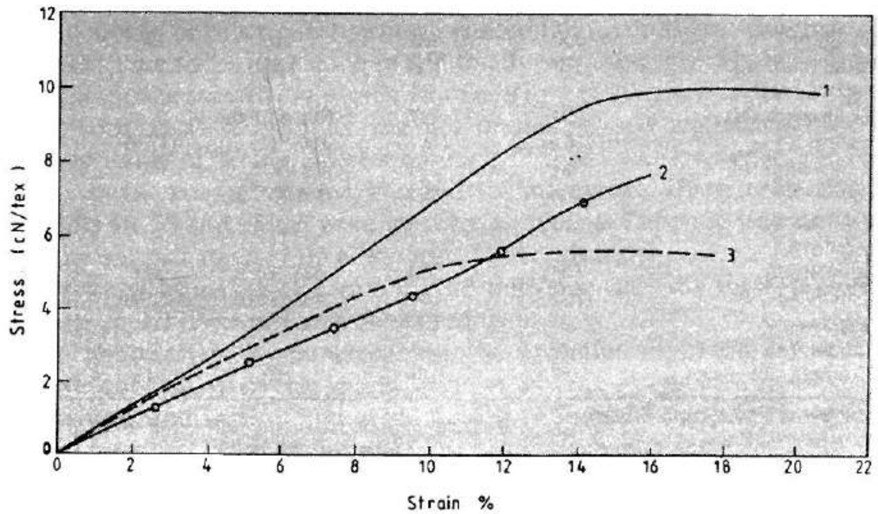

Fig. 17.2 Stress-strain behaviour of geocomposites
1. Geocomposite with only one side nonwoven (sample 1)
2. Geocomposite with both sides nonwoven (sample 2)
3. LDPE/HDPE combination

composite. Specific stress was calculated as suggested by Hearle [10] and expressed as cN/tex. It is clear that the geocomposites with nonwovens show a higher elongation in the initial region of stress-strain curve with adequate modulus than the LDPE/HDPE composite. Figures 17.3 and 17.4 show the

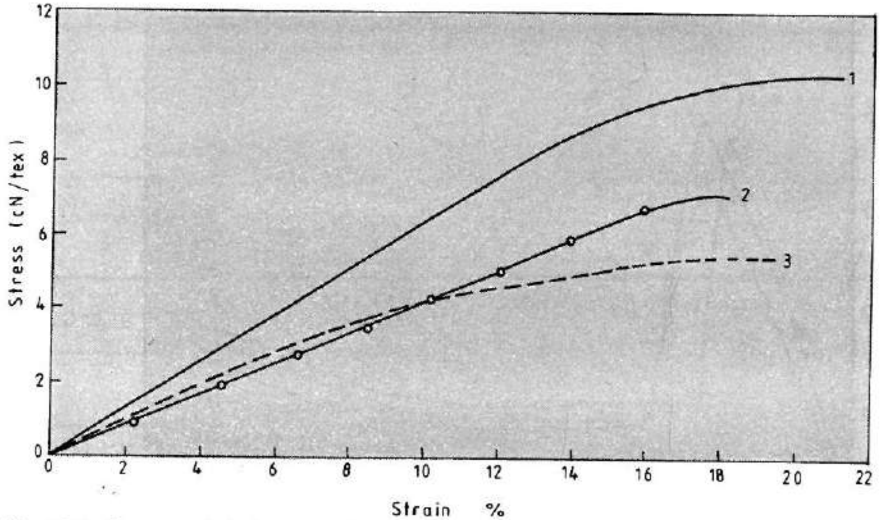

Fig. 17.3 Stress-strain behaviour of geocomposites after heat ageing
1. Geocomposite with only one side nonwoven (sample 1)
2. Geocomposite with both sides nonwoven (sample 2)
3. LDPE/HDPE combination

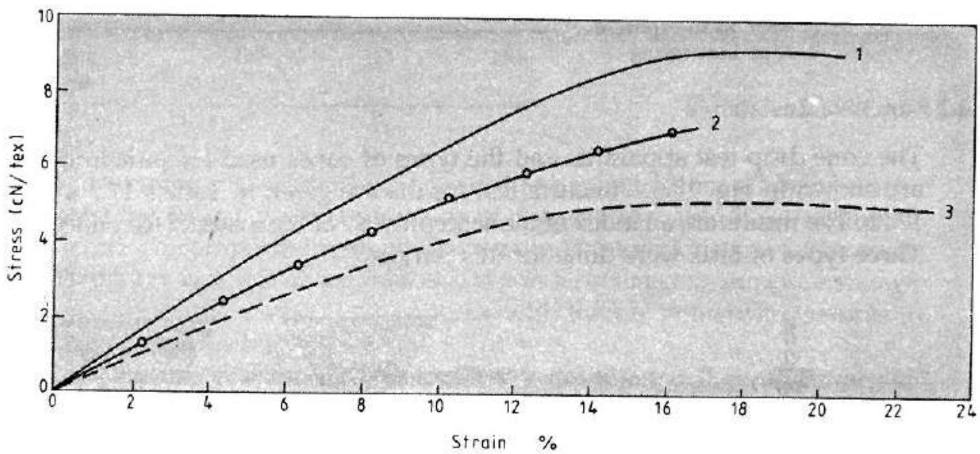

Fig. 17.4 Stress-strain behaviour of geocomposites after exposure to alkaline conditions
1. Geocomposite with only one side nonwoven (sample 1)
2. Geocomposite with both sides nonwoven (sample 2)
3. LDPE/HDPE combination

behaviour of these samples after heat ageing and exposure to alkaline conditions. Figure 17.5 shows the curve for sample 3 with heavier nonwoven on one side. It is clear that the geocomposites remain largely unaffected under these conditions. Further, the sample 1 was subjected to accelerated subgrade settlement and after this test the sample showed a breaking strength of 772 N as against 794 N before being subjected to the test, indicating almost no loss in strength.

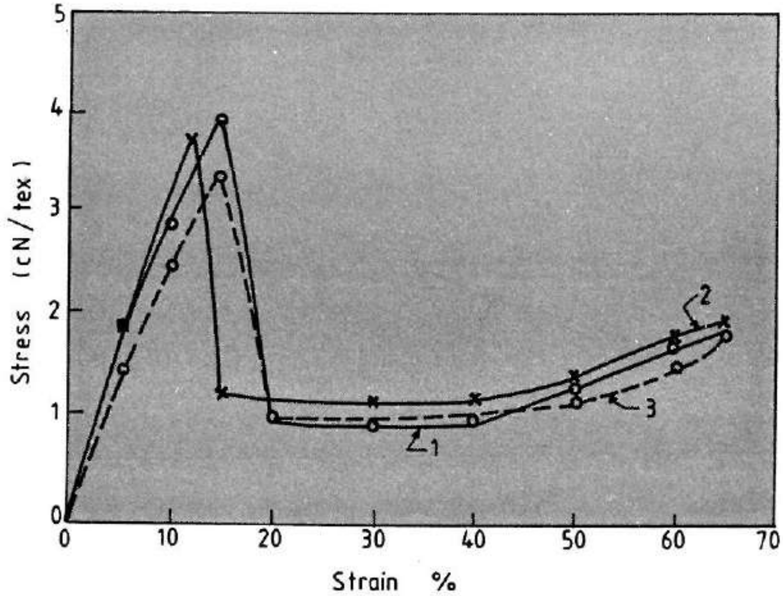

Fig. 17.5 Stress-strain behaviour of sample 3
1. Geocomposite with thicker nonwoven
2. After alkali exposure
3. After heat ageing

4.2 Puncture Resistance

The cone drop test apparatus and the types of cones used for puncture test are shown in Fig. 17.6. Puncture test results are given in Tables 17.2 a and 17.2b. The results are an index of the susceptibility of the material for puncture. Three types of tests were done for this purpose.

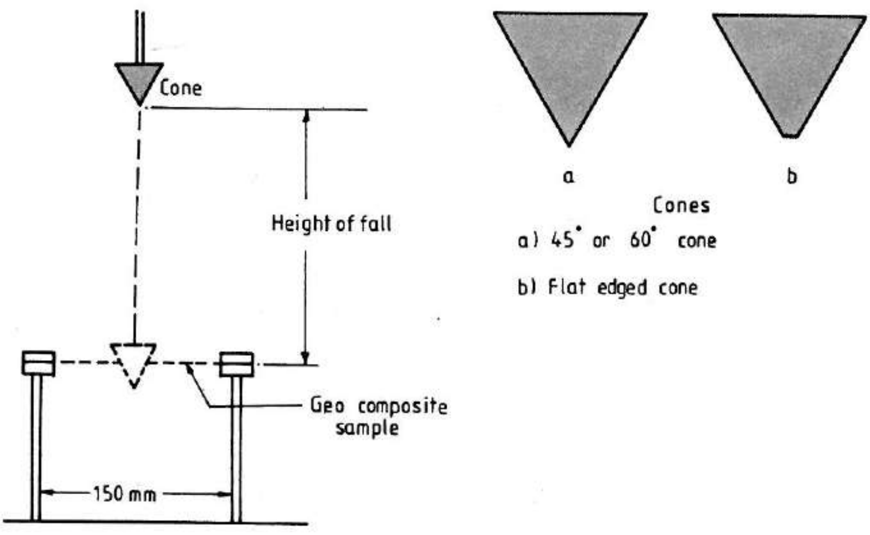

Fig. 17.6 Cone drop test apparatus and cones used in cone puncture test

TABLE 17.2A Comparison of Puncture Resistance of Geocomposites with LDPE/ HDPE Tape Material (Diameter of Hole in cms in Cone Drop Test)

Height cm Cone age	Sample 1			Sample 2			Sample 3			LDPE/HDPE Tape woven		
	45°	60°	F	45°	60°	F	45°	60°	F	45°	60°	F
40	2.0	2.0	1.2	1.8	1.7	1.8	1.4	1.4	0.6	2.1	1.9	1.4
50	2.3	2.2	1.9	2.9	2.7	2.3	1.8	1,8	1.1	2.0	2.2	2.0
55	2.6	2.4	2.0	3.2	3.0	2.5	2.1	2.1	1.3	2.6	2.4	2.6

TABLE 17.2B Cone Bursting Strength (N)

	Sample 1	Sample 2	Sample 3	LDPE/HDPE Tape Woven	LDPE Film
60° Cone moving at 100 mm/min	363	323	392	382	36

TABLE 17.2C Diaphragm Bursting Strength (N/cm²)

	Sample 1	Sample 2	Sample 3
Bursting Strength	240	210	260

(A) CONE DROP TEST

LDPE film could not be tested for cone drop test since it tore off being unable to resist the falling cone. The cone drop test results (Table 17.2a) show that while the geocomposites with nonwoven are far superior to LDPE film alone, the LDPE/HDPE tape woven material also shows a similar cone puncture strength as geocomposites, except the composite with thicker nonwoven (sample 3). The latter shows a higher puncture resistance.

The puncture resistance of the material is not much different between 45° and 60° cone but superior puncture resistance is found in the case of cone with flat edge which is understandable. The superiority of sample 3 over the LDPE/HDPE composite is more with flat edge cone.

(B) CONE BURSTING STRENGTH

The cone bursting strength tested on a horizontal tensile tester with a 60° cone shows similar trend for the various samples (Table 17.2b). Geocompo site with nonwoven as also the LDPE/HDPE liner have a much higher cone bursting strength than LDPE. The composite liner made with a thicker nonwoven on one side (Samples 3) has given the highest cone bursting strength. Figure 17.7 shows the force-extension curves for the cone puncture strength. This again indicates the superior performance of geocomposites made with nonwoven, vis-a-vis LDPE cone bursting strength of geocomposite is, however, comparable to LDPE/HDPE tape woven material.

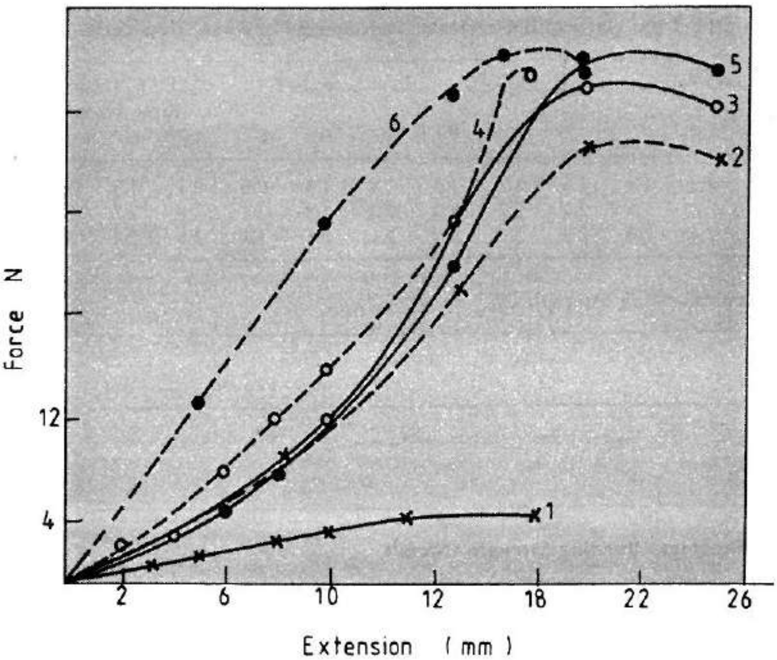

Fig. 17.7 Load extension behaviour of geocomposites in cone bursting test

1. LDPE film
2. Sample 2
3. Coated side—sample 1
4. Nonwoven side—sample 1
5. LDPE/HDPE
6. Sample 3

(c) Diaphragm Bursting Strength

The three samples of the geocomposite liners were tested for bursting strength. The results are given in Table 17.2c. Diaphragm bursting strength is also highest with sample 3.

(d) Accelerated Puncture Test

As mentioned earlier, the ability of the canal liner to withstand damage during use was assessed by simulated test where the specimen was sandwiched between two layers of stones and subjected to vibrations, for four hours. Afterwards, the water impermeability of the canal liner was tested in a hydrostatic pressure head tester. The LDPE membrane showed holes when subjected to this test and water passage was found even at 9 cm of water column pressure whereas the geocomposites sample 1 withstood water pressure of up to 54 cm. Samples 2 and 3 did not allow any passage of water even at 90 cm of water column. This shows that use of nonwoven on one or both sides efficiently protects the liner from damage when it is subjected to such stresses by small stones during use.

4.3 Shear Stress and Friction

Another type of load that acts on the canal liner is the one acting along the plane of the liner, i.e. shear forces. A smooth surface of liner results in a low frictional force and causes the cover material to slip or slough off. Further, laying of the canal liner on the slope will be facilitated if it has high frictional resistance with the soil. The shear test results show that the nonwoven shows a higher friction angle against sand of 38° (tan $\theta = 0.78$) as against a friction angle of 30° (tan $\theta = 0.6$) found with HDPE woven tape surface of LDPE/HDPE composite. Use of a nonwoven on one side of the canal liner improves the frictional resistance to soil of that side.

4.4 Bond Strength

Studies on bond strength of liner with cement mortar revealed that the LDPE film or its combination with HDPE has a poor bond strength with cement mortar. Bonding was so poor that the testing of the bond strength to the film of cement mortar could not be done. The poor bond strength causes micro hollowness between the cover and liner reducing the coherence and strength of the system. This is in contrast to the excellent bond strength with cement of the nonwoven surface of the canal liner. The force required to separate by peeling the cement layer from nonwoven surface of the composite canal liner was found to be 22 kg/2.5 cm width. The bond strength of the geotextile component of the composite canal liner is a measure of the interface strength between the geotextiles and cement mortar. Significant bond strength is developed between the two surfaces due to inter-locking between the fibrous layers of nonwoven and cement granules.

4.5 Comparison between the Three Types of Geocomposites

Among the three types of geocomposites, samples 1 and 3 have nonwoven material on one side whereas the sample 2 has nonwoven on both sides. In view of the higher frictional coefficient shown by the nonwoven surface, sample 2 with nonwoven on both surfaces would be ideal where liner slippage problem is also encountered along with the cover material slippage.

Sample 3 with a thick nonwoven is superior to the other two samples in terms of puncture resistance. The thick nonwoven layer acts as a protective mattress and prevents any mechanical damage to the membrane, in addition to providing better friction and adhesion with cement mortar. The cost of sample 3 is likely to be higher because of the heavier nonwoven used in making it. But this liner is expected to perform better under more adverse conditions where changes of damage to liner are high.

5. SEMI FIELD TRIALS CONDUCTED BY INDIRA GANDHI NAHAR PROJECT (IGNP), BIKANER [11]

Confirmation of the superior properties of geocomposite (sample 1) over LDPE is also reported by IGNP who conducted the model tests. Accelerated subgrade settlement and liner cracking tests were done by manually shattering with a heavy wooden or rubber hammer on the liners in the model tests so as to simulate long term settlement cracks. These results showed microcracks and holes in LDPE film of tile/film system but geocomposite developed at Bombay Textile Research Association (BTRA) did not develop any microholes and cracks. Friction and bond strengths of LDPE were very low as indicated by the ease with which the mortar could be separated and removed from the film. In case of the geocomposite, friction and bond strengths were much improved and were comparable to those of an imported composite. The bond strength was high and adhesion of mortar was intimate and stiff. The liner sample [1] was subjected to seepage tests after the accelerated subgrade settlement. The post damage seepage tests reveal a seepage loss of 0.36 $m^3/mm^2/sec$ with geocomposite liner system as against 1.26 $m^3/mm^2/sec$ with LDPE lining which indicates significant reduction in seepage loss with BTRA geocomposite.

BTRA developed geocomposite canal liner which helps to overcome many of the problems encountered with conventionally used LDPE film liner and is at the same time much cheaper than imported geocomposites while performing equally well in comparison to the latter.

6. COST STRUCTURE OF BTRA GEOCOMPOSITE VIS-A-VIS IMPORTED ONES

The cost structure per square metre for the geocomposite developed by BTRA is as follows:

Component	Rs/m^2 of the Product
LDPE	4.16
HDPE	6.30
Nonwoven	40.00
Conversion cost	5.00
Total	55.46

Hence the total cost of the product is expected to be in the region of Rs 56/m^2. This is cheaper than imported products such as butyl rubber, Hypolan or EPDM coated liners which are around Rs 170–180/sq. in.

7. CONCLUSIONS

(i) The conventionally used LDPE film as a canal liner has many drawbacks like poor puncture resistance, low friction and bond strength and susceptibility to develop microholes during installation as well as use.

(ii) LDPE when reinforced with HDPE woven tape shows better puncture resistance but is inferior in friction and bond strength to the composite with nonwoven on the outerside and is therefore likely to have some of the drawbacks of LDPE film as canal liner.

(iii) A composite made out of LDPE/HDPE woven tape and nonwoven fabric overcomes the above drawbacks and has better friction to soil and excellent bond strength to cement mortar. It is also less susceptible to develop holes and cracks during use as shown by the accelerated tests at BTRA and also at the site. The composite is not affected by heat ageing and alkaline conditions. It can be a successful and economic replacement for imported materials in seepage prevention.

(iv) Among the three composites developed, the one with a thicker nonwoven showed superior puncture resistance and is less susceptible to damage during use. This should be preferred under more severe conditions of usage.

8. ACKNOWLEDGEMENTS

The authors express their gratitude to the Central Water Commission and IGNP Bikaner for the financial support in carrying out this work. Thanks are due to Sri B.D. Bithu, Superintending Engineer, IGNP, for his active interest in the work and for conducting semifield trials. Thanks are also due Mr. K.R. Datye, consulting engineer, Bombay for useful discussions. The authors are also thankful to Dr. S.M. Betrabet, Director BTRA for his encouragement and interest in this work.

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Geotechnical Properties of Certain Nonwoven Needle Punched Jute Fabrics

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Nonwoven needle punched jute fabrics have been prepared for temporary unpaved road application weighing 350 and 450 g/m^2 with three needle penetration depths viz. 10, 12, 14 mm. These fabrics have been further treated with copper naphthanate, copper chromium arsenic (CCA) and acrylic binders and their properties and performances are compared. Geotechnical properties e.g., tensile, thickness, bursting, puncture, California Bearing Ratio (CBR), water permeability, pore size distribution have been tested for treated as well as untreated fabrics. Untreated jute fabrics function dominantly as separation and filtration media rather than reinforcement which is predominant in case of treated fabrics. Design chart have been developed to determine the aggregate thickness for geotextile reinforced unpaved roads using the above mentioned fabrics based on Giroud and Noiray [9] procedure.

1. INTRODUCTION

Geotextiles have found wide acceptance in the construction industry [1] all over the world in a comparatively short period of time because they facilitate simplified construction under adverse conditions, save time, their properties are more reliable than that of soil and are cost effective. Synthetic fibres, e.g. polypropylene, polyester, etc. are commonly used in geotextile applications, as they are resistant to biodegradation. In India the growth of geotextiles has been slow mainly because of high cost of synthetic fibres. Here jute is cheap and available in abundance but its biodegradability restricts its use as geotextile. Nevertheless, there are certain applications which are temporary and non-critical where jute can be used, e.g. for erosion control and construction of unpaved road [2]. The present work envisages the possibility of using jute for such applications.

2. EXPERIMENTAL

Jute sliver (TD4 variety) with 0.2% oil content was used to prepare the samples. The properties of jute fibres are as follows:

Denier	33.5
Tenacity (g/d)	3.3
Extn. at break (%)	3.5
Specific gravity	1.52
Fibre length (mm)	200–700
Fibre dia (μm)	40

The non-woven samples of 350 and 450 g/sq.m each with three types of needle penetration, viz. 10, 12 and 14 mm were prepared. Punches of 100 per sq. cm were kept constant. Samples were made on a nonwoven needle punching machine comprising of Cosmatex card, Asselin cross-lapper and Asselin needle punching machine. Machine parameters were as follows:

Doffer speed	20 m/min
Cross-lapper speed	20.2 m/min
Floor Apron speed	0.99 m/min for 350 g/m^2
	0.77 m/min for 450 g/m^2
Strokes/min	170

Acrylic binder was applied to improve the strength of the fabric whereas to make the jute resistant against microbial attack to a certain extent, antimicrobial agents were used. Binder with antimicrobial agent was mixed and applied to the samples. In the first case acrylic binder A and copper naphthanate (8% suspension) were mixed in the ratio of 15 : 2 by vigorous stirring, then the nonwoven samples were passed through the solution and squeezed in a padding mangle. Subsequently, the samples were dried and cured at 125°C for 5 min. In the second case acrylic binder B and copper chromium arsenic (i.e. CCA) as antimicrobial agent were used in the ratio of 10 : 1. They were treated in the same manner as that of first one.

The following sample codes were used to indicate the type of treated and untreated jute samples throughout the paper:

UJij	Untreated jute
PCNij	Acrylic binder A + Copper naphthanate treated jute
HCCAij	Acrylic binder B + Copper chromium arsenic treated jute
	Here, i = 1, 2 (350,450 g/sq.m. weight of the fabric.)
	j = 1, 2, 3 (10,12,14 mm needle penetration)
NDP	Needle penetration depth
MD	Machine direction
CD	Cross direction

3. RESULTS AND DISCUSSION

The basic physical properties of the treated and untreated fabrics are given in Table 18.1: From Table 18.1, it is observed that with acrylic binder A, the add on is about 30% as compared to acrylic binder B because of higher concentration of the solution. The results indicate that thickness of the fabric is reduced by about 5–6% for 350 g fabric and 8–9 %for 450 g fabric due to pressure applied during squeezing. Certain essential geotechnical properties of nonwoven jute fabrics are given in Tables 18.2, 18.3, and 18.4. Table 18.2 clearly shows that breaking strength of the untreated jute fabric is very low. The strength of the treated jute fabrics increases by about 5–7 times as

TABLE 18.1 Linear Density and Thickness

Variety	g/sq.m	Add-on (%)	Thickness (mm)
UJ 1	350.93	—	3.05
UJ 2	450.68	—	3.21
PCN1	455.50	29.80	2.85
PCN2	585.25	29.98	2.92
HCCA1	437.25	24.59	2.90
HCCA 2	562.50	24.81	2.95

TABLE 18.2 Mechanical Properties of Fabrics

Variety	Breaking Load (kN/m)		Breaking Elongation (%)		Sec. Modulus at 10% Strain (kN/m)		Bursting Strength (kN/m²)
	MD	CD	MD	CD	MD	CD	
UJ11	0.82	1.62	48.5	42.7	4.25	9.2	245.0
UJ12	0.95	1.75	45.7	41.7	4.50	10.1	225.4
UJ13	0.72	1.07	44.9	52.7	3.92	10.1	205.8
UJ21	2.04	3.82	49.5	45.5	7.62	20.6	274.4
UJ22	2.01	3.51	50.2	47.9	8.97	21.7	254.8
UJ23	1.92	3.25	51.2	46.9	6.25	19.8	250.7
PCN11	4.56	8.56	60.7	56.2	20.72	40.7	313.6
PCN12	4.25	8.32	62.7	57.9	19.67	38.5	303.8
PCN13	4.02	8.12	52.6	52.9	23.79	42.9	300.0
PCN21	12.55	20.15	67.2	52.9	50.15	90.9	343.8
PCN22	11.67	19.26	67.5	55.5	62.75	79.6	335.6
PCN23	10.85	19.85	57.8	56.2	59.20	89.7	330.5
HCCA11	8.65	16.24	42.2	41.1	40.52	100.2	340.8
HCCA12	8.25	12.93	38.9	42.0	47.29	107.9	340.2
HCCA13	8.14	13.63	36.6	47.0	48.20	96.2	335.2
HCCA21	14.50	22.67	47.6	33.7	70.76	112.7	354.2
HCCA22	14.02	21.72	32.7	36.2	72.19	107.3	346.2
HCCA23	14.01	22.13	36.9	32.7	82.60	100.7	332.9

compared to untreated samples. It has also been observed, the breaking strengths of the fabrics treated with acrylic binder B are higher, especially for 350 g/sq.m fabric whereas elongation-at-break are lower as compared to acrylic binder A. Results also indicate that there is a tendency for breaking load to reduce as the NDP increases but they are not statistically significant. Hearle [3] observed that the effect of NDP are complicated because of the interaction of number of barbs, needling density and web weight. Results also show that the breaking load in cross direction is always higher than the machine direction. This is expected as the orientation of fibres are mostly in cross direction because of use of cross-lapper.

Secant modulus at 10% strain has been presented in Table 18.2. Here also the decreasing trend observed with higher NDP which is similar to the breaking load and specially it is true in case of cross direction.

The results shown in Table 18.2 reveal that treated jute samples give 30–35% higher bursting strength as compared to untreated samples because

TABLE 18.3 Permeability and Constructability of Fabrics

Variety	Cone Drop Test hole dia (mm)	Water Permeability (lit/m²/sec)	Pore Size (microns)	CBR Push through Test	
				Load (kg)	Deformation (cm)
UJ11	—	94.3	41	9.31	2.10
UJ12	—	90.3	44	6.70	1.60
UJ13	—	92.1	45	4.55	1.20
UJ21	—	95.2	40	13.03	1.95
UJ22	—	96.2	39	9.31	1.56
UJ23	—	94.3	42	6.75	1.55
PCN11	32.0	47.2	36	28.80	1.76
PCN12	36.0	46.2	39	25.69	1.62
PCN13	38.0	48.9	40	21.20	1.70
PCN21	20.0	49.9	34	39.10	2.25
PCN22	25.0	50.2	36	36.25	2.15
PCN23	28.0	52.1	37	31.72	2.35
HCCA11	23.1	21.2	33	50.27	1.55
HCCA12	23.2	20.2	34	42.37	1.62
HCCA13	23.6	21.5	35	40.27	1.55
HCCA21	22.1	22.5	35	65.67	1.75
HCCA22	22.5	22.9	34	63.72	1.85
HCCA23	22.6	23.1	37	61.81	1.79

TABLE 18.4 CBR Test with Sand and Soil

Variety	Plunger Penetration Depth (mm)	Without Geotextile (C_2)	With Geotextile (C_1)	(C_1/C_2) Ratio
UJ11	2.5	6.27	6.15	0.98
	5.0	7.99	7.24	0.91
	7.5	7.82	7.37	0.94
UJ21	2.5	5.21	6.24	1.09
	5.0	6.52	7.27	1.19
	7.5	6.92	6.02	0.87
PCN11	2.5	6.24	7.52	1.20
	5.0	6.79	7.76	1.14
	7.5	5.75	7.24	1.26
PCN21	2.5	5.52	6.58	1.20
	5.0	6.27	10.20	1.63
	7.5	6.84	9.26	1.35
HCCA11	2.5	6.14	6.58	1.10
	5.0	7.54	9.59	1.27
	7.5	6.28	8.62	1.37
HCCA21	2.5	6.50	7.59	1.17
	5.0	6.82	10.76	1.57
	7.5	7.29	11.24	1.54

acrylic binders are flexible in nature and so the bonding of the jute fibres. For untreated samples the value reduces significantly as the needle penetration increases. But for treated samples the needle penetration has got no significant effect on the bursting strength of the fabric.

It is observed from cone drop analysis (Table 18.3) that untreated jute samples do not offer any resistance to cone drop and total failure occurs. The results indicate that samples treated with acrylic binder B sustain maximum puncture resistance. Apparently it appears that puncture resistance is highest for fabrics with 10 mm needle penetration and least for fabrics with 14 mm needle penetration. But there is no significant difference between them. Here smaller the hole diameter, the greater is the resistance of fabric to damage.

The results of water permeability are summarised in Table 18.3. It can be concluded that water permeability obviously decreases with the application of chemical binder. In case of acrylic binder B it has come down to 21.2 lit/sq.m/sec only whereas the value of the untreated variety UJ11 is 94.3 lit/sq.m/sec. Also there is no statistically significant difference with the increase in the needle penetration depth.

The pore size of the fabric were measured by Hydrometer method [4] which is based on Stoke's equation for velocity of a free falling sphere. The results (Table 18.3) indicate that with higher NDP, there is slight increasing trend of the pore size. This may be due to the deeper and harsher penetrating action of the needles to the fabric. The effect of needle penetration has no significant effect on the pore size. Also after applying the chemicals, pore size decreases for all the samples as expected.

The results of the California Bearing Ratio (CBR) [5] push through test where the load in kg and deformation (settlement) of the fabric at failure in cm on the CBR mould are given in Table 18.3. Here a substantial amount of load is taken by the acrylic binder B treated samples with less deformation at failure. Untreated jute fabric UJ21 (450 g/sq.m, NDP–10 mm) variety can withstand 13.03 kg load against 1.95 cm settlement at failure whereas acrylic binder B treated sample HCCA21 (450 g/sq.m, NDP–10 mm) is capable of bearing 5 times more load against 1.75 cm settlement at failure. For fabric, treated with acrylic binder A, the deformation at failure is more with lower bearing capacity than that of fabric treated with acrylic binder B. The results collaborate to the tensile property of the fabrics. The results indicate that as the depth of penetration increases the bearing capacity of the fabric against the plunger penetration increases.

CBR test has been carried out to find out the soil and fabric interaction. Mumbra sand having the following particulars has been used:

Specific gravity of soil	2.769 (Pynometer)
Loose density of dry soil sample	1.7785 g/ml
Vibrated density of dry soil	1.979 g/ml
Sieve analysis	D_{10} = 0.25 mm
	D_{30} = 0.60 mm
	D_{60} = 1.35mm

(percentage of slit, viz. particles finer than 0.075 mm (75 microns) = 2.9)

During CBR test the fabrics were placed at the surface of the soil in unfixed condition. From Table 18.4 it is seen that as the geotextile is introduced, the ratio C_1/C_2 (CBR with geotextile/CBR without geotextile) increases except in the case of untreated jute fabrics. Maximum value is obtained in case of the fabric treated with acrylic binder *B*. This indicates that treated jute nonwoven fabrics increase the bearing capacity of the soil considerably.

4. DESIGN METHOD WITH GEOTEXTILE

There are several methods available for the designing of geotextile reinforced unpaved road structure. These are proposed by Steward *et. al.* [6], Bender and Barenberg [7], Haliburton and Barron [8], and Giroud and Noiray [9]. Among these methods of designing, the method proposed by Giroud and Noiray is probably most reliable and practical as the effect of traffic has been taken into account and also the procedure is based on the combination of a theoretical analysis with an empirical formula deduced from full scale tests on aggregate roads.

The design criteria of Giroud and Noiray method [10] are based as follows:

(a) It does not consider a failure of the aggregate layer, i.e. it is assumed that there is sufficient friction between geotextile and fill to prevent the latter from sliding at the geotextile interface.
(b) Wheel load will be distributed uniformly according to 2 : 1 stress distribution procedure.
(c) Traffic will not exceed10,000 vehicle passages and will follow the same wheel path.
(d) Probable deflected shape of the fabric.

The aggregate thickness of the pavement for unreinforced and reinforced sections can be determined from the equations mentioned below for any rut depth for secondary roads.

$$C_u = \frac{P}{2\pi\left(\sqrt{P\,\frac{\sqrt{2}}{P_c}} + 2h_0 \tan\alpha_0\right)\left(\sqrt{\frac{P}{2P_c\sqrt{2}}} + 2h_0 \tan\alpha_0\right)} \qquad (1)$$

$$(\pi + 2)C_u = \frac{P}{2(B + 2h\tan\alpha)(L + 2\,h\tan\alpha)} - \frac{K\varepsilon}{\sqrt[a]{(1 + (a/2s)^2)}} \qquad (2)$$

Where, C_u = Undrained cohesion
P = Axle load
P_c = Tyre inflation pressure
B, L = Width and Length of loaded area
α, α_0 = Angle of dispersion of load using fabric and without fabric
h, h_0 = Aggregate thickness using fabric and without fabric
K = Tensile stiffness of fabric
a, s = Geometric parameters
ε = Elongation of fabric

The another equation given by Giroud and Noiray [11] where consideration of traffic has been taken into account, is as follows:

$$h_0' = (1.6193 \log N + 6.3964 \log P - 3.7892r - 11.8887)/C_u^{0.63} \qquad (3)$$

Where, h_0' = Aggregate thickness with consideration of traffic
N = Number of passes of axle load P
r = Rut depth

(This formula is not recommended for N larger than 10,000)

On the basis of Giroud and Noiray's equations, chart and figures have been presented to analyse the effect of different needle punched jute fabrics considered in the studies on soil and soil related characteristics [12] mentioned in equations (1), (2) and (3).

In this work we have studied the effect of treated and untreated nonwoven jute samples on the aggregate height of unpaved roads by using following three types of vehicles :

Type of Vehicles	Tyre Inflation Pressure (kPa)	Axle Load (kN)
Light vehicle	280	24
Medium vehicle	480	60
Heavy vehicle	620	80

The results shown in Fig. 18.1a, indicate that there is no point of using geotextile for very light vehicles unless the soil is very soft (below 0.75 CBR). For

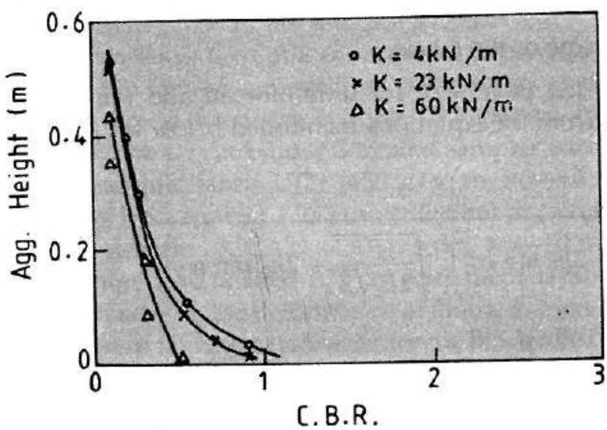

Fig. 18.1 (a)

medium and heavy vehicles (Fig. 18.1b, 18.1c), treated and untreated jute samples can be used. The results also indicate that the small change in the secant modulus do not have appreciable effect on the aggregate height. Untreated jute samples mostly behave as separation layer whereas treated jute, especially treated with acrylic binder B gives considerable reduction in aggregate height of the unpaved road. When the CBR value is high (more than 2) geotextile hardly plays any role in reinforcement of soil.

The results presented in Fig. 18.2a, 18.2b indicate that as the standard axle load increases the aggregate height also increases. The reinforcement property of the fabrics on the aggregate height reduces as the axle load increases because of deformation of the fabric. It is clear that the fabrics used in this work are suitable for axle load up to 80 kN.

Figure 18.3 establishes the relation between rut depth and required aggregate height when treated and untreated jute fabrics are used. The results

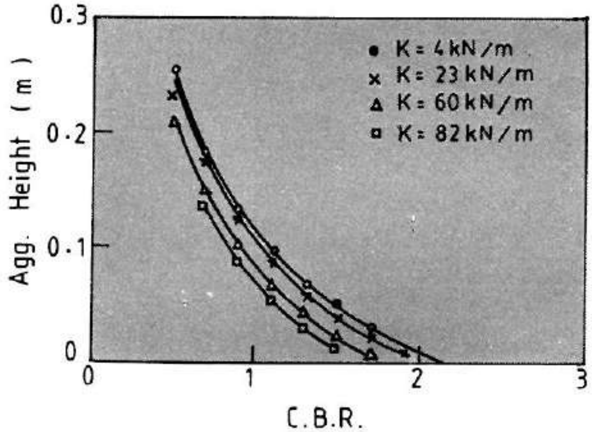

Fig. 18.1 (b)

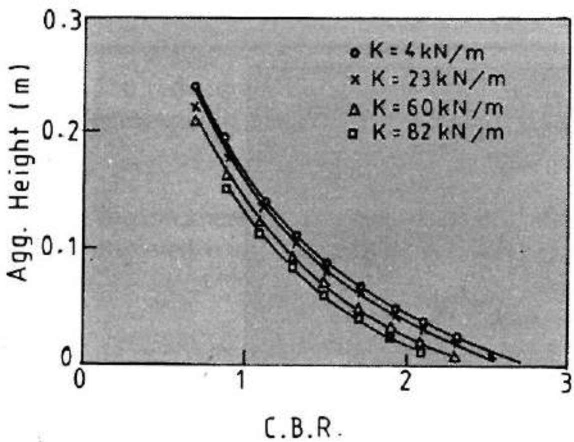

Fig. 18.1 (c)

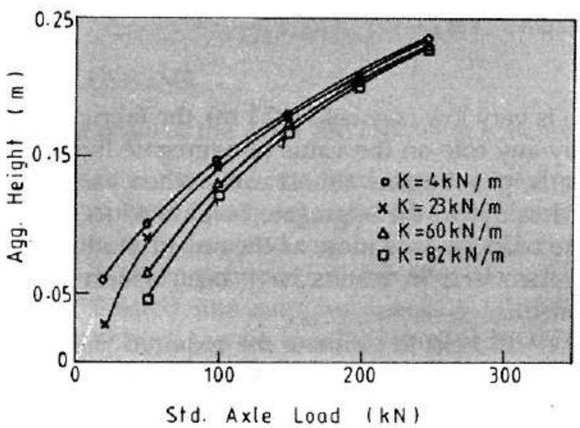

Fig. 18.2 (a)

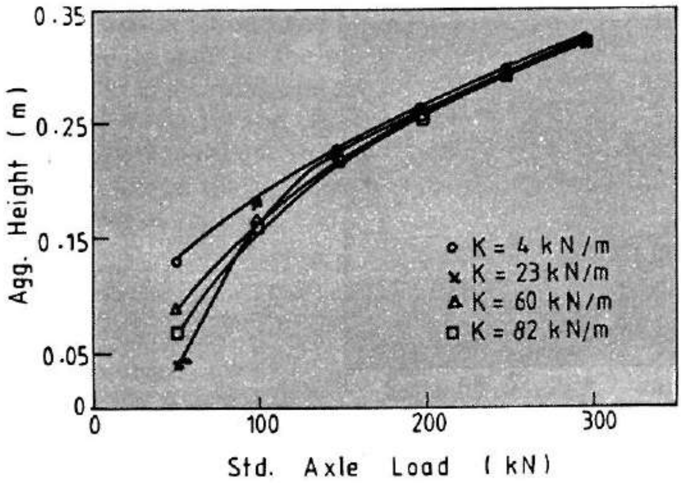

Fig. 18.2 (b)

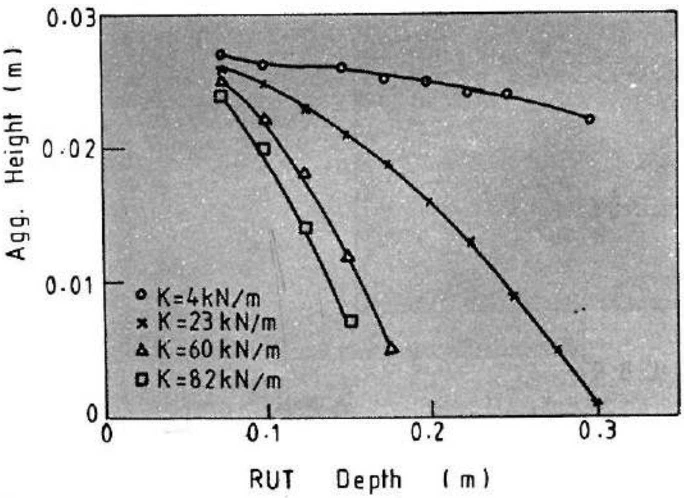

Fig. 18.3

show that when the rut depth is very low (say below 0.1 m), the fabrics used in this experiment do not play any role on the value of aggregate height of the unpaved road. Aggregate height remains almost same when untreated samples are used. For treated samples, the aggregate height reduces with increase in the rut depth. Rate of increase is more as the secant modulus of the fabric increases. The similar trend in results have been observed for medium and heavy vehicles also.

The chart given in Fig. 18.4 will help to estimate the required thickness where there is no geotextile and for the passes of 10 to 10,000 and also the reduction of possible aggregated thickness due to geotextile.

The thickness h' of aggregate layer when traffic is taken into account is determined in the case of unpaved road with geotextile by using the following procedures[9]:

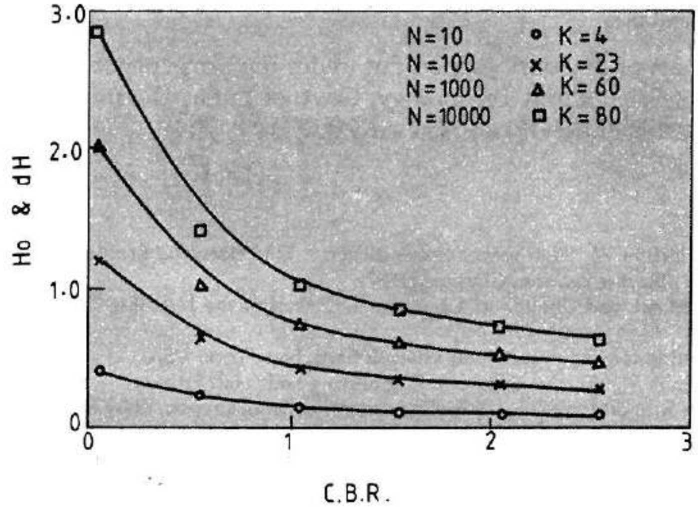

Fig. 18.4

(i) The reduction of aggregate thickness Δh, resulting from the use of a geotextile, is deduced from the quasi-static analysis by:

$$\Delta h = h_0 - h$$

(ii) The thickness, h' of aggregate layer in the case of a geotextile reinforced, unpaved road when traffic is taken into account is determined by:

$$h' = h_0' - \Delta h$$

Establishing charts giving the thickness as the function of all the parameters was found to be too cumbersome. Advantage was taken of the fact that h_o does not depend on the geotextile and Δh does not depend on the traffic. Two sets of curves were then presented where h_0 is a function of traffic and Δh is a function of geotextile modulus. User could then subtract and get thickness of aggregate required taking into account traffic and geotextile modulus.

5. CONCLUSIONS

On the basis of the work the following conclusions can be drawn:

(a) The untreated jute fabrics give very small reinforcement effect to the soil and mostly act as a separation layer. It does not offer any resistance to cone drop and may be damaged during installation due to dropping of sharp pointed or sharp edge of the stone.

(b) Treated jute samples specially with the needle penetration depth 10 mm, can be used for unpaved roads as it reinforces the soil and fulfill all the geotechnical properties studied in this work. Full scale trial may be carried out to find the possibility of using this fabric for unpaved roads. This design chart given in this work can be used as a tool to determine the aggregate height of the unpaved road.

6. ACKNOWLEDGEMENTS

This paper forms a part of the work carried out under the project sponsored by the Department of Science and Technology, Govt. of India. The financial support given by them is gratefully acknowledged.

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State of Art Report on Geoweb Geocell Reinforced Soil

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Geosynthetics are being increasingly used in civil Engineering activities. In most of the applications the geosynthetic inclusions are placed at the subgrade fill interface. For such applications the horizontal inclusion performs the reinforcement, separation and filtration functions. In many applications like paved roads and foundations the horizontal inclusion has to yield high resistance at low strains because of the low allowable rut depth. In such cases the inclusion should be of high modulus with adequate roughness. High modulus geotextiles are not manufactured in India. Therefore, other alternatives have to be looked into. Geoweb/geocell (three dimensional axisymmetric cells made of synthetic or natural nonwovens) come out as an attractive and economical solution. Geocells can be made of nonwoven geotextiles.

The paper presents a state of the art on geoweb reinforcement highlighting the various applications, advantages and merits. It has been brought out that the geoweb/geocell provides distinct benefit. Measured in terms of the Bearing capactiy Ratio the benefit is of the order of two to three times.

The paper also presents a method of analysing the nonwoven geocell reinforced backfill/sand layer with the help of Finite Element method. It also suggests a layered coefficient for the nonwoven geocell layer which can be used in the American Association of State Highway Officials (AASHO) pavement design method.

1. INTRODUCTION

Geosynthetics are being increasingly used in geotechnical engineering activities. When used in conjunction with soil it performs several functions like fluid transmission, filtration, separation, protection, tensioned membrane and tensile member as suggested by Giroud [1]

Initial applications of geosynthetics were for shore protection. However, in the last two decades they are being extensively used as tensioned membranes/tensile members (typical of unpaved roads).

Numerous pavement design methods using a horizontal layer of geotextile have been suggested. These methods cannot be used for paved roads (characterised by low allowable rut depth, vehicle wander and longer life). In paved raods the geotextiles have to yield high stresses at low strains. This necessitates the use of high modulus geotextiles or geocomposites like nonwoven geocells, soil filled tubes. High modulus geotextiles are not available in India. Geocells therefore, seem to be an attractive solution. (Fig. 19.1) Geocells can be made of nonwovens (synthetic or natural)

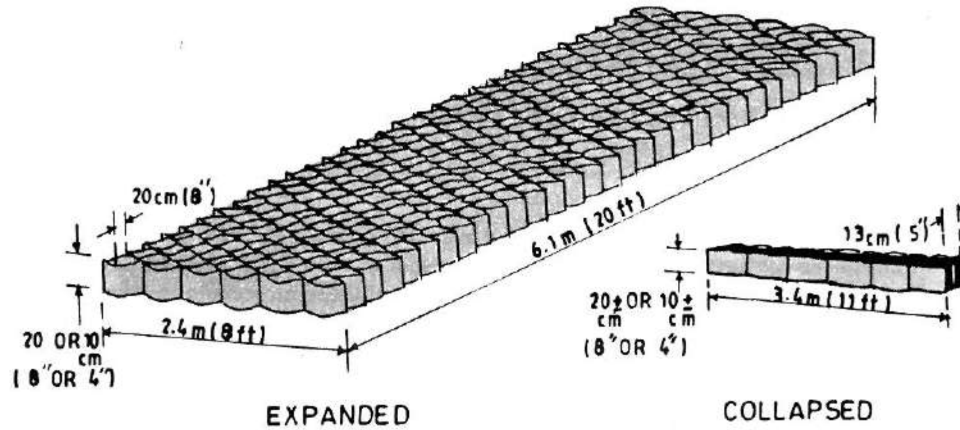

Fig. 19.1 Typical geocell structure (Presto Products)

Geocells have been used in paved roads in a few cases. However, the machanism of resistance of geocell to applied loads has not been investigated in great depth.

An overview of the pavement design methods with geosynthetics in the form of horizontal inclusions has been reviewed by Mandal and Mhaiskar [2]. This paper presents an overview of the geoweb/geocell applications.

2. GEOWEB/GEOCELL REINFORCED SOIL

From the literature review carried out on soil reinforced with horizontal inclusions it is clear that the transfer of vertical load on a fill and the resulting stresses on the subgrade can be taken up by the geotextile by two ways.

(a) At low rut depths the shear stresses can be taken up by the geotextile when it is placed between the fill and the geotextile. This mechanism of stress transfer takes place only when the geotextile has adequate tensile strength and roughness.

(b) At high rut depths the stresses can be taken up by the geotextile as a tensioned membrane. However, it should be noted that such rut depths can be allowed only when there is channelisation of traffic (like unpaved roads).

The high modulus geotextiles required for paved roads are not available in India. Therefore, the efficacy of solutions like geoweb/geocell or soil filled tubes (made from synthetic or natural nonwovens) has to be looked into. Geoweb/geocell have also been used for other applications.

2.1 Bearing Capacity Applications

Broms and Massarach [3] proposed the use of a grid mat (consisting of rectangular and triangular cells made up of metal) for different offshore structures. The cells are filled with sand or in case of soft subgrades are pushed into the soil. The bearing capacity, lateral and pull out resistance were analysed for cohesive and non-cohesive soils.

Failure of such cells can be caused by two mechanisms. First type of failure was the penetration failure and it occurs when the height of the cells is small compared to the circumference of the individual cells. The second failure mode, the bearing capacity failure, governs when the height of the cells is relatively large.

The penetration resistance for cohesionless soils can be calculated by considering forces acting on a slice located at a depth 'h' below the surface of the soil as shown in Fig. 19.2.

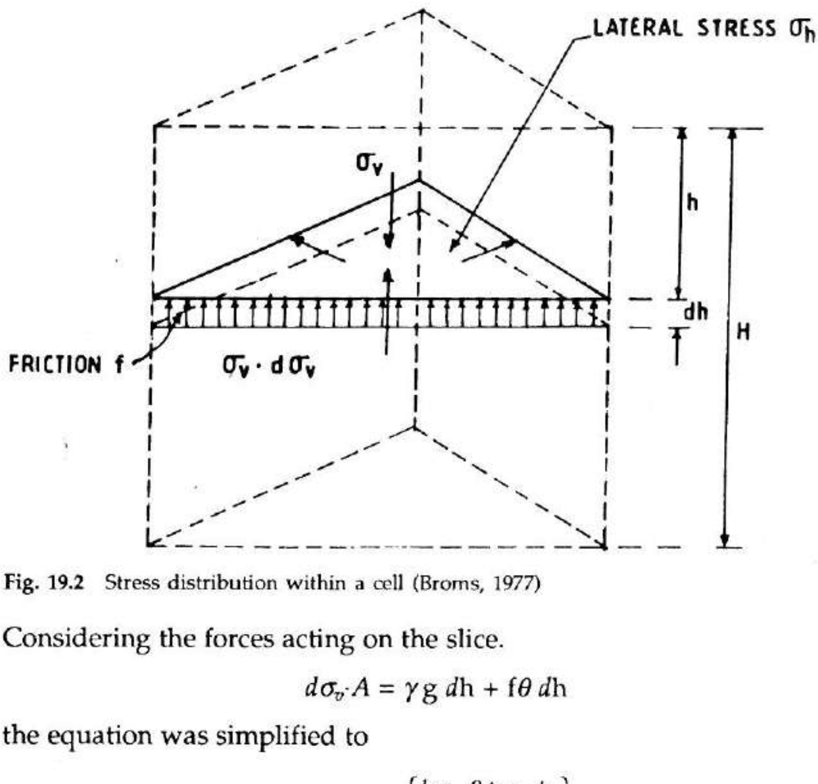

Fig. 19.2 Stress distribution within a cell (Broms, 1977)

Considering the forces acting on the slice.

$$d\sigma_v \cdot A = \gamma g \, dh + f\theta \, dh$$

the equation was simplified to

$$d\sigma_v = \gamma g + \left\{\frac{k\sigma_v \, \theta \tan \phi_a}{A_b}\right\} dh$$

The solution of this differential equation is

$$\sigma = \frac{\gamma g A_b}{k \, \theta \tan \phi_a} \left\{ e \, \frac{k \cdot \phi \, h \tan \phi_a}{A_b} \, \theta - 1 \right\}$$

where γ is the density of the backfill
g is the gravitational acceleration
ϕ_a is the frictional angle between the soil and the geocell wall
σ_v is the vertical stress, $d\sigma_v$ stress increase
θ is the perimeter of the cell
k is the earth pressure coefficient
A_b is the area of the cell
h is the location of the slice of thickness dh, and
f is the friction along the wall

Similarly, the penetration resistance for cohesive soils was calculated. The bearing capacity in both cases (c and ϕ soils) was calculated by the Terzaghi's bearing capacity equation.

It was concluded that the penetration resistance increased rapidly with increasing depth. The bearing capacity for cells with triangular shape was larger than that of the rectangular cells at the same penetration depth.

Guido *et al.* [4] investigated the effectiveness of the geocell structure and the factors affecting its performance. The effect of

* texturisation of the cell material,
* number of layers of the cell reinforcement (N),
* depth below the loaded plate to the top of the first, layer of the geocell reinforcement (u)
* size (extent) of the geocell reinforcement (b) and
* relative density of the fill material

was studied.

Geocells of an a/b ratio of 1.0 made up of high density polyethylene were used. Texturisation roughness of the geotextile was measured by the parameter Root Mean Square (RMS) defined as

$$\text{RMS} = \sqrt{\Sigma\, Y^2/n}$$

Three types of RMS values were used (9–12, 130–150, 500–600 in micro inches). Direct shear tests between the geotextile and sand indicated that the efficiency was maximum for the medium textured (1.10–1.20) while those for the coarse and normal RMS's gave an efficiency of 1.05–1.5 and 0.6–0.7. This indicated that there is a relationship between the depth of roughness pattern and the grain size of the soil reinforced. At high RMS values some of the soil grains embedded themselves into the coarse texture pattern.

Plate load tests were conducted using a poorly graded sand (SP) laid in a square wooden box. Load tests on untextured geocells showed that at N = 4 or more (4 layers placed at $u/B = 0.50$, and $\Delta z/B = 0.25$, $b/B = 2.0$; Fig. 19.3, where B is the width of the loaded area and Δz is the spacing between the layers) the Bearing Capacity Ratio (BCR) did not show any increase, indicating that $N = 4$ is an optimum value. For the medium texturised geocell at $N = 4$ the BCR value is still increasing.

Results of the studies on the depth of placement of the geocell (u) indicated that as the depth of placement decreased the BCR increased and settlement

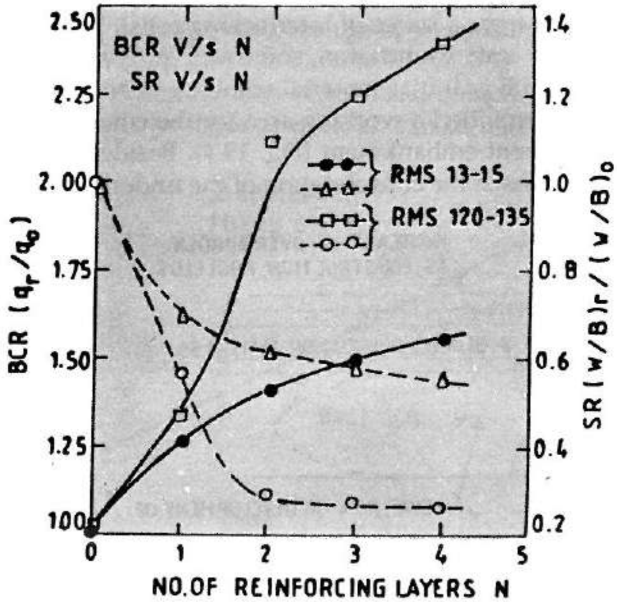

Fig. 19.3 Variation of BCR & SRF with number of layers (Guido, 1989)

decreased. For the untextured geocell at a ratio of 1.0, while for the textured geocell at u/B ratio 1.25 the reinforced structure behaved like an unreinforced case.

As the b/B (length of geocell/width of the loaded area) increased, the BCR increased upto a value of 2.0 beyond which there was only a marginal improvement (for the untextured case). For the medium textured case the corresponding value was 3.0.

Studies carried out on the effect of relative density indicated that for poor quality soil tremendous benefits can be had from the inclusion of untextured or textured geocell, whereas for better quality soil the benefits may be only marginal.

It was recommended that the results should not be extrapolated to a sand fill over a clay subgrade.

Shimizu *et al.* [5] carried out model tests to investigate the mechanism of resistance of geocell structure. Paper/cardboard cells were embedded in loose sand. The geocells used had a/b ratios of 0.5 and 0.66. X-ray photographs of displacement of lead shots were used to study the movement of sand. The X-ray photographs have shown that at relatively small displacement the movement of the particle is restricted by the cell wall and the load carrying capacity increases. At higher loads sand began to pass under the wall to regions outside the cell. It was also concluded that an a/b ratio of 0.66 was optimum.

2.2 Embankment Applications

Bush *et al.* [6, 7] reported the use of geocell foundation mattress (a honeycombed structure formed from a series of interlocking cells). The cells were fabricated directly on a soft foundation soil from polymer grid reinforcement and then filled with granular material resulting in a structure 1.0 m deep. This mattress also provided a working area for the construction of geocell mattress and subsequent embankment (Fig. 19.4). Besides, it also provided a drainage blanket to assist the consolidation of the underlying soft

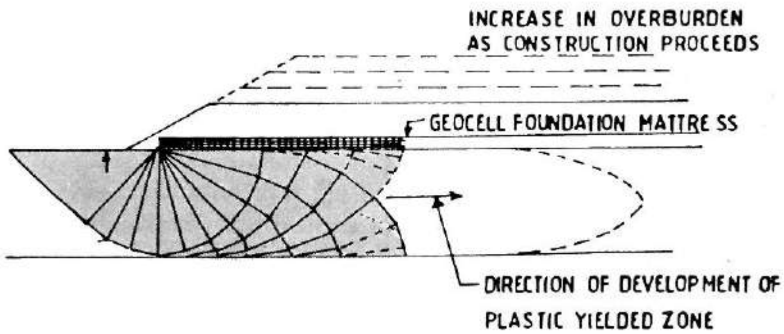

Fig. 19.4 Typical geocell mattress below an embankment (Basett, 1989)

foundation. The incorporation of a geocell foundation gave the following characteristics to the embankment foundation.

* a rough interface between the soft foundation and a contained granular fill.
* a stiff platform that ensured even distribution of load onto the foundation.

These features enabled the geocell mattress to exert a degree of restraining influence on the deformation in the soft foundation. It also rotated the principal stress direction in the nearly vertical or outward direction in the embankment fill to up to 45 degree inclined inward at the top of the foundation soil. This altered the potential slip mechanisms in the foundation soil and resulted in an enhanced bearing capacity.

It has also been reported that the geocell mattress performed well compared to a horizontal reinforcement. Besides, it also proves to be economical.

Paul [8] has also reported the use of 'Tensar' grid formed geocell mattress in Scotland after having considered four options of

(a) Partial excavation of soft soil and replacement by backfill,
(b) Installation of drainage followed by staged construction,
(c) Complete excavation of the soft layer and replacement with a rockfill,
(d) Construction of a geocell mattress (2 m thick) which was found to be the economical and most rapid way of construction of an embankment over very soft clays without normal problems for mechanical plants/ machinery. Besides the construction could also proceed in all weather conditions. This system also helped in reducing the differential settlements.

Datye [9] has suggested the use of a geocell mattress for erosion control and as a placement and for narrow filters (Fig. 19.5). The composite filter and drainage system is also economical compared to the conventional system. Nonwoven (synthetic or natural) can be used for this purpose.

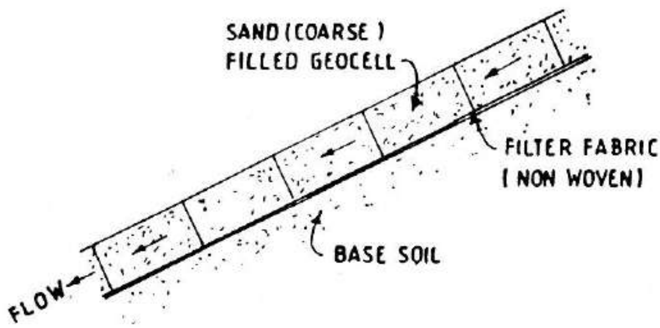

Fig. 19.5 A composite system of sandfilled geocell and filter fabric (Datye, 1988)

2.3 Pavement Applications

Red and Mitchell [10] investigated the performance of inter-connected paper cells filled with sand as a reinforced layer for application in low cost highway construction. The influence of,

* width of loaded area (B) to the cell width (*a*)
* the ratio of the cell width (*a*) to cell depth (*b*)
* the influence of subgrade stiffness and
* effect of repeated loading

was investigated with the help of laboratory model tests.

In these experiments the subgrade was simulated using springs. The mechanism of resistance was summarised as :

* The sand gets confined and restricted against lateral movement, till strength of the reinforcement exceeds.
* Tension in the reinforcement gave a corresponding compression on the sand in the cell, thus giving increasing stiffness beyond the edges of the loaded area.
* Development of slip surfaces (shear planes) through the reinforcement is inhibited.

The paper cells used in the experiments were square in shape when expanded. The cell width was kept constant (2 inches/51 mm). To obtain different ratios of width of loaded area *b* to width of cell *a* the size of loading plate was varied. Similarly different ratios of cell depth *b* to cell width *a*, i.e. *b*/*a*, were obtained using cells of different depths.

Failure in the static tests was observed at 0.3 inches (7.6 mm) due to rupture of the reinforcing material. The optimum B/*a* ratio was in the range of 1.5 to 2.0. As the *a*/*b* ratio decreased bearing capacity also increased. Little benefit was gained beyond an a/b ratio of 0.44. The cell reinforced sand also showed better resistance to repeated loadings.

Additional tests were recommended to establish the influence of,

(a) reinforcing material strength,
(b) sand (backfill) density, and
(c) surcharge loading and different surface treatments.

De Garidel *et al.* [11] investigated the suitability of continuous filaments (Texsol), micro-geogrids (Tensor) and geotextile cells filled by soils for road construction. The mechanical behaviour of these structures was investigated by field studies. Geocells used in these tests had a/b ratios of 0.5 (Armater) and 0.1 (Nidaplast). On the basis of the tests it was concluded that the reinforced structures do not show increased rigidity at small displacements. However, the strengthening influence at large displacements is noteworthy, especially for honeycomb structures.

Khay *et al.* [12] investigated the suitability and mechanical behaviour of various geotextile structures for low cost highways. The geotextiles included, cells (ARMATER), fibres in soil (TEXSOL) and prefabricated sheets of polyamide threads (ENKAMAT). The subgrade consisted of granular materials (sand). Geocells used had an a/b ratio of 0.5 with varying b of 10, 15, 20 cm. The geocell structure showed considerable trafficability enhancement. The settlement of geocell structure was markedly low indicating the slab effect of these structures.

Kazerani *et al.* [13] studied the effectiveness of a three dimensional grid cell confinement system for the construction of unbound pavements. When the grid cell confinement system is filled with a granular fill and is subjected to monotonic or repeated loading, each shell shares its load with the adjacent cells to form a well stabilized composite material in which the lateral movement (spreading) and shear failures are resisted by both tensile hoop strength of the cell walls and the passive resistance of the adjacent cells (Fig. 19.6). As a result of this behaviour the grid cell structure offers a substantial increase in stiffness and ability to support large traffic loads with

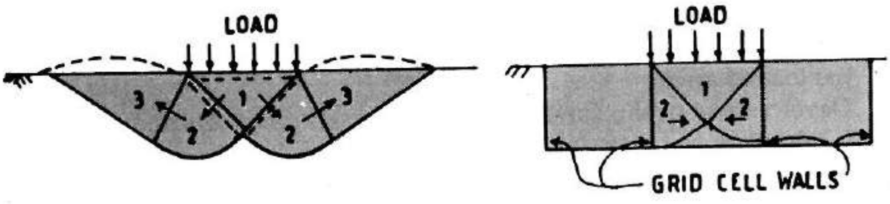

Fig. 19.6 Unreinforced and reinforced soil behaviour (Kazerani, 1987)

minimal vertical deformation. This could lead to a considerable reduction in thickness. The confinement mechanism also prevents failure wedge formation in the base. Besides, the frictional interlock between the fill material and cell walls assist in the distribution of concentrated loads to adjacent cells, thereby reducing transmitted stresses at base/subgrade interface (Fig. 19.7).

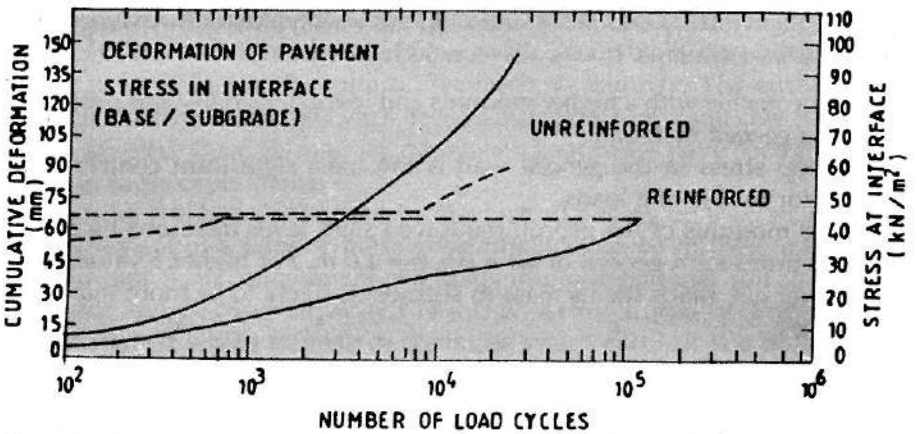

Fig. 19.7 Deformation and interface stresses of pavements with poorly graded base soil on the soft subgrade (Kazerani, 1987)

The efficiency of the geocell structure was investigated by large cell experiments using a granular subgrade and geocells having *a*/*b* ratio of 1.0, made up of woven geotextile. Finite element analysis was adopted to predict the stresses and deformation of pavement structures. PAFEC a Finite Element (FE) package was used for this analysis.
With the help of above studies it was concluded that:

(a) The stress strain relationship showed a marked improvement due to confinement of the fill material by grid cells.
(b) The cyclic response of a grid cell reinforced base is considerably improved (Fig. 19.7).

Khay *et al.* [14] carried out laboratory and full scale tests to investigate the performance of the geocell on a fine sand subgrade. Geocells of different *a*/*b* ratios and shapes were used. The modulus of the soil increased by using horizontal and geocell reinforcement. Geocell reinforcement also proved to be a cost effective solution for pavements.

Mhaiskar and Mandal [15] have investigated the efficacy of the nonwoven geocell structure on a soft clay subgrade. The geocells were filled by sand. Experimental and Finite Element (ANSYS a general purpose Finite Element package) procedures have been used for the above purpose.

Considerable amount of improvement in the ultimate load and reduction in settlement was observed from the experimental results. The results of the Finite Element analysis can be used to study the improvement in stiffness.

In the FE analysis of the nonwoven the geocell layer was considered as a layer with an equivalent stiffness. In the unreinforced case the sand layer was assigned an average modulus based on the Duncan and Chang Eq. [16]. The modulus of the geocell layer was varied till the load settlement curve showed a fairly good match. A fairly good agreement was seen at modulus of two times that in the unreinforced case.

Nonwoven (425 A—Tata Mills) and woven slit film type were used in the experimental investigations. Illustration 19.1 shows a typical nonwoven geocell used in the experiments. It was also concluded that:

(a) A geotextile with a higher modulus and less extensibility was desirable as a geocell material.
(b) Hoop stress in the geocell wall is the most significant contributing factor in resisting loads.
(c) The modulus of the geocell reinforced sand layer increased by about 2.0 times for a geocell of $a/b = 0.5$, $b = 4.0$ in. For higher b values and lower a/b ratios the increase in stiffness is likely to be more than two times.

Basset [17] has also inferred that in laboratory studies, three dimensional geocells proved about a five times stiffer in bending than the same weight of two dimensional sheets of similar grid materials with sand placed on top of the same depth as the geocell.

Mhaiskar and Mandal [18] have investigated the efficacy of a nonwoven geocell structure and compared it with the performance of a horizontal inclusion. It has been brought out that:

(a) Introduction of a horizontal inclusion at the sand clay interface result only in a marginal benefit. The benefit being evident only near failure (Fig. 19.8).

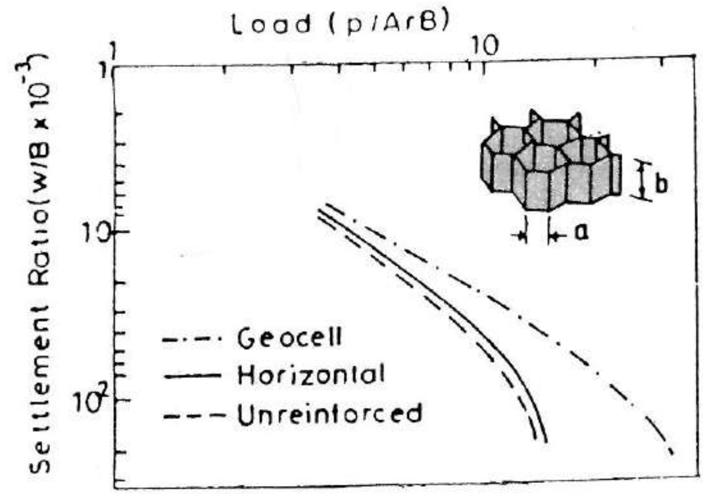

Fig. 19.8 Load settlement curves for unreinforced and reinforced sand (nonwoven, geocell and horizontal inclusion) $c = 11$ kPa

(b) Reinforcing the sand with a nonwoven geocell results in a large benefit. The benefit being of the order of 2–3 times
(c) Whereas interface friction and modulus are important properties when a geotextile is used as a horizontal inclusion. Modulus is the single most important property when used to form a nonwoven geocell.

In view of the immense potential of geoweb/geocell for pavement applications, extensive research is being carried out at the Geotextile/Geosynthetic Testing Laboratory at Indian Institute of Technology, Bombay. The efficacy of the geocell structure backfilled with dense sand resting on a soft clay subgrade is being studied. Geocells made of nonwoven geotextiles have been extensively used in these experiments.

Koerner [19] has also suggested that instead relying on friction, arching or entanglement of a fibre or mesh geosynthetics can be formed to effectively contain soil. Such containment can vastly improve granular soil strength and enhance the bearing capacity. The U.S. Army Corps of Engineers has experimented with a number of confining systems. It has also been reported that such a system resulted only in slight rutting when subjected to 10,000 passes of a 230 kN tandem-axle truck loads. Without the same system the same trucks got bogged down in deep ruts after only 10 passes.

The system can also be analysed for statically loaded foundation bearing capacity problems (Fig. 19.9). The failure mode is interrupted by vertical walls of the geocell structure. Failure only occurs when the sand in a particular

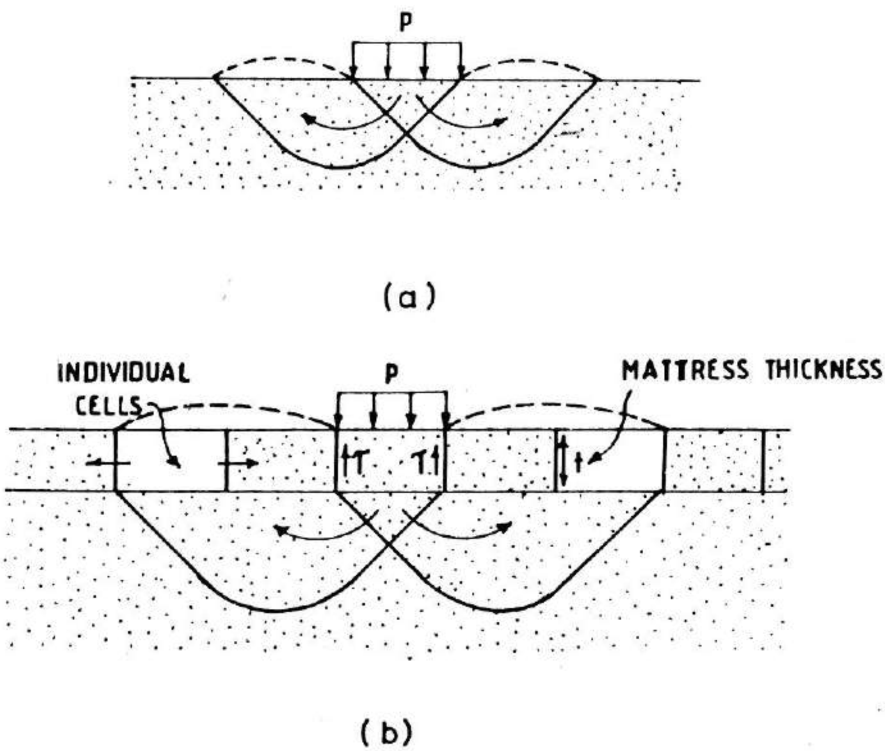

Fig. 19.9 Bearing capacity failure mechanisms of sand without and with geocell confinement systems (a) without mattress (b) with mattress. (R.M. Koerner)

cell overcomes friction punches out of it, thus loading the sand below the level of the mattress. The relevant equations can be summarised as follows:

without mattress

$$p = cN_c\zeta_c + qN_q\zeta_q + 0.5\gamma BN_\gamma\zeta_\gamma$$

with mattress

$$p = 2\tau + cN_c\zeta_c + qN_q\zeta_q + 0.5\gamma BN_\gamma\zeta_\gamma$$

where p is the maximum bearing capacity
c is cohesion (zero for a granular soil)
q is surcharge load
B is width of the applied pressure system
γ is the unit weight of the soil in the failure zone
N_c, N_q, N_γ are bearing capacity factors .
$\zeta_c, \zeta_q, \zeta_\gamma$ are shape factors.
τ is the shear strength between the geocell wall and the soil contained within it. It is a function of δ the angle of friction between the soil and the wall (δ = approx. 35 degrees for sand and nowoven geotextile.)

3. PAVEMENT DESIGN PROCEDURE USING NONWOVEN GEOWEB/GEOCELL

The AASHO Road Test [20, 21] introduces a road user definition of pavement failure rather than one based on structural failure concepts (e.g. Cracking, deformation) i.e. the function of any road is to safety and smoothly carry vehicular traffic from one point to another description several important concepts were introduced [Yoder, 22].

The method relates the number of daily equivalent single axle load repetitions (W_{t18}) required to reach on predefined terminal serviceability level. (p_t) for any given pavement structure number (SN), climatic conditions (R) and subgrade soil support (S). A nomographic solution is accomplished by first finding the unweighted SN for a given soil support S and W_{t18} value. This SN value is then corrected by the regional climatic condition factor (R) to determine the required SN.

The SN is defined as an index number derived from analysis of traffic, road bed soil conditions and regional factor that may be converted to thickness of various flexible-pavement layers through the use of suitable layer coefficients related to the type of the pavement structure.

The layered coefficients (a_1, a_2, a_3, shown in Fig. 19.10) are used in an empirical relationship between SN for a pavement structure and layer thickness. This relationship expresses the relative ability of a material to function as a structural component of the pavement

$$SN = a_1 D_1 + a_2 D_2 + a_3 D_3$$

where D_i values are the respective layer thicknesses.
a_i values are the structural coefficients

In the AASHO road test four types of basic materials were used namely

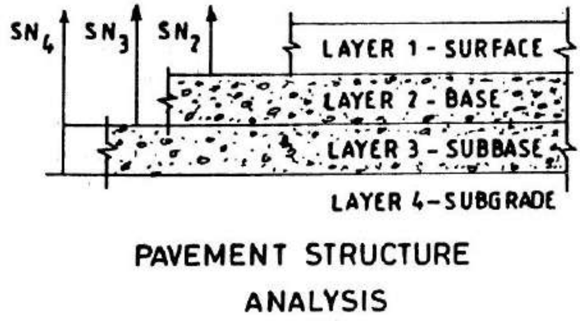

Fig. 19.10 Alternate procedure for determing flexible pavement layer thicknesses (AASTTO Interim Guide, 1972)

(a) Crushed stone
(b) Gravel
(c) Cement treated gravel
(d) Bituminous treated gravel.

Based upon the results of the study along with an estimation from results of special base studies at the test layer coefficients were established by the AASHO Committee on Design (Table 19.1 presents typical values of the structural layer coefficients.

TABLE 19.1 Structural Layer Coefficients Proposed by the AASHO Committee on Design (1961)

Pavement Component	Coefficient
Surface course	
plant mix (high stability)	0.44
Base Course	
Sandy gravel	0.07
Crushed stone	0.14
Bituminous treated	
Sand asphalt	0.30
Lime treated	0.15–0.30
Subgrade course	
Sandy gravel	0.11
Sand or sandy clay	0.05–0.10

Similar nomographic charts have been presented by Asphalt Institute and correlations from other states.

Experiments carried out on the reinforced sand (at the Geosynthetic Laboratory of Indian Institute of Technology, Bombay as a part of an extensive research to prove the efficacy of the nonwoven geocell structure) have shown a California Bearing Ratio (CBR) of 22. This corresponds to a structural coefficient of 0.09. Similar experiments carried out on nonwoven geocell reinforced sand yielded a CBR or 75. This corresponds to a structural coefficient of 0.13.

A surface course of (structural coefficient of 0.44) 5 inches may be assumed in design. For a subgrade strength of c =10 kPa, CBR = 0.33 and a soil support value $S = 0.75$ the Structural Number of 6.0 would result. (Corresponding to a 1,000 18 kip daily equivalent single axle load repetitions). If regional factor of 1.0 is assumed the weighted structural number of 5.8 may result.

In the unreinforced case a sand thickness of 40 inches (101.6 cm) would be required assuming a structural coefficient 0.09. For the reinforced case a thickness of 26 inches would be required (structural coefficient of 0.13). This would result in a substantial saving of 35%. (Fig. 19.11)

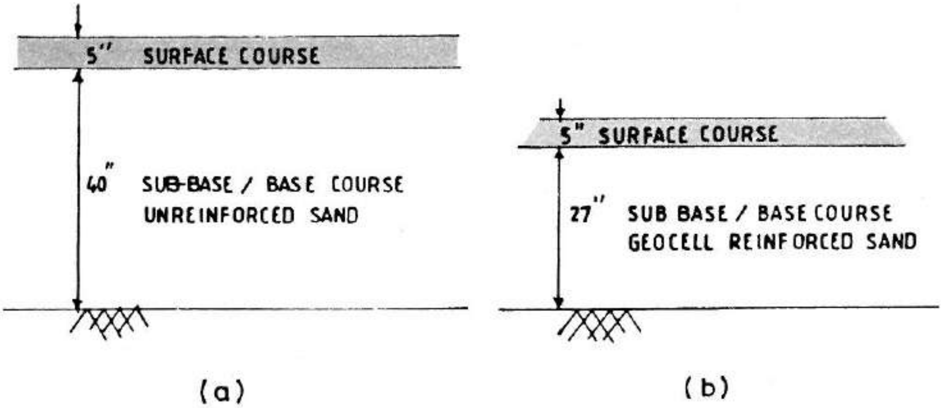

Fig. 19.11 Typical cross section of the pavement (a) Unreinforced (b) Reinforced

4. CONCLUSIONS AND REMARKS

(1) A nonwoven geocell structure which is a mattress formed of geotextile to derive beneficial results, can be used in various applications.

(2) The performance of nonwoven geocell mattress can be evaluated by using the Finite Element Method or slip line theory.

(3) Such a mattress is both economical and advantageous in construction. Besides it results in large benefits.

(4) A nonwoven geocell mattress performs better compared to nonwoven horizontal inclusion.

(5) It has been shown that for pavement (paved road) use of a nonwoven geocell structure would result in a benefit of about 35%.

(6) Nonwovens (even low modulus) geotextiles available in India can be used to form a geocell.

5. ACKNOWLEDGEMENT

The authors are greatly indebted to Prof. B. Nag, Director, Indian Institute of Technology, Bombay for the encouragement given. The authors also wish to thank Soil Mechanics Laboratory Staff of IIT, Bombay for helping the authors during the experimental investigations and the Computer Aided Design (CAD) Centre for permitting the usage of ANSYS available at their centre.

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20

Perpendicular Laid Nonwovens STRUTO

O. JIRSÁK, J. HANUŚ, and M. PLOCAROVÁ

The thermo-insulating and filling properties are a function of the thickness of the textile material. Besides the thickness the thermo-insulating property also depends on the fineness of the fabric. The thermal resistance of the fabric decreases with increasing fibre fineness in spite of simultaneous decrease in the thermal conductivity. It is due to the lower compression resistance of the textile fabric made from fine fibres.

In the nonwoven textiles, STRUTO, a carded web is formed into perpendicular positioned lamellae. This type of fibre orientation leads to high compressive resistance and high resilience of the textiles. The main advantages of the technology are: low investment, low built-up plant area, low energy consumption and high production rate. The STRUTO textiles show improved thermo-insulation and can be used in clothing and construction industry.

1. INTRODUCTION

The thickness of bulky textile materials depends on the design, structure, compression and compressive behaviour. Some properties of textiles such as thermo-insulating and filling properties are functions of the textile thickness [1, 2]. An example of this dependence is the reduction of thermal resistance of a textile sample due to its compression.

Thermal resistance is defined as follows:

$$R = \frac{A \cdot \Delta T}{Q} = \frac{L}{l} \tag{1}$$

where ΔT is the difference in temperature on both the surfaces of the textile material (K)

Q the amount of heat passing through the textile material in a given time unit (J/s)

L the textile thickness (m)

l the thermal conductivity $(W.m^{-1}.K^{-1})$ defined from

$$Q = l \cdot \frac{A \cdot \Delta T}{L} \tag{2}$$

Where A is the area of the sample.

Whereas the thermal conductivity of the textile sample l does not change considerably during its compression, the sample thickness L decreases. As follows from Eq. (20.1) this leads to the decrease in thermal resistance R during the sample compression.

Another example shows the significance of fibre fineness for the thermo-insulating properties of the bonded nonwoven fabrics. A series of nonwovens have been made from the blends of PET fibres 0.55 dtex and 6.7 dtex. Thermal resistance R and thermal conductivity l have been measured at the sample compression of 400 Pa. As follows from the results in Table 20.1, the thermal resistance R of the textiles decreases with increasing content of fine fibres in spite of simultaneous decrease in the thermal conductivity. It is due to the lower compression resistance of the textiles made from fine fibres as also follows from Table 20.1. These results show the significance of the compression resistance of the textiles for some end-use properties.

TABLE 20.1 The Influence of Ratio 0.55 dtex : 6.7 dtex on Thermal Conductivity, Thermal Resistance and Thickness

Ratio 0.55 : 6.7 dtex	Thermal Conductivity 10^3 ($W.m^{-1}.K^{-1}$)	Thermal Resistance $R.10^3$ ($W^{-1}.K.m^2$)	Thickness (mm)
0 : 100	42.7	410	17.5
33 : 67	33.2	416	15.8
50 : 50	30.9	358	11.0
67 : 33	29:0	309	8.9
100 : 0	27.4	203	5.5

Area weight 170 g/m^2, measured at compression of 400 Pa.

The compressive resistance of bulky textiles consisting of fibres pedominantly laid in the sample area depends mainly on the bending rigidity of the fibres. A possibility for increasing this important property consists in constructing fibre sheets of fibres mainly oriented perpendicular to the textile area.

Our paper describes the technology of perpendicular laid nonwovens and some properties of the textiles.

2. PERPENDICULAR LAID NONWOVENS

2.1 Technology

Two principles of the perpendicular laying of carded web have been developed in our University [3, 4, 5]. A typical continuous production line (Fig. 20.1) consists of a carding machine or of another source of the web, of the perpendicular lapper and of the thermobonding through air chamber.

The carded web, made of a mixture of basic and of thermoplastic bonding fibres, is brought toward the perpendicular lapper. This device folds the web into perpendicularly oriented lammellae. This sheet of lamellae, which are more or less compressed together, is led into the thermobonding chamber for strengthening.

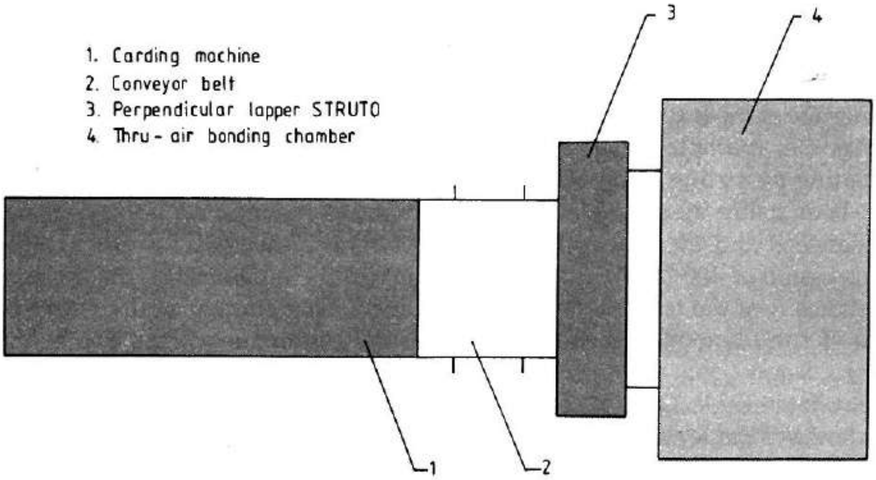

Fig. 20.1

The vibrational lapper (Fig. 20.2) was developed as a laboratory model and later as a production line of 2.2 m in width. The first series of machines has been installed. The rotation lapper (Fig. 20.3) showing practically unlimited performance in terms of known carding devices is ready for production in widths of 2, 2.5 and 3 m.

Any kind of basic fibres can be processed using a perpendicular lapper. Polypropylene, co-polyester or various bi-component fibres are typical bonding materials used in fibre blends in the ratio of 10–40 weight per cent.

Depending on the kind of fibres, bonding fibres ratio, process parameters and bonding temperature the perpendicular laid textiles of a thickness of 5 to 40 mm and volume mass of 5 to 30 kg/m^3 can be produced.

The main advantages of the thermobonding technology are:

- ✶ wide range of products as to raw materials, volume and area weight and end uses;
- ✶ low cost of the device, low energy consumption (no water evaporation is required);
- ✶ no chemical binders, no water pollution and no problems of hygiene in end-use; and
- ✶ small build-up area and high performance.

A typical example of our 2.2 m production line:

- ✶ total width of the bonding chamber: 4.5 m
- ✶ length of the chamber: 1.6 m (N.B. one point six metres only)
- ✶ heating energy consumption: 30–40 kW
- ✶ production rate: up to 10 m/min
  up to 100 kg/hour
- ✶ size of the perpendicular lapper: 2.5 × 0.6 × 0.5 m.

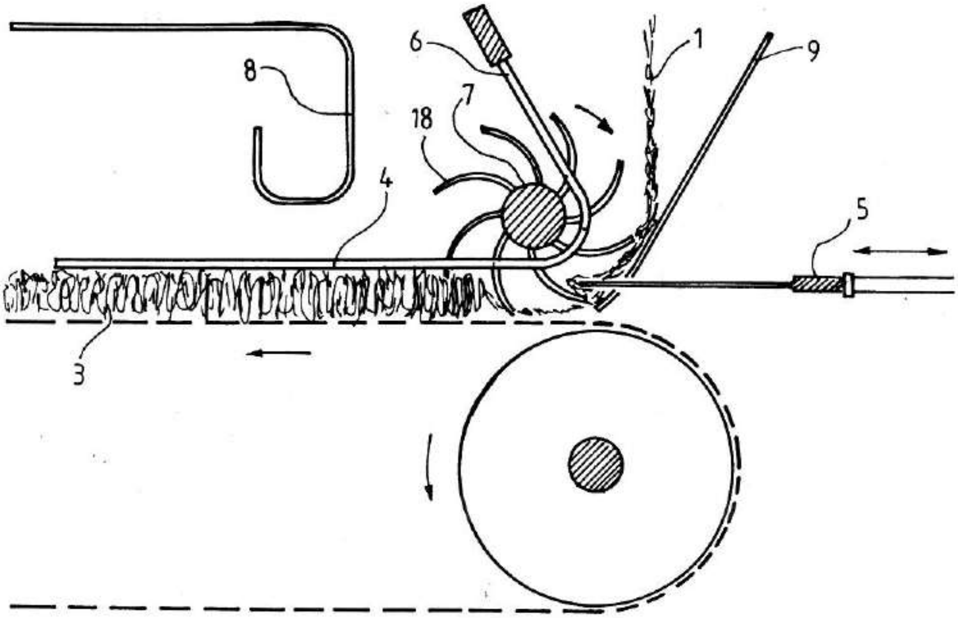

Fig. 20.2

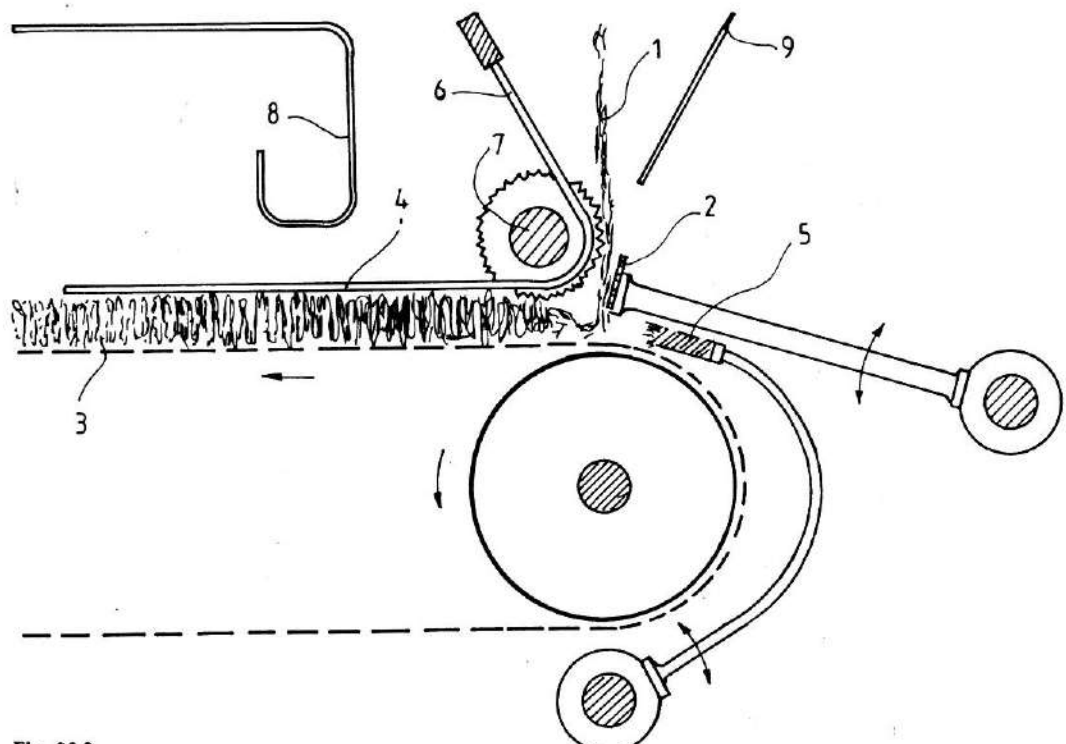

Fig. 20.3

2.2 Perpendicular Laid Textiles

STRUCTURE

The textiles STRUTO consist of a carded web formed into perpendicular positioned lamellae, so that a predominant portion of the fibres are oriented perpendicular to the textile area (Fig. 20.4). The fibre orientation leads to high compressive resistance and high resilience of the textiles. On the contrary, the strength is low, especially that in a longitudinal direction. If necessary the strength can be increased using supporting material. In this case, the supporting material is fed into the bonding chamber simultaneously with the perpendicular laid web and both the sheets are combined in one process.

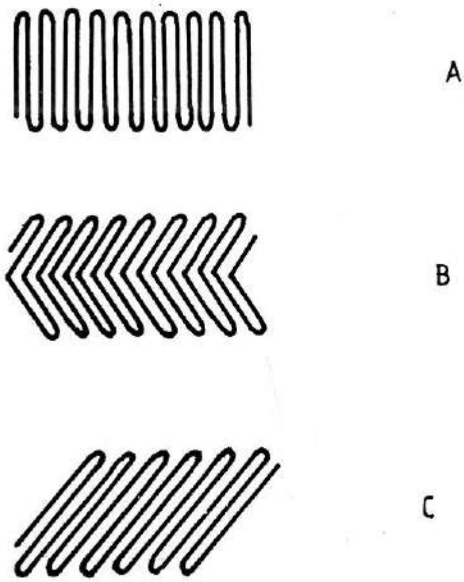

Fig. 20.4

PROPERTIES

Compressive properties of perpendicular-laid textiles are compared with those of cross-laid and air-laid fabrics in Fig. 20.5. Perpendicular-laid textiles show lower loss of thickness during the loading-deloading cycle .

The compressive properties depend on the fibre fineness as is shown in Figs. 20.6 and 20.7. In Fig. 20.8 there is the dependence of the thermal conductivity on the fibre fineness and in Fig. 20.9 that of thermal resistance, measured at a medium load.

In Fig. 20.10 the thermo-insulating properties of perpendicular-laid and cross-laid fabrics are compared. The thermal resistance is shown as a function of compression. As emerges from the results, the use of perpendicular-laid fabrics is especially advantageous at middle and high compression (clothing, sleeping bags, furniture, car seats).

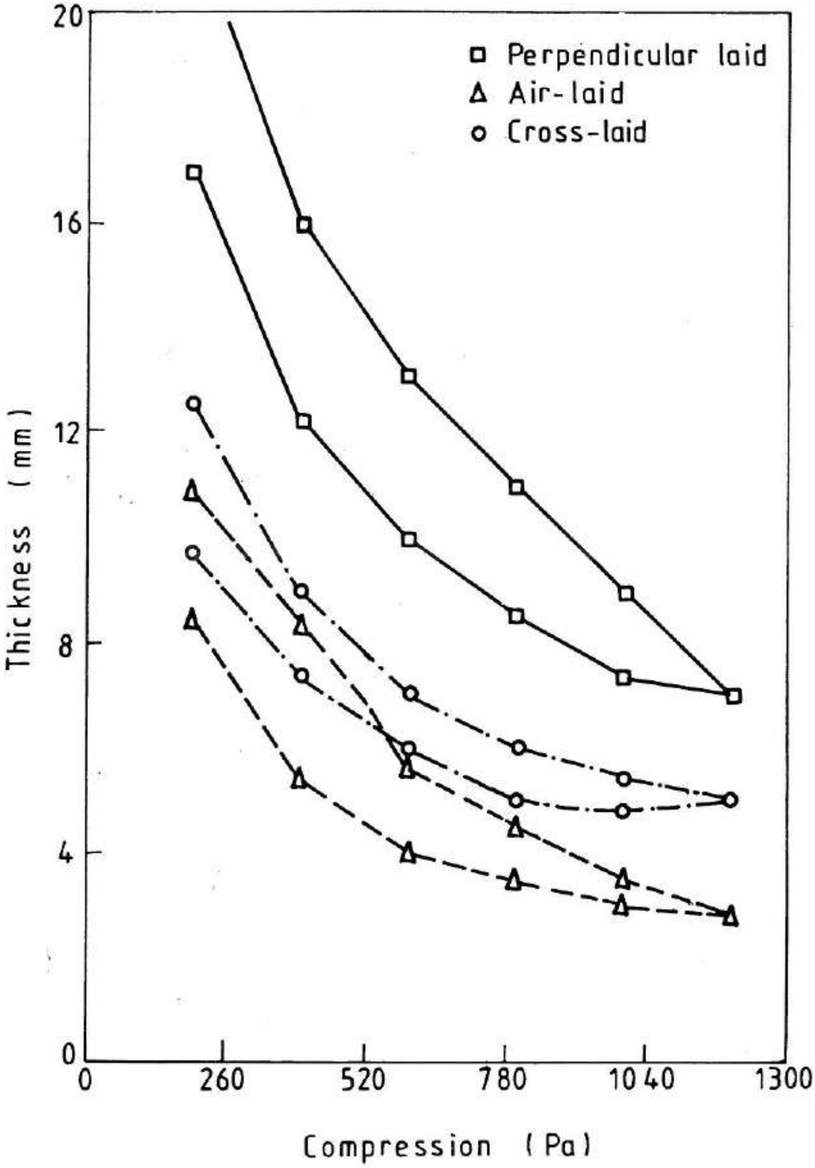

Fig. 20.5

3. CONCLUSIOUS

Perpendicular-laid textiles STRUTO is a new nonwoven technology which is bringing in a new generation of textiles. The main advantages of the technology consist in low investment, low built-up plant area, low energy consumption and high production rate. The textiles show improved quality as thermo-insulaing materials in the clothing and the construction industry, as filters, in furniture and automotive industry. The textiles are extremely interesting as replacements for polyurethane foams for their positive hygienic properties and their recyclability.

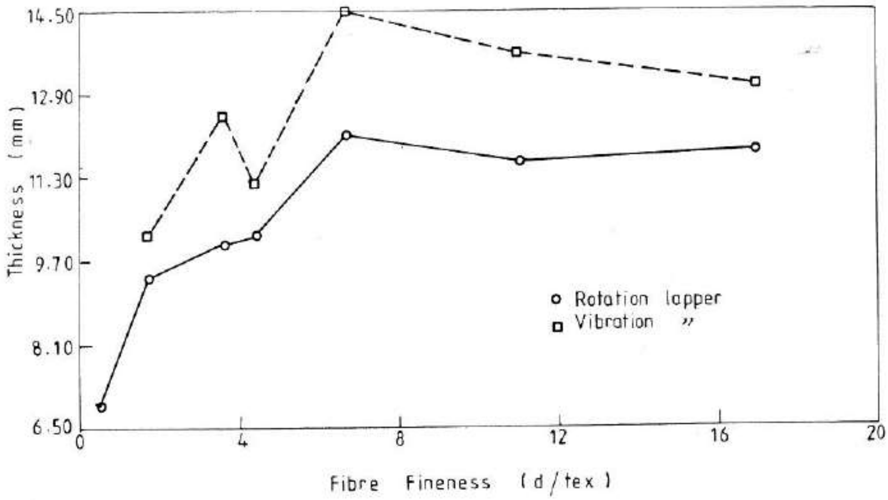

Fig. 20.6

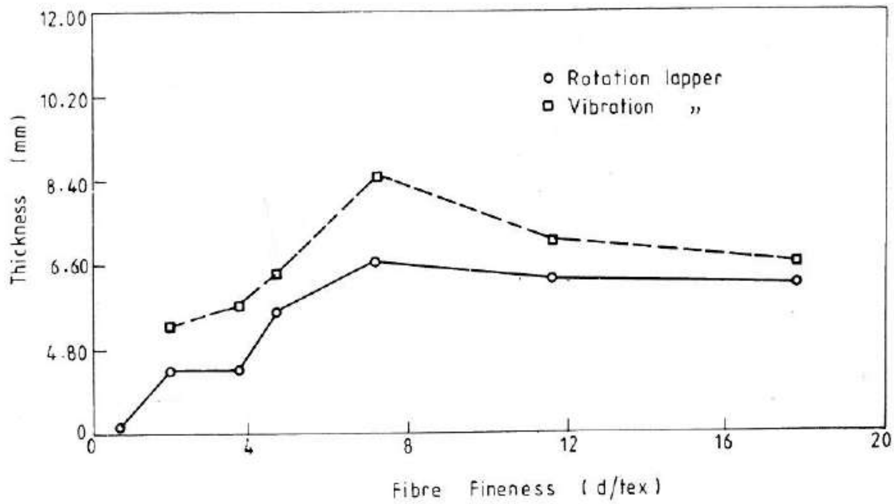

Fig. 20.7

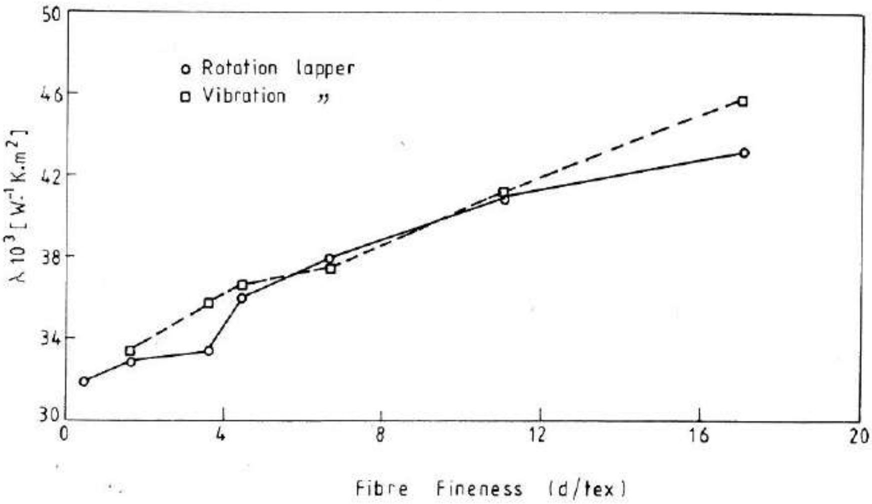

Fig. 20.8

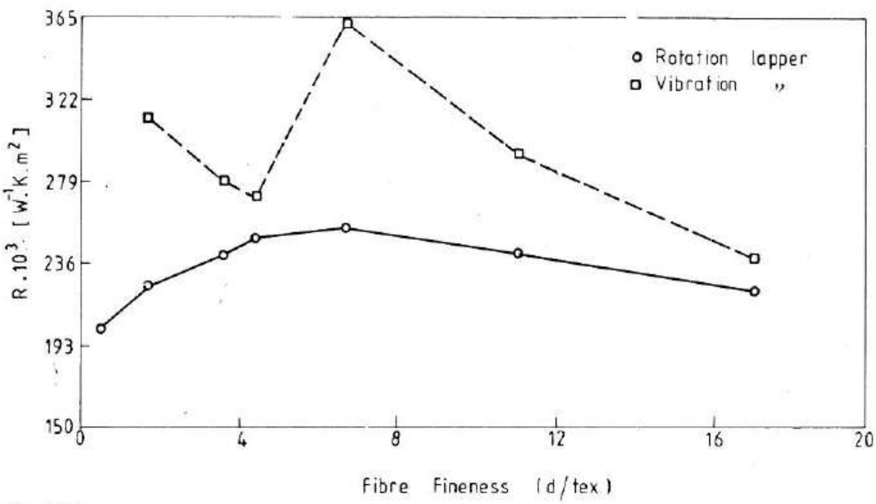

Fig. 20.9

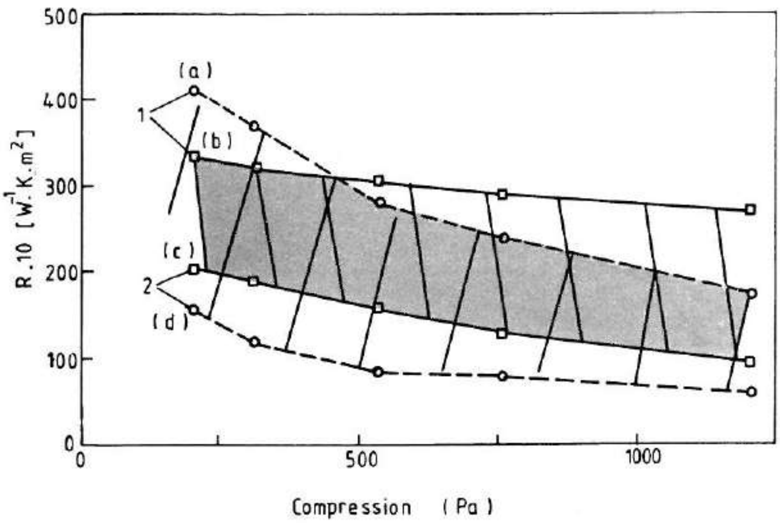

Fig. 20.10

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21

Low Cost Soil Reinforcement for Developing Countries

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At Boulton Institute significant research work relating to Reinforced Soil has been undertaken on the use of cohesive-frictional fill and non-metallic reinforcements. Much of the work has concerned the shearing interaction between geogrids and geotextiles and various fill types. This research is now being extended to cover the use of reinforcements made from natural fibres, e.g. coconut fibre (coir) and jute, within cohesive-frictional fill. The prime objective is to develop low cost soil reinforcement systems for use in slope repair and for strengthening flood banks. Both of these situations are important for developing countries.

Assistance has been obtained from the European Commission to enable a research programme to be initiated between Bolton Institute, (UK) and Moratuwa University (Sri Lanka). As a first step two 'model' retaining walls (each 3.3 m high by 6 m long) have been constructed and loaded in the Large Scale Test Facility. The reinforcements are coconut rope (coir) and jute rope laid, in a similar manner to that for conventional steel strips, in FTA fill. The PFA has similar grading and shear strength properties to soil from Sri Lanka and Bangladesh.

In addition shearing interaction tests, between the fill and the reinforcements, have been undertaken using the direct shear.

1. INTRODUCTION

Soils generally have little or no tensile strength under long-term loading, although they usually exhibit significant compressive strength. The availability and relatively low cost of soil materials promotes their use in bulk fill situations where the quantity of fill is likely to be the dominant economic factor. 'Reinforced Soil' is a soil improvement technique and construction method in which relatively stiff, tensile reinforcement is included within the fill. The strengthening effect is similar to that of the reinforcement placed in concrete although the interaction mechanism between the reinforcement and the surrounding medium is different.

The commercial applications of soil reinforcement date back only about twenty years. To date its main use has been in the construction of retaining walls and bridge abutments but it has also been used to enhance the stability of slopes. This latter application, which includes both conventional reinforced soil construction with a sloping front facing and the construction of slope buttresses, has great potential for remedial treatment and stabilization of unstable slopes. As the reinforced soil technique has gained acceptance as a reliable and advantageous method of construction so has the variety of engineering materials (chiefly bulk fill and reinforcements) which have been successfully used. Many developing countries have practical situations for which the reinforced soil technique is eminently suited, e.g. slope stabilization, flood bank construction, strengthening of unbound roads. However, for the technique to be appropriate for these regions it must be in harmony with the regional environment (climate, soil type), and it must be affordable. Obviously local soil/rock will have to be used, if at all possible, because of transport costs (even if it means re-using material from a slope that has slipped) and the finished product will be dependent on local construction methods and equipment. Consequently it is logical to use local, indigenous materials for the reinforcements and to use a reinforcement type which can be easily manufactured by local industry. The authors received a grant from the European Commission for a preliminary investigation of the use of indigenous materials for soil reinforcing in developing countries and their initial findings about the performance of elements made from jute and coconut fibres are reported herein.

2. REINFORCED SOIL

When a dense granular material is loaded then as it deforms it dilates, i.e. there is an overall increase in volume. This dilation, which results from particle interlock, causes the shearing resistance to be developed rapidly as the soil is distorted. If we make a dense, sand sample and apply a vertical load to it then small vertical settlements will be accompanied by substantial lateral expansion due to sample dilation. If we place stiff, tensile reinforcements horizontally within the sand (as indicated schematically in Fig. 21.1) then any vertical loading would induce extension of the reinforcements. However, this extension would be very small in comparison to the attempted expansion of the fill. The stress acting normal to the soil-reinforcement interface generates frictional resistance along the interface—adhesion (or adherence) between the fill and the reinforcement may enhance this 'bond' even further. Consequently, as the soil attempts to move outwards (at a faster rate than the reinforcement) the shear strength of the interface acts to confine the fill. If the 'bond' is sufficiently high then the fill cannot slide over the reinforcement and deformation of the composite material is controlled by the extensibility of the tensile inclusions.

In its practical form the basic elements of a reinforced soil structure are bulk fill, tensile reinforcements, and some form of facing to span between reinforcing elements on the external boundary of the structure and prevent localised egress of the bulk fill.

The ideal fill for Reinforced Soil structures would have the following

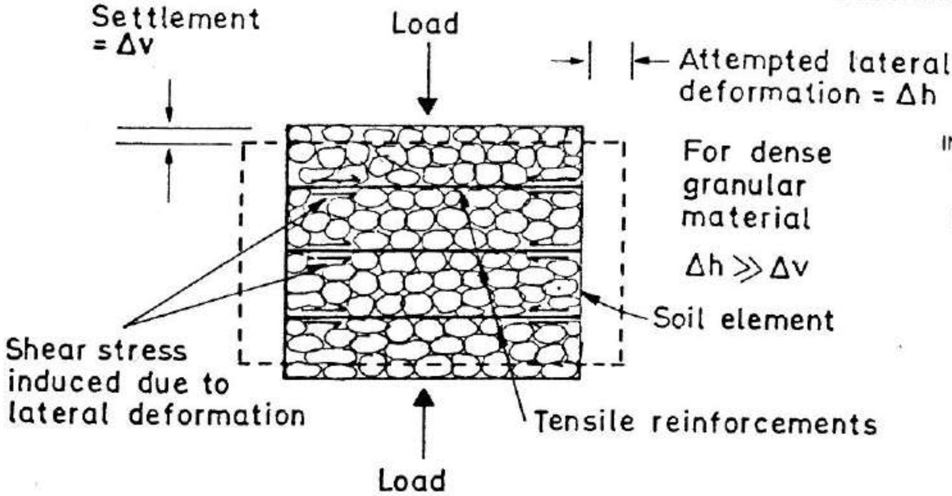


Fig. 21.1 Reinforced soil element

characteristics; high internal strength, a free-draining nature, increase in volume during shear, ready-availability, low cost. Indeed the first successful, marketed form of Reinforced Soil did use good-quality, free draining granular fill with steel strip reinforcement. However this fill is expensive and not always readily available. Furthermore as environmental awareness and recognition of the need to conserve resources has grown the increasing use has been made of 'poorer' quality fills (often waste materials or industrial by-products) such as fly ash, coal mining spoil, chalk, quarry waste, shale, cohesive soils [6]. Because of the potential aggressiveness of the damp environment usually provided by the alternative fills, and to try to reduce the cost of this form of construction, new forms of reinforcing element (grids, sheets, ropes) have been manufactured in a wide variety of ways such as sheets of polypropylene, glass fibres bonded in resin, concrete planks, bundles of polyester fibres encapsulated in sheathes. These reinforcing materials are still expensive—most likely prohibitively so, for developing countries. However, we can use the knowledge gained with these 'advanced' materials to select the most suitable and efficient form of soil reinforcement which can be produced at low cost using local materials and technology. The resultant structure is unlikely to be as durable as that produced in the United Kingdom (where a 120-year design life is required) but it will be affordable and its low cost will mean that it can be replaced as necessary.

3. RESEARCH PROGRAMME

At Bolton Institute a large amount of research has been undertaken on the shearing interaction between strip reinforcements, geogrids and geotextiles and various types of soil. The research has been extended to cover the behaviour of reinforcements made from natural fibres in conjunction with cohesive-frictional soil since this is generally the most readily-available type of fill. The first two fibres to be studies are jute and coconut (coir). The prime objective of the work is the development of a low-cost reinforcement system for use in slope repair and for strengthening flood banks. As a first step two 'model' retaining walls, each 3.3 m high and 6 m long approximately, have been erected and loaded to failure in the Large Scale Test Facility. The reinforcements were jute and coir ropes contained within Pulverised Fuel Ash (PFA) fill. PFA was used because it has similar grading and shear strength characteristics to tropical soils from Sri Lanka and Bangladesh. To design, and analyse the walls the shearing interaction between the fill and the reinforcements was measured using the direct shear box apparatus.

3.1 The Fill

Tropical soils are mainly residual soils, i.e. they are formed *in-situ* by physical, chemical or biological weathering. The most commonly-occurring residual soils derive from igneous, sedimentary and metamorphic rocks. If the parent rock is igneous or metamorphic the resulting particles typically range in size from silt to gravel. Tropical residual soils may be classified into two groups, i.e. Laterite and Saprolitic. Laterites are formed from the parent rock by chemical weathering under warm, humid conditions. Rainwater leaches out soluble rock material leaving behind the insoluble hydroxides of iron and aluminium which give the laterites their characteristic red-brown colour. These soils form a valuable source of construction material which is often used in road building. Saprolitic soil is also formed by chemical weathering but it retains all of the structural features of the parent rock.

The research programme was specifically orientated towards applications in Sri Lanka and Bangladesh. There are obviously differences between the soils of these countries, and also variations in the soils encountered within each country. However, the soils met in soil instability situations and in flood banks are likely to have similar material properties to those given in Table 21.1. Since it was clearly not possible to import from Sri Lanka or Bangladesh the fill needed for 'model' testing, i.e. 200 m^3, it was decided to use Pulverised Fuel Ash (PFA) as a 'substitute tropical soil'. The grading curve and shear strength parameters for the PFA were quite similar to typical values for Sri Lankan and Bangladeshi soils.

TABLE 21.1 Typical Soil Properties

Soil Type	P.S.D. (%)			S.G.	LL (%)	PL (%)	M.C. (%) (mg/m^3)	Bulk Density	Strength Parameters	
	Clay	Silt	Sand						c' (kN/m^2)	φ' (°)
Bangladesh	15	75	7	2.62	33	21	30	1.80	3	32
Sri Lanka	15	42	40	2.79	35	22	17	2.07	15	25
PFA	2	79	19	2.20	27	NP	22	1.56	5	30

3.2 Reinforcing Materials

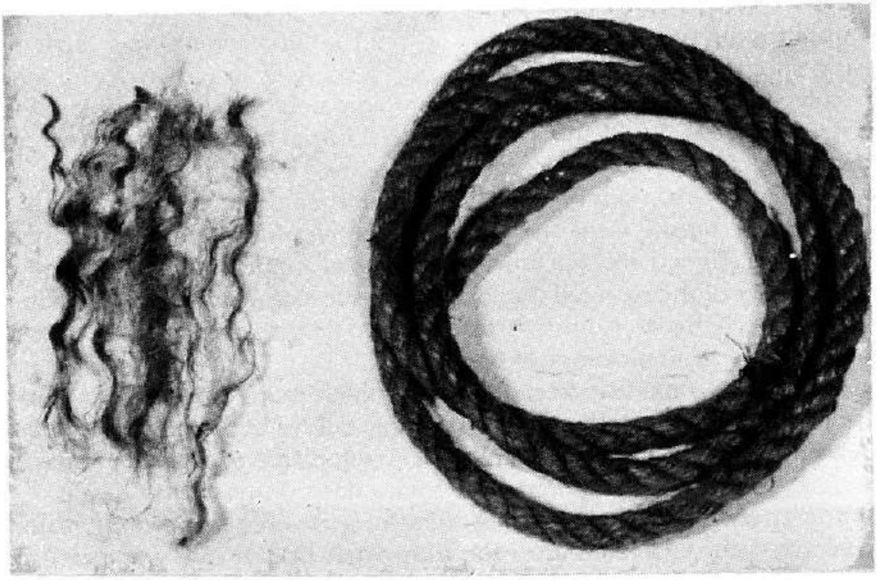
Tensile testing of both the jute and coconut reinforcements was carried out using specimens approximately 300 mm long held in the jaws of a testing machine so that the free length was approximately 180 mm. Samples of each rope were tested 'fresh' and after prolonged burial in the fill to be used in the model wall tests. The reinforcements are shown in Plates 1 and 2.

The tensile behaviour of both types of reinforcing element is shown in Fig. 21.2. At low tensile force the jute stretched significantly as the individual fibres were aligned and slackness in them was eliminated. Subsequently the extensibility of the rope fell drastically and the stress-strain relationship was approximately linear. Failure occurred due to progressive snapping of strands rather than a sudden complete breakage.

For coconut rope the stress-strain curve was more-or-less linear from the start of loading and after large extension failure occurred by progressive snapping of the individual strands. The coconut rope was much more extensible than that composed of jute with the failure strains being 85% and 33%, respectively. The properties of both ropes were significantly different from strength data relating to the individual fibres. This was particularly true for the coconut fibres where reported values of tensile strength and strain at failure have typically been of the order of 150×10^3 kN/m^2 and 30% respectively [2, 3]. The differences result from the way in which the individual fibres are intertwined to form a continuous rope.

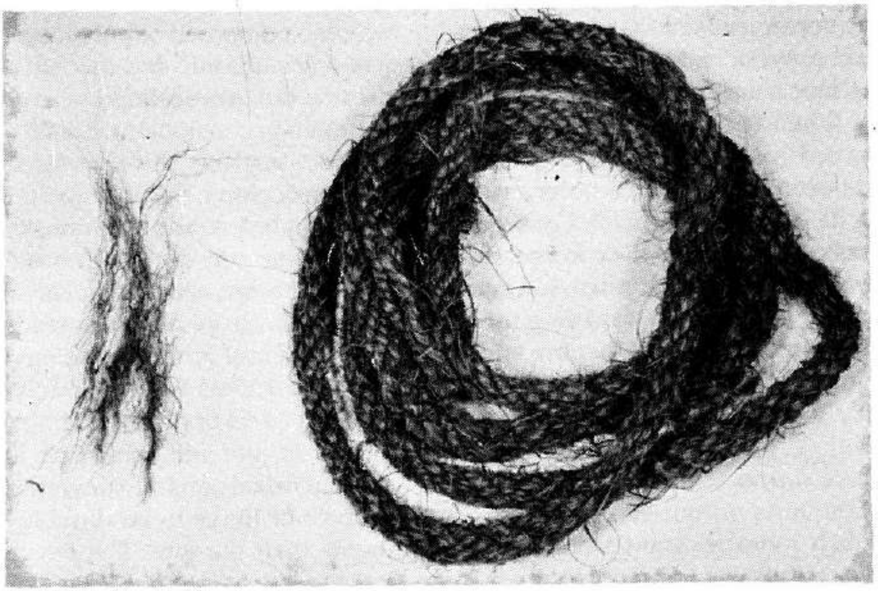
The comparative data in Table 21.2 show that the ropes tested are considerably weaker and more extensible than both traditional steel strip reinforcement and the newer reinforcing materials composed of polypropylene and polyesters. However, in their country of origin the jute and coconut fibre products are extremely cheap by comparison to the other reinforcements.

When tensile tests were carried out on rope specimens which had been buried in the fill for ten months, it was found that the jute rope had lost between 70% and 80% of its strength whilst the coconut had lost about 20% of its strength—Fig. 21.3. Consequently, although the jute rope was still much less extensible than the coconut, the load-carrying capacity of the two materials was very similar. It must be remembered that the test specimens had been buried in PFA which was being used as a substitute for tropical soil for studying the immediate strengthening effect of jute and coconut reinforcing elements. Since the pH of the PFA was 8.7 the strength reductions were probably the result of the alkaline environment rather than an effect of the moisture in the 'soil'. Previous investigations of the durability of jute and coir fibres [4, 5] have found them to be quite resistant to acid/alkali attack. Nevertheless these tests on buried specimens do show coconut fibres to be durable and much more resistant to hostile environments than the jute. The effects of extensibility of the coconut ropes could be overcome by pre-tensioning of the ropes to remove much of the original stretch as the fibres are straightened and pulled together.



(a) Fibres (b) Rope

Jute Reinforcement Plate 1



(a) Fibres (b) Rope

Coconut Reinforcement Plate 2

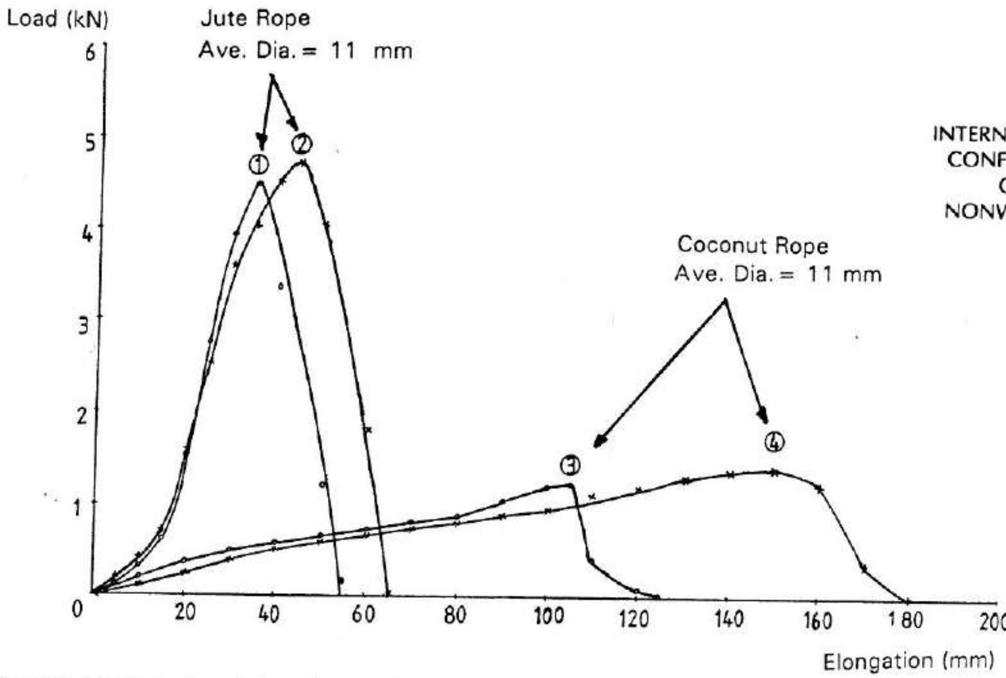


Fig. 21.2 Tensile tests on jute and coconut ropes

TABLE 21.2 Typical Reinforcement Stress-strain Data

Reinforcing Material	Ultimate Tensile Strength ($kN/m^2 \times 10^3$)	Modulus of Elasticity ($kN/m^2 \times 10^3$)	Strain at Failure (%)
Steel strip	410	210,000	5
Plastic grid	520	5,300	15
Geotextile	85	850	20
Jute rope	49	340	33
Coconut rope	14	16	85

3.3 Retaining Wall Tests

The model retaining wall apparatus consists of a facing of length 12 m (10 panels each 1.2 m wide) and height 3.3 m which is located across the open face of a three-sided bunker. Soil which is placed within the bunker (which extends for a distance of 6 m back from the facing) is contained by the facing. The soil may contain horizontal reinforcement (in which case the facing is attached to this reinforcement) or it may be unreinforced (in which case the facing is supported by a system of horizontal jacks). A front view of the model wall is shown in Plate 3.

In this preliminary work on the use of natural fibres in soil reinforcement two walls were erected and tested at the same time. On the right-hand side of the retaining wall the fill behind the outer four panels was reinforced with coconut ropes whilst on the left-hand side the outer four panels contained jute reinforcing elements—Plate 4. The reinforcements were placed

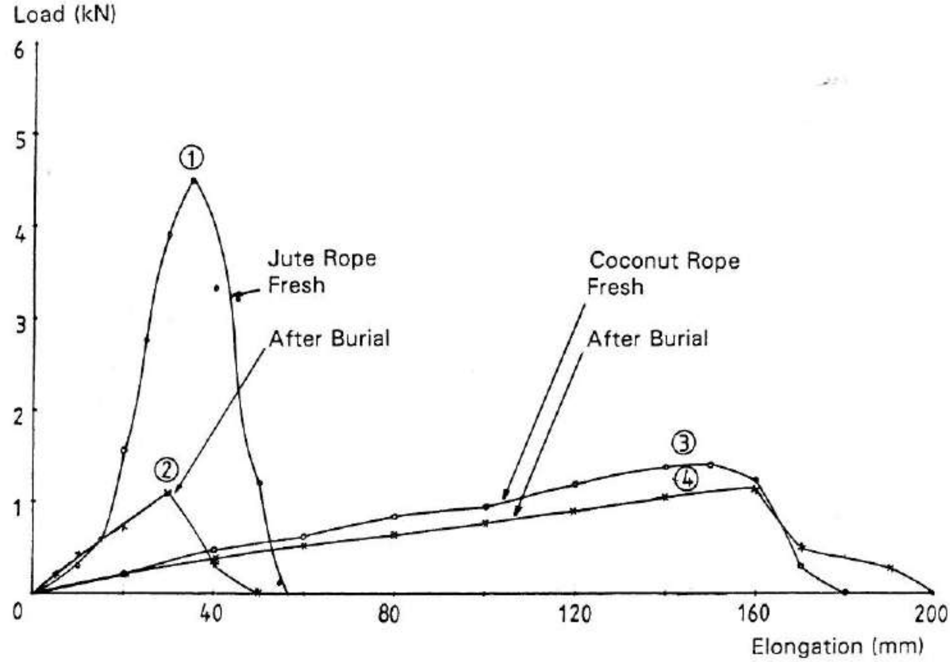


Fig. 21.3 Effect of burial on the rope

horizontally with a spacing of 250 mm in four identical layers at 812 mm centres vertically. Each reinforcement comprised a loop of rope which was passed around a horizontal steel bar. The ends of each steel bar rest against the outer flange of vertical steel columns. Horizontal timber planks are located in the vertical grooves formed by the flanges of the steel columns so that pressure by the fill on the timber planks is transmitted to the steel columns. Outward movement of the columns is constrained by the horizontal steel bars which are effectively 'anchored' in position by the ropes which pass back into the fill. The rope reinforcements extended a distance of 2.4 m, i.e. approximately three-quarters of the wall height, back into the soil behind the facing.

Fill was placed in 18 layers, each approximately 180 mm thick after compaction. Undisturbed cores were taken from each layer to check the density and moisture content. After construction of the walls they were brought to failure by placing concrete blocks and other kentledge on top of the fill. The surcharge was increased in stages, and at each stage measurements of boundary stresses and displacements were made.

The relationship between the applied surcharge and the movement of the wall face is shown in Figs. 21.4 and 21.5 for the wall containing jute reinforcement. The initial increment of load caused very little movement because it hardly exceeded the stresses imposed during the compaction process. Further loading gave an approximately linear relationship between surcharge intensity and outward movement up to almost 90% of the ultimate load capacity of the wall at which time the movement was approximately

Front view of 'Model' Retaining Wall Plate 3

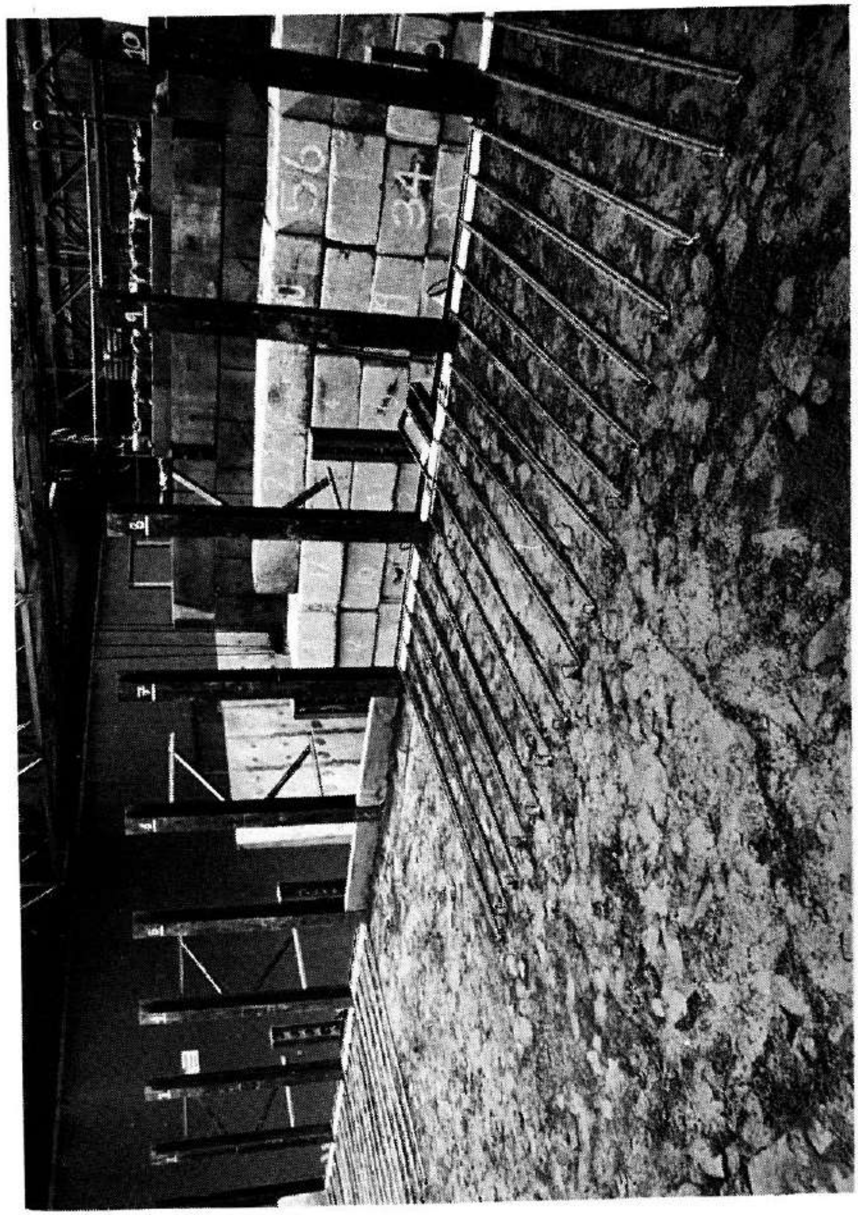


Plate 4 Arrangement of Rope Reinforcements

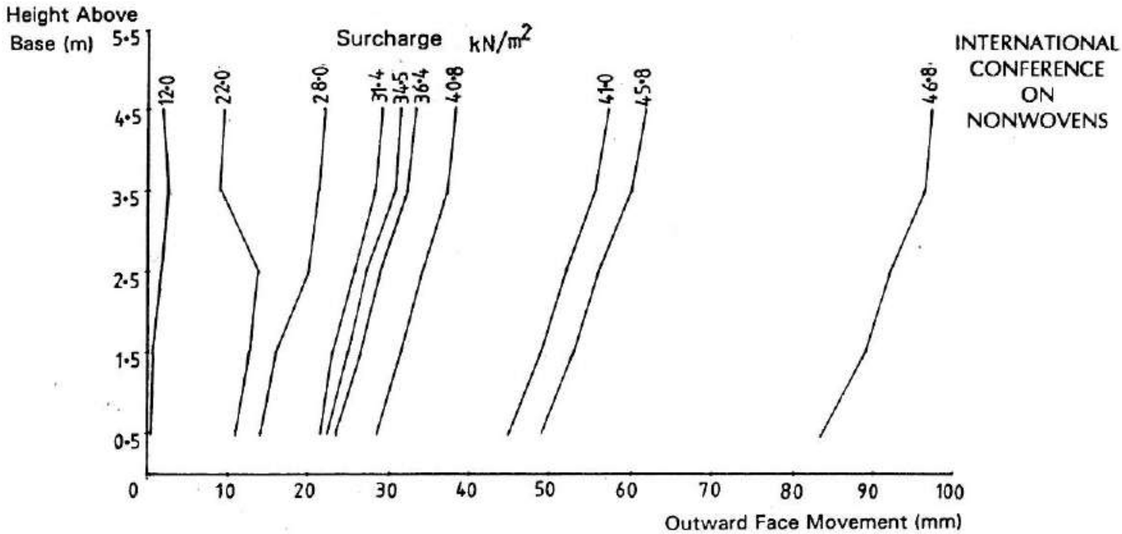


Fig. 21.4 Movement of wall face due to surcharge (Jute Reinforcement)

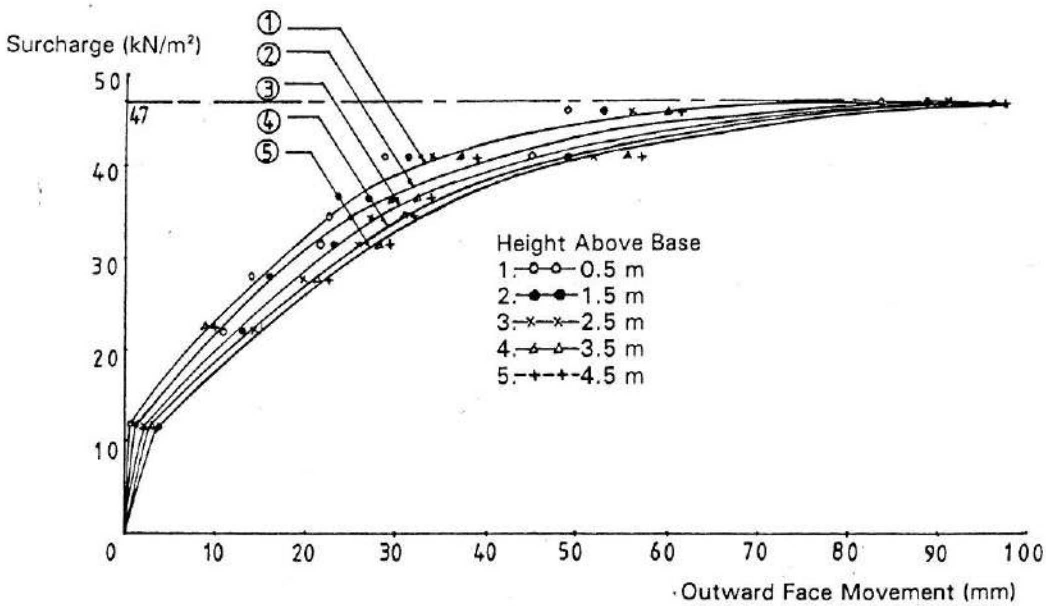


Fig. 21.5 Load-deformation behaviour of jute-reinforced wall

1.2% of the wall height. Increasing the surcharge then produced large outward movements of the wall and the surcharge to cause failure was estimated at 47

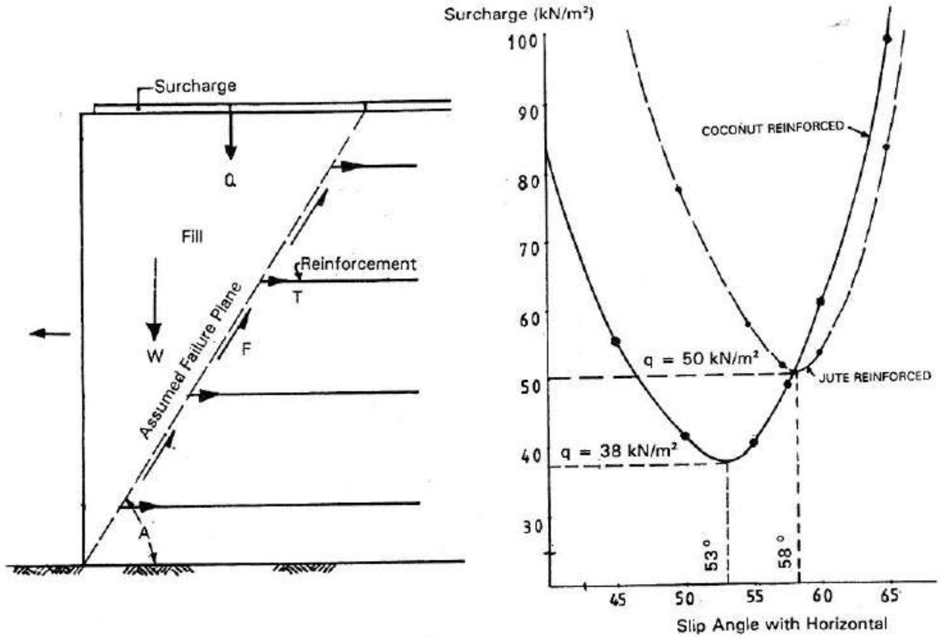


Fig. 21.6 Analysis of the retaining walls

kN/m^2. The model containing coconut reinforcements showed very similar trends but the surcharge to cause it to fail was only 36 kN/m2. It was estimated that the equivalent retaining wall containing plain PFA would fail under its own self weight. The load-carrying capacity of the reinforced walls was calculated using the tie-back approach contained within Technical Memorandum BE 3/78. In this method it is assumed that the imposed surcharge will cause a coherent wedge of fill to slide along a straigth line failure surface inclined at an angle A to the horizontal as indicated in Fig. 21.6 (a).

Resistance to failure comes from both the internal strength of the fill (F) and the anchoring effect of soil reinforcement which extends from the sliding wedge into the stable soil behind it. The anchor force (T) provided by each reinforcement is either; its ultimate tensile strength or, the bond resistance at the interface between the reinforcement and the fill for that part which protrudes beyond the sliding wedge. The value of the surcharge to cause failure depends on the orientation of the failure plane, as indicated in Fig. 21.6 (b) from which the load carrying capacity of the walls was estimated. For the jute-reinforced wall the failure was predicted to be due to insufficient bond resistance between the reinforcement and the fill. On the other hand it was predicted that failure of the coconut-reinforced wall would be accompanied by tensile failure of the upper two layers of reinforcement.

There was good correspondence between predicted and actual failure surcharges for both of the walls and the position and orientation of the failure planes was very similar to that assumed in the analysis. None of the reinforcements failed in tension but this may have been due to the limited extension of the reinforcements so that the breaking strains were not reached. The face of the retaining walls moved significantly more than would be the case with conventional reinforcements (under the same load), however if the system were employed primarily with slopes then such movements would be acceptable.

4. CONCLUDING REMARKS

These preliminary walls have demonstrated that readily-available simple ropes made from natural fibres can be used to enhance the strength of soils significantly. The resultant composite, i.e. Reinforced Soil, can be used to increase the stability of slopes or it can be used to form buttresses or embankments. Although the reinforcements used are fairly extensible most of their extension will occur during construction and thus will not affect their visual performance. Further research into the use of these natural materials could identify forms and shapes of reinforcement that are more efficient and useable than simple ropes.

5. ACKNOWLEDGEMENTS

The authors are grateful to the European Community for providing a fellowship to permit Prof de Alwis to undertake collaborative research work in the Large Scale Test Facility at Bolton Institute. The hard work of the technicians at the latter institute is much appreciated. Mr Ali's involvement with the project resulted from his postgraduate studies at Bolton Institute and he would like to thank the Overseas Development Agency for their support during this time, and the Directorate of Technical Education (Bangladesh) for granting him leave of absence.

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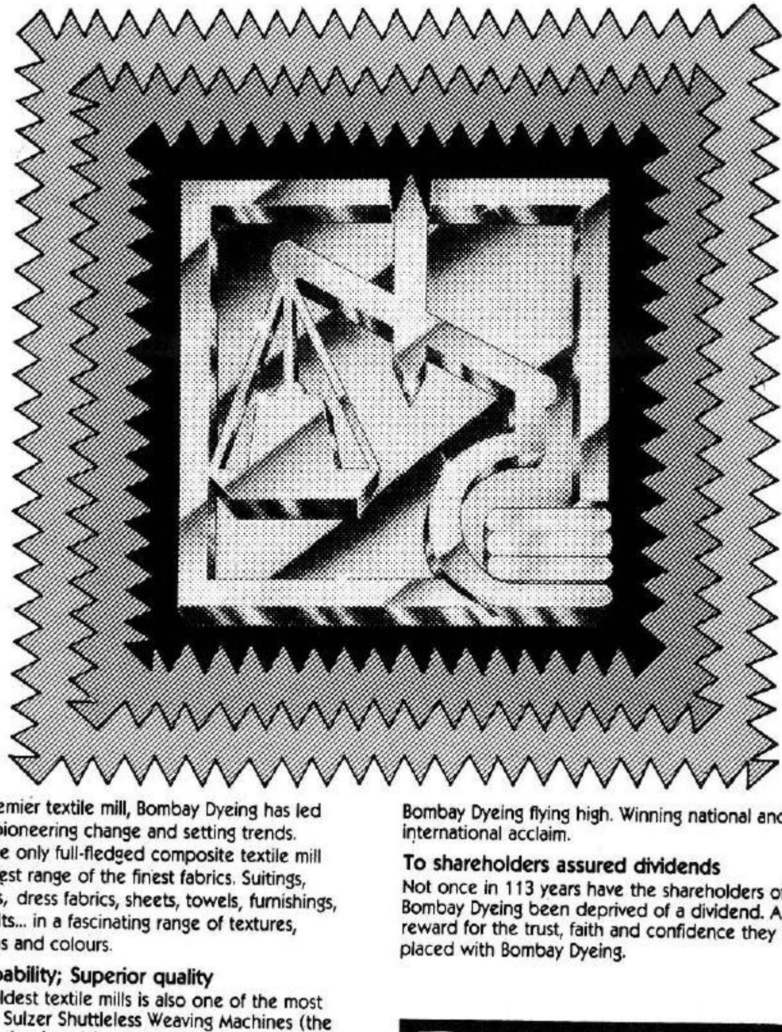

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