1

Technical textiles market – an overview

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1.1 Introduction

Although 'technical' textiles have attracted considerable attention, the use of fibres, yarns and fabrics for applications other than clothing and furnishing is not a new phenomenon. Nor is it exclusively linked to the emergence of modern artificial fibres and textiles. Natural fibres such as cotton, flax, jute and sisal have been used for centuries (and still are used) in applications ranging from tents and tarpaulins to ropes, sailcloth and sacking. There is evidence of woven fabrics and meshes being used in Roman times and before to stabilise marshy ground for road building – early examples of what would now be termed geotextiles and geogrids.

What is relatively new is a growing recognition of the economic and strategic potential of such textiles to the fibre and fabric manufacturing and processing industries of industrial and industrialising countries alike. In some of the most developed markets, technical products (broadly defined) already account for as much as 50% of all textile manufacturing activity and output. The technical textiles supply chain is a long and complex one, stretching from the manufacturers of polymers for technical fibres, coating and speciality membranes through to the converters and fabricators who incorporate technical textiles into finished products or use them as an essential part of their industrial operations. The economic scope and importance of technical textiles extends far beyond the textile industry itself and has an impact upon just about every sphere of human economic and social activity.

And yet this dynamic sector of the textile industry has not proved entirely immune to the effects of economic recession, of product and market maturity, and of growing global competition which are all too well known in the more traditional sectors of clothing and furnishings. There are no easy paths to success and manufacturers and converters still face the challenge of making economic returns commensurate with the risks involved in operating in new and complex markets. If anything, the constant need to develop fresh products and applications, invest in new processes and equipment, and market to an increasingly diverse range of customers, is more demanding and costly than ever.

Technical textiles has never been a single coherent industry sector and market segment. It is developing in many different directions with varying speeds and levels of success. There is continual erosion of the barriers between traditional definitions of textiles and other 'flexible engineering' materials such as paper and plastics, films and membranes, metals, glass and ceramics. What most participants have in common are many of the basic textile skills of manipulating fibres, fabrics and finishing techniques as well as an understanding of how all these interact and perform in different combinations and environments. Beyond that, much of the technology and expertise associated with the industry resides in an understanding of the needs and dynamics of many very different end-use and market sectors. It is here that the new dividing lines within the industry are emerging.

An appreciation of the development and potential of technical textile markets therefore starts with some clarification of the evolving terminology and definitions of scope of the industry and its markets. This chapter goes on to consider some of the factors – technical, commercial and global – which are driving the industry forward.

It also considers how the emergence of new geographical markets in China and other rapidly industrialising regions of the world looks set to be one of the major influences on the growth and location of technical textiles manufacturing in the first 10 years of the 21st century.

1.2 Definition and scope of technical textiles

The definition of technical textiles adopted by the authoritative *Textile Terms and Definitions*, published by the Textile Institute[1], is 'textile materials and products manufactured primarily for their technical and performance properties rather than their aesthetic or decorative characteristics'.

Such a brief description clearly leaves considerable scope for interpretation, especially when an increasing number of textile products are combining both performance and decorative properties and functions in equal measure. Examples are flame retardant furnishings and 'breathable' leisurewear. Indeed, no two published sources, industry bodies or statistical organisations ever seem to adopt precisely the same approach when it comes to describing and categorising specific products and applications as technical textiles.

It is perhaps not surprising that any attempt to define too closely and too rigidly the scope and content of technical textiles and their markets is doomed to failure. In what is one of the most dynamic and broad ranging areas of modern textiles, materials, processes, products and applications are all changing too rapidly to define and document. There are even important linguistic and cultural perceptions of what constitutes a technical textile from geographical region to region in what is now a global industry and marketplace.

1.2.1 Technical or industrial textiles: what's in a name?

For many years, the term 'industrial textiles' was widely used to encompass all textile products other than those intended for apparel, household and furnishing end-uses. It is a description still more widely favoured in the USA than in Europe and elsewhere (see, for example, the Wellington Sears Handbook of Industrial Textiles).[2]

This usage has seemed increasingly inappropriate in the face of developing applications of textiles for medical, hygiene, sporting, transportation, construction, agricultural and many other clearly non-industrial purposes. Industrial textiles are now more often viewed as a subgroup of a wider category of technical textiles, referring specifically to those textile products used in the course of manufacturing operations (such as filters, machine clothing, conveyor belts, abrasive substrates etc.) or which are incorporated into other industrial products (such as electrical components and cables, flexible seals and diaphragms, or acoustic and thermal insulation for domestic and industrial appliances).

If this revised definition of industrial textiles is still far from satisfactory, then the problems of finding a coherent and universally acceptable description and classification of the scope of technical textiles are even greater. Several schemes have been proposed. For example, the leading international trade exhibition for technical textiles, Techtextil (organised biennially since the late 1980s by Messe Frankfurt in Germany and also in Osaka, Japan), defines 12 main application areas (of which textiles for industrial applications represent only one group):

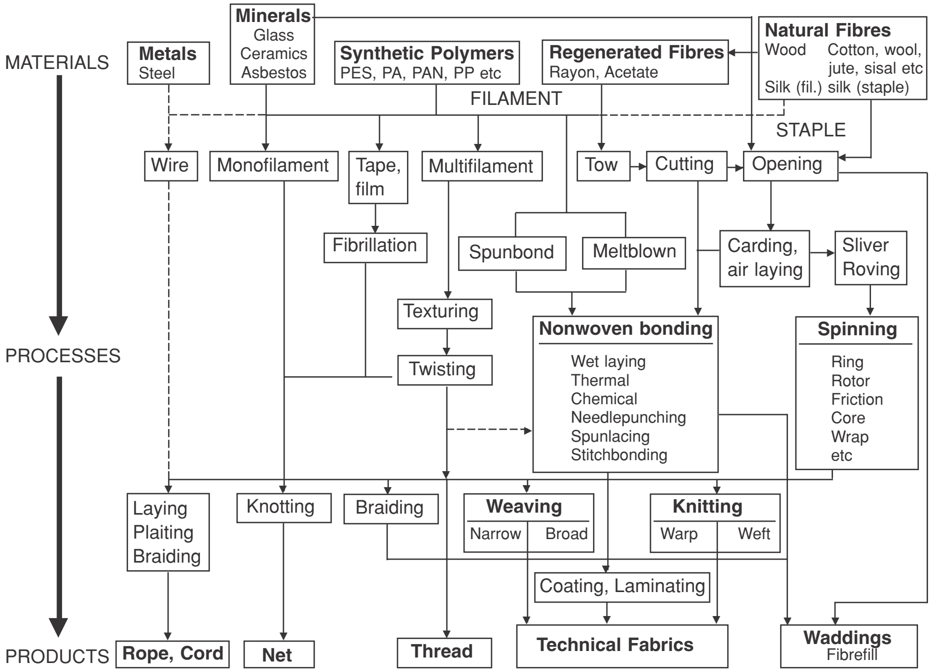
- agrotech: agriculture, aquaculture, horticulture and forestry
- buildtech: building and construction
- clothtech: technical components of footwear and clothing
- geotech: geotextiles and civil engineering
- hometech: technical components of furniture, household textiles and floorcoverings
- indutech: filtration, conveying, cleaning and other industrial uses
- medtech: hygiene and medical
- mobiltech: automobiles, shipping, railways and aerospace
- oekotech: environmental protection
- packtech: packaging
- protech: personal and property protection
- sporttech: sport and leisure.

The search for an all embracing term to describe these textiles is not confined to the words ‘technical’ and ‘industrial’. Terms such as performance textiles, functional textiles, engineered textiles and high-tech textiles are also all used in various contexts, sometimes with a relatively specific meaning (performance textiles are frequently used to describe the fabrics used in activity clothing), but more often with little or no precise significance.

1.2.2 Operating at the boundaries of textiles

If the adjective ‘technical’ is difficult to define with any precision, then so too is the scope of the term textiles. Figure 1.1 summarises the principal materials, processes and products which are commonly regarded as falling within the scope of technical textiles manufacturing.

However, there remain many grey areas. For example, the manufacture and processing of metallic wires into products such as cables, woven or knitted screens and meshes, and reinforcing carcasses for tyres are not generally regarded as lying within the scope of the textile industry. This is despite the fact that many of the techniques employed and the final products obtained are closely related to conventional textile fibre equivalents.

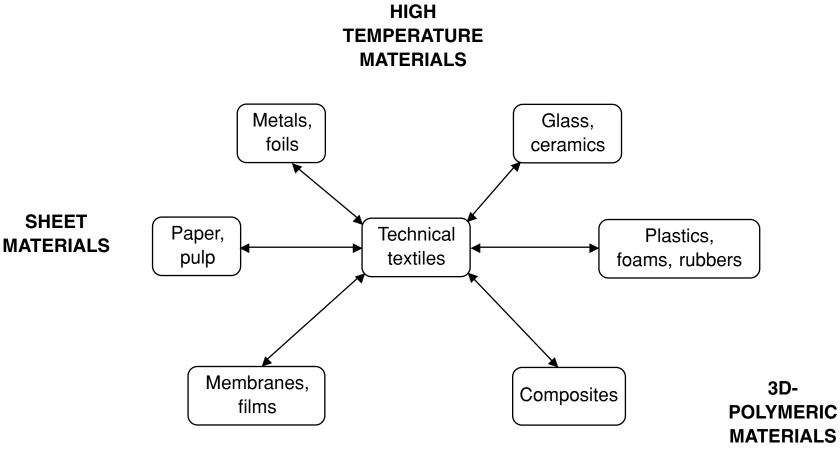


1.1 Technical textile materials, processes and products. PES = polyester, PA = polyamide, PAN = polyacrylonitrile.

Within the composites industry, woven, knitted, braided, nonwoven and wound yarn reinforcements made from glass, carbon fibre and organic polymer materials such as aramids are all now widely accepted as being technical textile products. On the other hand, more loosely structured reinforcing materials such as chopped strand mat, milled glass and pulped organic fibres are often excluded.

The nonwovens industry has developed from several different technology directions, including paper manufacturing. The current definition of a nonwoven promulgated, for example, under the International Standards Organization standard ISO 9092[3] acknowledges a number of borderline areas, including wet-laid products and extruded meshes and nets. Likewise, distinctions between textile fibres and filaments, slit or fibrillated films, monofilaments and extruded plastics inevitably boil down to some fairly arbitrary and artificial criteria. Diameter or width is often used as the defining characteristic, irrespective of the technologies used or the end-uses served. Many of the definitions and categories embodied within existing industry statistics reflect historical divisions of the main manufacturing sectors rather than a functional or market-based view of the products involved.

Polymer membranes, composite materials and extruded grids and nets are other products which challenge traditional notions of the scope of technical textile materials, processes and products. Increasingly, technical textiles are likely to find their place within a broader industry and market for ‘flexible engineering materials’ (Fig. 1.2). A number of companies and groups have already adopted this outlook and operate across the boundaries of traditional industry sectors, focusing a range



1.2 Scope of flexible engineering materials.

of materials, process technologies and product capabilities upon specific functions and markets such as filtration and health care.

1.2.3 Inconsistent statistical reporting

To add to this complexity, different geographical regions and countries tend to adopt rather different viewpoints and definitions with regard to all of the above. A widely quoted misconception that technical textiles in Japan account for over 40% of all textile output or nearly twice the level in Western Europe can largely be put down to the different statistical bases employed. In Europe, the most authoritative source of fibre consumption (and therefore textile output) data is CIRFS (Comité International de la Rayonne et des Fibres Synthétiques), the European artificial fibre producers association. However, CIRFS' reported statistics (at least until recently) have specifically excluded tape and film yarns (a significant proportion of all polyolefin textiles), coarser monofilaments and all glass products (as well as natural fibres such as jute, flax, sisal, etc.). The merger of CIRFS and EATP, the European Polyolefin Textiles Association, should go some way towards resolving this anomaly.

The Japanese 'Chemical' Fibres Manufacturers Association, JCFA, at the other extreme, includes all these products, including natural fibres, within its definition of technical/industrial textiles while the Fiber Statistics Bureau in the USA includes polyolefin tape and monofilament yarns but excludes glass. Table 1.1 attempts to restate the relative usage of the main technical fibres and yarns on a more consistent basis.

In this new light, Japan still retains a leading position worldwide in terms of the proportion of its total textile manufacturing output devoted to technical textiles. However, this is largely a reflection of the importance of its automotive manufacturing industry (a key user of technical textiles) combined with the relatively smaller size of its apparel and furnishing textile sectors (especially floor coverings). The USA apparently accounts for the lowest proportion of technical

Table 1.1 Comparative levels of technical fibre mill consumption, 1995

	% Total fibre consumption + kg per capita		
	Textile fibres only	Textile fibre, PP tape and monofilaments	Textile fibre, PP tape, monofilaments and glass
W Europe	21%	28%	34%
	2.8 kg	4.2 kg	5.6 kg
USA	18%	22%	30%
	4.9 kg	6.4 kg	9.7 kg
Japan	30%	35%	41%
	3.3 kg	4.3 kg	5.5 kg

Source: CIRFS, Fiber Organon, JCFA and David Rigby Associates estimates.
PP = polypropylene.

textile output of the three major industrial regions but still produces and consumes the largest quantity per capita, especially when all glass textile and technical fibre uses are included.

1.3 Milestones in the development of technical textiles

Although the development of technical and industrial applications for textiles can be traced back many years, a number of more recent milestones have marked the emergence of technical textiles as we know them today. Very largely, these have centred upon new materials, new processes and new applications.

1.3.1 Developments in fibre materials – natural fibres

Until early in the 20th century, the major fibres available for technical and industrial use were cotton and various coarser vegetable fibres such as flax, jute and sisal. They were typically used to manufacture heavy canvas-type products, ropes and twines, and were characterised by relatively heavy weight, limited resistance to water and microbial/fungal attack as well as poor flame retardancy.

Some of the present day regional patterns of technical textiles manufacturing were established even then, for example Dundee, on the east coast of Scotland and located at the centre (then) of an important flax growing area as well as being a whaling port. Following the discovery that whale oil could be used to lubricate the spinning of the relatively coarse jute fibres then becoming available from the Indian subcontinent, jute fabrics were widely used for sacking, furniture and carpet manufacturing, roofing felts, linoleum flooring, twine and a host of other applications.

Although its jute industry was to decline dramatically from a peak at around 1900 owing to competition from other materials as well as from cheaper imports, Dundee and the surrounding industry subsequently become a nucleus for development of the UK polypropylene industry in the 1960s. The then newly available polymer proved not only to be an ideal technical substitute for the natural product but was also much more consistent in terms of its supply and price.

Traditional end-uses for sisal were similarly rapidly substituted throughout the established rope, twine and net making centres of Europe and America.

Wool proved far less versatile and economic for most industrial applications although it is still valued for its insulating and flame retardency properties and finds use in several high temperature and protective clothing applications. Silk is an even more exotic fibre, rarely used in technical applications other than for highly specialised uses such as surgical suture thread. However, the traces of the early silk industry are still to be seen in the present day location of centres for technical filament weaving such as the Lyons area of France. The traditional silk industry has also contributed to the development of technical textiles in Asia, especially in Japan.

1.3.2 Viscose rayon

The first commercially available synthetic fibre, viscose rayon, was developed around 1910 and by the 1920s had made its mark as reinforcement material for tyres and, subsequently, other mechanical rubber goods such as drive belts, conveyors and hoses. Its relatively high uniformity, tenacity and modulus (at least when kept dry within a rubber casing), combined with good temperature resistance, proved ideal for the fast emerging automotive and industrial equipment markets.

At a much later stage of its lifecycle, other properties of viscose such as its good absorbency and suitability for processing by paper industry-type wet laying techniques contributed to its role as one of the earliest and most successful fibres used for nonwoven processing, especially in disposable cleaning and hygiene end-uses.

1.3.3 Polyamide and polyester

Polyamide (nylon) fibre, first introduced in 1939, provided high strength and abrasion resistance, good elasticity and uniformity as well as resistance to moisture. Its excellent energy absorbing properties proved invaluable in a range of end-uses from climbing ropes to parachute fabrics and spinnaker sails. Polyamide-reinforced tyres are still used much more extensively in developing countries where the quality of road surfaces has traditionally been poor as well as in the emerging market for off-road vehicles worldwide. This contrasts to Western Europe where average road speeds are much greater and the heat-resistant properties of viscose are still valued.

From the 1950s onwards, the huge growth in world production of polyester, initially for apparel and household textile applications, provided the incentive and economies of scale needed to develop and engineer this fibre as a lower cost alternative to both viscose and polyamide in an increasing range of technical applications.

Nowhere is this more true than Japan and the developing industrial economies of Asia, including China, where production capacities for both polyester staple and filament yarn are extremely high and there is an urgent search for new applications. Some high volume applications for technical textiles which would typically use polyolefins in western Europe and North America such as geotextiles, carpet backing and coverstock are more likely to use polyester in Asia largely because of the greater availability and better economics of fibre supplies in those regions.

At a slightly less obvious level, differences in the polyamide supply situation – Western Europe and North America are more strongly oriented towards nylon 66 while Asia and Eastern Europe produce predominantly nylon 6 – are reflected in different manufacturing practices, product types and technical applications for this fibre.

Yet another example is the production and use of Vinylon (PVA, polyvinyl alcohol) fibres in Japan, where they were developed for a variety of industrial and technical applications at a time when that country lacked other raw materials and fibre production capabilities. Use of this fibre for technical textiles is almost non-existent in the West.

1.3.4 Polyolefins

The development of polyolefin (mostly polypropylene but also some polyethylene) fibres as well as tape and film yarns in the 1960s was another milestone in the development of technical textiles. The low cost and easy processability of this fibre, combined with its low density and good abrasion and moisture-resistant properties, have allowed its rapid introduction into a range of applications such as sacks, bags and packaging, carpet backings and furniture linings as well as ropes and netting. Many of these markets were directly taken over from jute and similar fibres but newer end-uses have also been developed, including artificial sports surfaces.

Properties of the polyolefins such as their poor temperature resistance and complete hydrophobicity have been turned to advantage in nonwovens. Initially used in conjunction with viscose to permit thermal bonding, polypropylene has now benefited from a growing appreciation of the important role that moisture wicking (as opposed to absorption) can play in hygiene applications such as coverstock for diapers (nappies). Finally, the relatively low extrusion temperatures of the polyolefins have proved ideally suited to the fast developing technologies of spin laying (spun bonding and melt blowing).

As noted above, the development of the polypropylene industry was initially focused on European and North American markets. However, it is undergoing a major expansion worldwide as new investment in polymer capacity offers more favourable economics to new geographical markets.

1.3.5 High performance fibres

The above 'conventional' fibre types, both chemical and natural, still account for over 95% of all organic fibre technical textiles in use (i.e. excluding glass, mineral and metal fibres). Many of them have been modified and tailored to highly specific end-uses by adjustment of their tenacity, length, decitex, surface profile, finish and even by their combination into hybrid and bicomponent products. However, it is the emergence of the so-called high performance fibres since the early 1980s that has provided some of the most significant and dramatic impulses to the evolution of technical textiles.

First and foremost of these are the aramids, both the highly temperature-resistant *meta*-aramids (widely used in protective clothing and similar applications) and the high strength and modulus *para*-aramids (used in a host of applications ranging from bulletproof vests to reinforcement of tyres, hoses, friction materials, ropes and advanced composites). From their commercial introduction in the 1970s, world demand for *p*-aramids is expected to reach almost 40000 tonnes per annum by 2000 while for *m*-aramids, consumption will be around 17–18000 tonnes.

While not huge in overall terms (representing less than 0.5% of total world technical fibre and yarn usage in volume terms but closer to 3–4% in value), the aramids represent a particularly important milestone in the development of the technical textiles industry. Partly practical and partly symbolic, the introduction of the aramids not only led to the injection of large amounts of technical and market support into the industry and for users by leading fibre manufacturers such as DuPont and Akzo, but also concentrated the minds of many developers of new products upon the possibilities (and practicalities) of using similar new generation materials.

The early success of the aramids was a welcome contrast to the development of carbon fibres, which have been commercially available since the 1960s but largely constrained by their high material and processing costs to selected high value markets, particularly aerospace applications. Total world demand for carbon fibres was still only some 8–9000 tonnes per annum as recently as 1995. In fact, their market actually shrank in the early 1990s owing to cutbacks in military spending.

At long last, carbon fibres appear to be emerging from the doldrums, with the appearance not only of important new civil aerospace markets but also of high technology sporting goods and industrial applications such as wind generator turbine blades and reinforced fuel tanks. As new manufacturing methods and greater economies of scale start to bring prices down, the feasibility of even larger scale applications such as the reinforcement of buildings and structures in earthquake zones becomes more attractive. Currently, (2000), consumption is considered to be over 13 000 tonnes per annum, rising to almost 19 000 tonnes by the year 2005.

The introduction of other high performance fibres proliferated, particularly during the late 1980s, and in the wake of the aramids. These included a range of heat and flameproof materials suitable for protective clothing and similar applications (such as phenolic fibres and PBI, polybenzimidazole), ultra-strong high modulus polyethylene (HMPE) for ballistic protection and rope manufacture, and chemically stable polymers such as polytetrafluoroethylene (PTFE), polyphenylene sulphide (PPS) and polyethyletherketone (PEEK) for use in filtration and other chemically aggressive environments.

Individually, none of these other fibres has yet achieved volume sales anywhere near those of the aramids (or even carbon fibres). Indeed, the output of some speciality fibres can still be measured in tens of tonnes per year rather than hundreds or thousands. The widespread industrial recession of the early 1990s caused many fibre manufacturers to review their development strategies and to focus upon narrower ranges of products and markets.

1.3.6 Glass and ceramics

Glass has, for many years, been one of the most underrated technical fibres. Used for many years as a cheap insulating material as well as a reinforcement for relatively low performance plastics (fibre glass) and (especially in the USA) roofing materials, glass is increasingly being recognised as a sophisticated engineering material with excellent fire and heat-resistant properties. It is now widely used in a variety of higher performance composite applications, including sealing materials and rubber reinforcement, as well as filtration, protective clothing and packaging.

The potential adoption of high volume glass-reinforced composite manufacturing techniques by the automotive industry as a replacement for metal body parts and components, as well as by manufacturing industry in general for all sorts of industrial and domestic equipment, promises major new markets. Total world consumption of 'textile' glass in technical applications was some 2.3 million tonnes per annum in 1995 and is considered likely to be over 2.9 million tonnes at 2000, representing over 20% of all technical fibre consumption.

Various higher performance ceramic fibres have been developed but are restricted to relatively specialised applications by their high cost and limited mechanical properties.

1.4 Textile processes

Figure 1.1 summarises the wide range of processes employed in the manufacture of technical textiles. Apart from the use of plaiting and knotting for the manufacture of ropes and nets, weaving was, for many years, the pre-eminent technology employed in the manufacture of 'industrial' textiles. In terms of the total weight of textiles produced, weaving still plays a leading role and developments such as three-dimensional and crimpless weaving have opened up many new product and end-use possibilities.

However, the historical progress of technical textiles has seen the advance of alternative textile forming technologies, most prominently the broad family of nonwoven techniques but also warp and weft knitting, stitchbonding and modern braiding methods. The use of loose fibres with sophisticated cross-sectional profiles for insulation, protection and fibrefill applications is another important growth area. Fibres, yarns and textiles of all types also provide the starting point for a diverse and fast expanding range of composite reinforcement and forming technologies.

According to a major study of the world technical textiles industry and its markets projected to 2005 (see Table 1.2), nonwovens are set to overtake weaving (in terms of the total weight of textiles produced) by around 2002/2003. In area terms, nonwovens already far exceed woven and other fabric forming methods because of their lower average weight per unit area. On the other hand, woven and other yarn-based fabrics will remain in the lead in value terms, at least for the foreseeable future.

There is, therefore, something for every section of the textile industry in the future of technical textiles. Most product areas will see more rapid growth in value

Table 1.2 Worldwide consumption of technical textiles by product type, 2000–2005

	10^3 tonnes			\$ million		
	2000	2005	Growth (% pa)	2000	2005	Growth (% pa)
Fabrics	3760	4100	1.7%	26710	29870	2.2%
Nonwovens	3300	4300	5.4%	14640	19250	5.6%
Composites	1970	2580	5.5%	6960	9160	5.6%
Other textiles[a]	2290	2710	3.4%	11950	14060	3.3%
All textile products	11320	13690	3.9%	60260	72340	3.7%

Source: David Rigby Associates/Techtextil.

[a] Includes ropes, twines, thread, fibrefill etc.

Table 1.3 Worldwide consumption of technical textiles by application, 2000–2005

	10^3 tonnes			$ million		
	2000	2005	Growth (% pa)	2000	2005	Growth (% pa)
Transport textiles (auto, train, sea, aero)	2220	2480	2.2	13080	14370	1.9
Industrial products and components	1880	2340	4.5	9290	11560	4.5
Medical and hygiene textiles	1380	1650	3.6	7820	9530	4.0
Home textiles, domestic equipment	1800	2260	4.7	7780	9680	4.5
Clothing components (thread, interlinings)	730	820	2.3	6800	7640	2.4
Agriculture, horticulture and fishing	900	1020	2.5	4260	4940	3.0
Construction – building and roofing	1030	1270	4.3	3390	4320	5.0
Packaging and containment	530	660	4.5	2320	2920	4.7
Sport and leisure (excluding apparel)	310	390	4.7	2030	2510	4.3
Geotextiles, civil engineering	400	570	7.3	1860	2660	7.4
Protective and safety clothing and textiles	160	220	6.6	1640	2230	6.3
Total above	**11340**	**13680**	**3.9**	**60270**	**72360**	**3.7**
Ecological protection textiles[a]	230	310	6.2	1270	1610	4.9

Source: David Rigby Associates/Techtextil.

[a] Already counted in several categories above.

than in volume as technical textiles become increasingly sophisticated and employ more specialised and higher value raw materials. On the other hand, the total value of yarns and fibres and of all technical textile products will grow slightly less fast than their volume because of a changing mix of materials and technologies, especially reflecting the growth of nonwovens.

1.5 Applications

The same study identified size and growth trends in each major application area for technical textiles, as defined by the organisers of Techtextil. The results are presented in Table 1.3.

Ecological textiles were identified as a separate and potentially important growth segment but are not consolidated in the total consumption figure because they have already been counted under headings such as industrial textiles (filtration media, oil spill protection and absorption) and geotextiles (geomembrane liners for toxic waste pits, erosion protection textiles, etc.).

Some selected examples of these broad trends which illustrate key aspects of the development and use of technical textiles are discussed in further detail below.

1.5.1 Transport textiles

Transport applications (cars, lorries, buses, trains, ships and aerospace) represent the largest single end-use area for technical textiles, accounting for some 20% of the total. Products range from carpeting and seating (regarded as technical rather than furnishing textiles because of the very stringent performance characteristics which they must fulfil), through tyre, belt and hose reinforcement, safety belts and air bags, to composite reinforcements for automotive bodies, civil and military aircraft bodies, wings and engine components, and many other uses.

The fact that volume and value growth rates in these applications appear to be amongst the lowest of any application area needs to be interpreted with caution. The automotive industry (which accounts for a high proportion of all transport textiles) is certainly one of the most mature in market terms. Growth rates in new end-uses such as air bags and composite materials will continue to outstrip the above averages by a considerable margin for many years to come. However, total technical textile usage is, in many ways, a victim of its own success. Increasing sophistication in the specifications and uses of textile materials has led to the adoption of lighter, stronger, more precisely engineered yarns, woven and knitted fabrics and nonwovens in place of established materials. The decreasing weight per tyre of textile reinforcing cord in modern radial constructions is one example of this. Interior textiles in cars are also making use of lighter weight and lower cost nonwovens.

Modern textiles also last longer. Hoses and belts which used to use substantial quantities of textile reinforcements are now capable of lasting the lifetime of a vehicle, removing much of the large and continuing 'after-market' for textile products.

The automotive industry has led the world in the introduction of tightly organised supply chain structures and textiles are no exception. Technical textile producers have had to learn the language and practice of precision engineering, just-in-time supply relationships and total quality management. The ideas and systems developed to serve the automotive industry have gradually filtered through to other markets and have had a profound effect in many different areas. Meanwhile, the major automotive companies have become increasingly global players in a highly competitive market and have demanded of their suppliers that they follow suit. The supply of textiles to this market is already dominated by a relatively few large companies in each product area. Worldwide manufacturing capabilities and strategic relationships are essential to survival and many smaller players without these resources have already exited from the market. Recessionary cycles in automotive markets as well as in military and civil aerospace applications have dealt some severe blows and only those companies with the long term commitment and strength to survive are likely to benefit from the better times that the market also periodically enjoys.

1.5.2 Industrial products and components

Set to rival transport textiles for first place by the year 2005 or shortly thereafter (in volume terms, although not yet in value) is the diverse field of 'industrial' textiles. As now more precisely defined, this includes textiles used directly in industrial processes or incorporated into industrial products such as filters, conveyor belts and abrasive belts, as well as reinforcements for printed circuit boards, seals and gaskets, and other industrial equipment.

Use of nonwovens already considerably outweighs that of woven and other fabric types here; consumption in 2000 is estimated at 700 000 tonnes and a little over 400 000 tonnes, respectively. However, both are surpassed by the use of technical fibres and textiles for composite reinforcement, over 740 000 tonnes in 2000.

Growth rates are generally well above average in most areas. Because of the universal nature of many industrial requirements, some large companies have emerged with worldwide manufacturing and distribution to dominate markets for industrial textile products. They include companies such as Scapa (UK) and Albany (US), leaders in papermaking felts and related product areas, Milliken (USA) in textiles for rubber reinforcement and other industrial applications and BWF (Germany) in filtration.

1.5.3 Medical and hygiene textiles

The fact that medical and hygiene textiles are expected to show below average growth in volume but above average growth in value reflects the contrasting prospects of at least two main areas of the market.

The largest use of textiles is for hygiene applications such as wipes, babies' diapers (nappies) and adult sanitary and incontinence products. With the possible exception of the last of these, all are relatively mature markets whose volume growth has peaked. Manufacturers and converters now seek to develop them further by adding value to increasingly sophisticated products. Nonwovens dominate these applications which account for over 23% of all nonwoven use, the largest proportion of any of the 12 major markets for technical textiles.

Concern has been expressed at the growth of disposable products and the burden which they place upon landfill and other waste disposal methods. Attempts have been made to develop and introduce more efficient biodegradable fibres for such end-uses but costs remain high. Meanwhile, the fastest areas of growth are in developing and newly industrialised markets where product penetration is still relatively low; Asia is a particular target for many of the big name brand manufacturers who operate in this area.

The other side of the medical and hygiene market is a rather smaller but higher value market for medical and surgical products such as operating gowns and drapes, sterilisation packs, dressings, sutures and orthopaedic pads. At the highest value end of this segment are relatively tiny volumes of extremely sophisticated textiles for uses such as artificial ligaments, veins and arteries, skin replacement, hollow fibres for dialysis machines and so on. Growth prospects in these areas are potentially considerable although the proving and widespread introduction of new life-critical products takes time.

1.5.4 Home textiles

By far the largest area of use for other textiles as defined above, that is other than fabrics, nonwovens and composite reinforcements, over 35% of the total weight of fibres and textiles in that category, lies in the field of household textiles and furnishing and especially in the use of loose fibres in wadding and fibrefill applications. Hollow fibres with excellent insulating properties are widely used in bedding and sleeping bags. Other types of fibre are increasingly being used to replace foams in furniture because of concern over the fire and health hazards posed by such materials.

Woven fabrics are still used to a significant extent as carpet and furniture backings and in some smaller, more specialised areas such as curtain header tapes. However, nonwovens such as spunbondeds have made significant inroads into these larger markets while various drylaid and hydroentangled products are now widely used in household cleaning applications in place of traditional mops and dusters.

1.5.5 Clothing components

This category includes fibres, yarns and textiles used as technical components in the manufacture of clothing such as sewing threads, interlinings, waddings and insulation; it does not include the main outer and lining fabrics of garments, nor does it cover protective clothing which is discussed later.

Although the world's consumption of clothing and therefore of these types of technical textile continues to increase steadily, the major problem faced by established manufacturers is the relocation of garment manufacturing to lower cost countries and therefore the need to develop extended supply lines and marketing channels to these areas, usually in the face of growing local competition.

As for home textile applications, this is a major market for fibrefill products. Some of the latest and most sophisticated developments have seen the incorporation of temperature phase change materials into such insulation products to provide an additional degree of control and resistance to sudden extremes of temperature, be they hot or cold.

1.5.6 Agriculture, horticulture and fishing

Textiles have always been used extensively in the course of food production, most notably by the fishing industry in the form of nets, ropes and lines but also by agriculture and horticulture for a variety of covering, protection and containment applications. Although future volume growth rates appear to be relatively modest, this is partly due to the replacement of heavier weight traditional textiles, including jute and sisal sacking and twine, by lighter, longer lasting synthetic substitutes, especially polypropylene.

However, modern materials are also opening up new applications. Lightweight spunbonded fleeces are now used for shading, thermal insulation and weed suppression. Heavier nonwoven, knitted and woven constructions are employed for wind and hail protection. Fibrillated and extruded nets are replacing traditional baler twine for wrapping modern circular bales. Capillary nonwoven matting is used in horticulture to distribute moisture to growing plants. Seeds themselves can be incorporated into such matting along with any necessary nutrients and pesticides. The bulk storage and transport of fertiliser and agricultural products is increasingly undertaken using woven polypropylene FIBCs (flexible intermediate bulk containers – big bags) in place of jute, paper or plastic sacks.

Agriculture is also an important user of products from other end-use sectors such as geotextiles for drainage and land reclamation, protective clothing for employees who have to handle sprays and hazardous equipment, transport textiles for tractors and lorries, conveyor belts, hoses, filters and composite reinforcements in the construction of silos, tanks and piping.

At sea, fish farming is a growing industry which uses specialised netting and other textile products. High performance fibres such as HMPE (e.g. Dyneema and Spectra) are finding their way into the fishing industry for the manufacture of lightweight, ultra-strong lines and nets.

1.5.7 Construction – building and roofing

Textiles are employed in many ways in the construction of buildings, both permanent and temporary, dams, bridges, tunnels and roads. A closely related but distinct area of use is in geotextiles by the civil engineering sector.

Temporary structures such as tents, marquees and awnings are some of the most obvious and visible applications of textiles. Where these used to be exclusively made from proofed heavy cotton, a variety of lighter, stronger, rot-, sunlight- and weatherproof (also often fireproof) synthetic materials are now increasingly required. A relatively new category of 'architectural membrane' is coming to prominence in the construction of semipermanent structures such as sports stadia, exhibition centres (e.g. the Greenwich Millenium Dome) and other modern buildings.

Nonwoven glass and polyester fabrics are already widely used in roofing applications while other textiles are used as breathable membranes to prevent moisture penetration of walls. Fibres and textiles also have a major role to play in building and equipment insulation. Glass fibres are almost universally used in place of asbestos now. Modern metal-clad roofs and buildings can be lined with special nonwovens to prevent moisture condensation and dripping.

Double wall spacer fabrics can be filled with suitable materials to provide sound and thermal insulation or serve as lightweight cores for composite materials.

Composites generally have a bright future in building and construction. Existing applications of glass-reinforced materials include wall panels, septic tanks and sanitary fittings. Glass, polypropylene and acrylic fibres and textiles are all used to prevent cracking of concrete, plaster and other building materials. More innovative use is now being made of glass in bridge construction. In Japan, carbon fibre is attracting a lot of interest as a possible reinforcement for earthquake-prone buildings although price is still an important constraint upon its more widespread use.

Textiles are also widely employed in the course of construction operations themselves, in uses as diverse as safety netting, lifting and tensioning ropes and flexible shuttering for curing concrete.

The potential uses for textiles in construction are almost limitless. The difficulties for textile manufacturers operating in this market include the strongly cyclical nature of the construction industry and the unevenness of major projects, the long testing and acceptance procedures and, perhaps above all, the task of communicating these developments to a diverse and highly fragmented group of key specifiers, including architects, construction engineers and regulatory bodies. The construction requirements, practices and standards of just about every country and region are different and it has, so far, proved very difficult for any acknowledged global leaders to emerge in this market as they have, for example, in industrial and automotive textiles.

1.5.8 Packaging and containment

Important uses of textiles include the manufacturing of bags and sacks, traditionally from cotton, flax and jute but increasingly from polypropylene. The strength and regularity of this synthetic material, combined with modern materials handling techniques, has allowed the introduction of FIBCs for the more efficient handling, storage and distribution of a variety of powdered and granular materials ranging from fertiliser, sand, cement, sugar and flour to dyestuffs. 'Big bags' with typical carrying capacities from one half to 2 tonnes can be fitted with special liners, carrying straps and filling/discharge arrangements. The ability to re-use these containers in many applications in place of disposable 'one-trip' bags and sacks is another powerful argument for their wider use.

An even faster growing segment of the packaging market uses lighter weight nonwovens and knitted structures for a variety of wrapping and protection applications, especially in the food industry. Tea and coffee bags use wet-laid nonwovens. Meats, vegetables and fruits are now frequently packed with a nonwoven insert to absorb liquids. Other fruits and vegetable products are supplied in knitted net packaging.

Strong, lightweight spunbonded and equivalent nonwoven paper-like materials are particularly useful for courier envelopes while adhesive tapes, often reinforced with fibres, yarns and fabrics, are increasingly used in place of traditional twine. Woven strappings are less dangerous to cut than the metal bands and wires traditionally used with densely packed bales.

A powerful driver of the development and use of textiles in this area is increasing environmental concern over the disposability and recycling of packaging materials. Legislation across the European Union, implemented especially vigorously in countries such as Germany, is now forcing many manufacturers and distributors of products to rethink their packaging practices fundamentally.

1.5.9 Sport and leisure

Even excluding the very considerable use of textiles in performance clothing and footwear, there are plenty of opportunities for the use of technical textiles throughout the sports and leisure market. Applications are diverse and range from artificial turf used in sports surfaces through to advanced carbon fibre composites for racquet frames, fishing rods, golf clubs and cycle frames. Other highly visible uses are balloon fabrics, parachute and paraglider fabrics and sailcloth.

Growth rates are well above average and unit values are often very high. The sports sector is receptive to innovation and developers of new fibres, fabrics and coatings often aim them at this market, at least initially. Many of the products and ideas introduced here eventually diffuse through to the volume leisure market and even the street fashion market.

1.5.10 Geotextiles in civil engineering

Although still a surprisingly small market in volume and value terms, considering the amount of interest and attention it has generated, the geosynthetics market (comprising geotextiles, geogrids and geomembranes) is nevertheless expected to show some of the highest growth rates of any sector over the foreseeable future.

The economic and environmental advantages of using textiles to reinforce, stabilise, separate, drain and filter are already well proven. Geotextiles allow the building of railway and road cuttings and embankments with steeper sides, reducing the land required and disturbance to the local environment. Revegetation of these embankments or of the banks of rivers and waterways can also be promoted using appropriate materials. There has been renewed interest in fibres such as woven jute as a biodegradable temporary stabilising material in such applications.

As in the case of construction textiles, one of the problems faced by manufacturers and suppliers of these materials is the sheer diversity of performance requirements. No two installations are the same in hydrological or geological terms or in the use to which they will subsequently be put. Suppliers to this market need to develop considerable expertise and to work closely with engineers and consultants in order to design and specify suitable products.

Because of the considerable areas (quantities) of fabric that can be required in a single project, cost is always a consideration and it is as essential not to overspecify a product as not to underspecify it. Much of the research and development work undertaken has been to understand better the long term performance characteristics of textiles which may have to remain buried in unpredictable environments (such as landfill and toxic waste sites) for many years and continue to perform to an adequate standard.

Nonwovens already account for up to 80% of geotextile applications. This is partly a question of economics but also of the suitability of such textile structures for many of the filtration and separation duties that they are called upon to perform. Current interest is in 'composite' fabrics which combine the advantages of different textile constructions such as woven, knitted, nonwoven and membrane materials. To supply the diversity of fabrics needed for the many different applications of geotextiles, leading specialist manufacturers are beginning to assemble a wide range of complementary capabilities by acquisition and other means.

1.5.11 Protective and safety clothing and textiles

Textiles for protective clothing and other related applications are another important growth area which has attracted attention and interest somewhat out of proportion to the size and value of the existing market. As in the case of sports textiles, a number of relatively high value and performance critical product areas have proved to be an ideal launch pad for a new generation of high performance fibres, most notably the aramids, but including many other speciality materials.

The variety of protective functions that needs to be provided by different textile products is considerable and diverse. It includes protection against cuts, abrasion, ballistic and other types of severe impact including stab wounds and explosions, fire and extreme heat, hazardous dust and particles, nuclear, biological and chemical hazards, high voltages and static electricity, foul weather, extreme cold and poor visibility.

As well as people, sensitive instruments and processes also need to be protected. Thus, clean room clothing is an important requirement for many industries including electronics and pharmaceuticals.

In Europe and other advanced industrial regions, strict regulations have been placed upon employers through the introduction of legislation such as the Personal Protective Equipment (PPE) at Work Regulations (European Union). Under such legislation, it is not only necessary to ensure that the equipment and clothing provided is adequate to meet the anticipated hazards but also that it is also used effectively, that is that the garments are well designed and comfortable to wear. This has opened up a need for continuing research not only into improved fibres and materials but also into increasingly realistic testing and assessment of how garments perform in practice, including the physiology of protective clothing.

In many developing countries, there has not been the same legislative framework in the past. However, this is rapidly changing and future market growth is likely to concentrate less on the mature industrial markets than upon the newly industrialising countries of Asia and elsewhere. The protective clothing industry is still highly fragmented with much of the innovation and market development being provided by the major fibre and other materials producers. This could change as some global suppliers emerge, perhaps without their own direct manufacturing but relying on contract producers around the world, very much as the mainstream clothing industry does at present.

1.5.12 Ecological protection textiles

The final category of technical textile markets, as defined by Techtextil, is technical textiles for protection of the environment and ecology. This is not a well defined segment yet, although it overlaps with several other areas, including industrial textiles (filtration media), geotextiles (erosion protection and sealing of toxic waste) and agricultural textiles (e.g. minimising water loss from the land and reducing the need for use of herbicides by providing mulch to plants).

Apart from these direct applications, technical textiles can contribute towards the environment in almost every sphere of their use, for example by reducing weight in transport and construction and thereby saving materials and energy. Improved recycleability is becoming an important issue not only for packaging but also for products such as cars.

Composites is an area which potentially presents problems for the recycleability of textile reinforcing materials encased within a thermosetting resin matrix. However, there is considerable interest in and development work being done on thermoplastic composites which should be far simpler to recycle, for example by melting and recasting into lower performance products.

1.6 Globalisation of technical textiles

If North America and Western Europe have the highest levels of per capita consumption of technical textiles at present (see Table 1.1), then they are also relatively mature markets. The emerging countries of Asia, Eastern Europe and the rest of the world are becoming important markets in almost every sphere, from automotive manufacture through to sporting and leisure goods. Technical textiles for food production, construction and geotextiles are likely to be particularly important. In the case of the last of these, geotextiles, consumption up to the year 2005 is expected to grow at over 12% per annum across the whole of Asia compared with less than 6% in Western Europe and the USA. In the case of Eastern Europe and South America, annual growth rates could be as high as 18% and 16% per annum respectively, although from relatively small base levels at present.

In 2000, the major existing users, North America, Western Europe and Japan, are expected to account for less than 65% of total technical textile consumption; by the year 2005, this could be down to 60% and perhaps below 50% by 2010. Consumption of technical textiles in China already exceeds that of Japan, in weight terms at

Table 1.4 Worldwide consumption of technical textiles by geographical region, 2000–2005

	10^3 tonnes			$ million		
	2000	2005	Growth (% pa)	2000	2005	Growth (% pa)
Western Europe	2690	3110	2.9	13770	15730	2.7
Eastern Europe	420	560	5.9	2500	3260	5.5
North America	3450	3890	2.4	16980	18920	2.2
South America	350	430	4.2	1870	2270	3.9
Asia	3560	4510	4.8	20560	25870	4.7
Rest of the world	870	1190	6.5	4590	6280	6.5
Total	**11340**	**13690**	**3.9**	**60270**	**72330**	**3.7**

Source: David Rigby Associates/Techtextil.

least. In 2000, Chinese technical textiles are expected to account for almost 20% of all textile manufacturing in that country and over 12% of total world consumption (see Table 1.4).

But globalisation is not just about increasing internationalisation of markets. It is also about the emergence of companies and supply chains which operate across national and continental boundaries. Such globalisation has already proceeded furthest in the automotive and transport industry, the largest of the 12 market segments defined above. It is a path already being followed within the other major segments, most notably industrial textiles and medical/hygiene textiles and will become increasingly evident in the remainder.

Characteristics of globalisation include higher levels of international trade and increased specialisation of manufacture within individual districts, countries and regions, according to availability of materials, local industry strengths and regional market characteristics.

Relatively low unit value products requiring a significant amount of making-up or other fabrication such as bags and sacks have already seen a significant shift of manufacturing towards the Far East and Eastern Europe. Textiles for tents, luggage and the technical components of footwear and clothing are now increasingly sourced close to where many of these products are manufactured for export, for example China and Indonesia.

Manufacturers in the newly industrialising world are rapidly adopting the latest materials and processing technologies. Taiwan already has an important composites manufacturing sector specialising in sports equipment.

1.7 Future of the technical textiles industry

The future of technical textiles embraces a much wider economic sphere of activity than just the direct manufacturing and processing of textiles. The industry's suppliers include raw materials producers (both natural and artificial), machinery and equipment manufacturers, information and management technology providers, R&D services, testing and certification bodies, consultants, education and training organisations. Its customers and key specifiers include almost every conceivable

able 1.5 Technical textile functions, markets and end-uses

arkets	Segments	Function						
		Protection	Insulation	Reinforcement	Containment	Filtration	Absorption	Miscellaneous
dustry	Engineering Food, pharmaceuticals Chemicals, plastics Other manufacturing Power, oil, gas Mining, quarrying	High temperature textiles Welders anti-spatter sheets Fire blankets Dustproof fabric Electrostatic shielding Debris, safety nets Solar protection	Acoustic barriers Thermal insulation Seals, joints Packings Pressed felt components Electrical insulation tape Heating elements Electromagnetic shields Electroconductive fabrics Dielectric fabrics Aerials	Composites – FRP and advanced Printed circuit boards Optical fibre/electrical cables Electrical cables Jacquard harness Pressure hoses Drive belts Conveyor belts Bearing materials Abrasive discs	Bags & sacks FIBCs Balewrap Tape Curing tape Hosepipes Nets Webbing Diaphragms Envelopes Floppy disc liners	Dust filtration Air conditioning Process liquid Effluent treatment Papermakers felts Battery separators Tea/coffee bags Cigarette filters Food casing Machine clothing Printers blankets Laundry textiles	Oil spillages Wicks	Thermal stencil paper
ransport	Road Aviation Marine (Military)	Seat belts Air bags Flotation devices Inflatable boats Parachutes Ropes, cables Barriers, nets Camouflage, decoy FR textiles	Sound barriers for roofs, bonnets etc. Tank insulation	Tyre cord Hoses, pipes, drive belts & other MRG Brake/clutch lining Gaskets, seals Composites – FRP & advanced Tow ropes	Containers Tarpaulins Covers Cordage Twine Cargo nets, straps Balloons Sailcloth Gliders Hovercraft skirts	Air filters (engine) Air filters (passenger) Oil filters Fuel filters	Oil booms	Decorative/functional interior textiles (UV, FR)

onstruction	Buildings Road, rail, tunnel	Tarpaulins Sunblinds, awnings Debris, safety nets Roofing Stadium dome	Silo liners Soundproof panels Swimming pool liners	Inflatable buildings, frames Tape Elevator belts Pipe/sewer linings Ropes Concrete Plaster board	Cordage Ropes Twines Nets Cement shuttering			Wall coverings, blinds
eotextile	Land Marine	Erosion protection Environmental protection		Road, railway embankment stabilisation Concrete, tarmac	Geomembranes Reservoir lining Waste pit lining	Drainage		
rming	Agriculture Horticulture Fishing	Wind, storm, frost protection Solar protection Insect/bird nets			Sacks, bags Baler twine Fruit collection Fishing nets Fish farming Other netting Seeding tapes	Drainage	Moisture retention Capillary matts	
edical & hygiene	Hospital Nursing home Domestic	Gauze Plaster Face masks Gowns Tents Bandages Support stockings X-ray machine parts	Wadding	Sutures Adhesive tape Prostheses Support bandages Ligaments Tendons Implants	Body bags Netting Thread Sacks, bags Stretchers Wheelchairs	By-pass filters Dialysis Infusion Stoma Membranes Blood	Pads Towels Swabs Napkins Wipes Cotton wool Sponges Mops, brushes Dusters	Veins, arteries Artificial skin
chnical apparel	Industry Offshore oil Forestry Miltary/security	Water/windproof linings Chemical proof Gas tight Anti-radiation NBC suits Bulletproof Diving suits		Sewing thread Binding tape Interlinings Shoe/boot linings Fasteners (Velcro) Shoe/boot laces				Labels

able 1.5 *Continued*

arkets	Segments	Function						
		Protection	Insulation	Reinforcement	Containment	Filtration	Absorption	Miscellaneous
echnical apparel *continued*		Pressure suits Survival suits Fire-retardant Heat-resistant Dust, asbestos Clean room Chain saw protection Helmets Motor cycle garments Gloves, armguards Aprons Hair nets High visibility Camouflage						
eisure & environment	Sports Mountaineering Leisure	Tents Climbing ropes Harnesses Safety nets Parachutes Ski fences Muscle supports	Sleeping bags Ground sheets Artificial turf	Rackets Fishing rods Fishing lines Bicycle frames Golf clubs Skis Bow strings Ropes Cords	Marquees Tents Sports nets Bags, rucksacks Luggage Sports balls Litter systems Mosquito nets Book covers Pet leads Equestrian webs			Painters canvasses Cinema screens
urnishing, decorative		FR fabrics	Carpet underlay Fibre fillings	Webbings Curtain header Carpet backing Linoleum scrim Garden furniture Hammocks	Furniture/ mattress bases Wallcoverings Gift wrapping			Flags/banners

R = fire retardant, FRP = fibre reinforced plastic, NBC = nuclear biological and chemical.

downstream industry and field of economic activity, including the architects, engineers, designers and other advisors employed by those industries. In between lie many other interested parties, including environmental, health, safety, business and free trade regulators, patent and intellectual property agents and lawyers, investors, bankers, regional investment agencies and providers of development aid.

The task of disseminating and communicating information to all these organisations and individuals is undertaken by a growing number of specialist and generalist publications as well as by international and local trade exhibitions, fairs, seminars and conferences.

The economic importance of technical textiles worldwide therefore undoubtedly far exceeds the $60 billion estimated in Tables 1.2–1.4 just for basic fibres, yarns and textiles.

1.7.1 A changing strategic environment

If the 1980s was a period when the technical textiles industry enjoyed a rapid and increasing awareness of its existence by the outside world (as well as within the mainstream textile industry), then the 1990s was an era of more mature commercial development and consolidation as fibre producers and textile manufacturers alike concentrated on overhauling and refocusing their businesses in the wake of world recession.

The new millennium promises even fiercer international competition which will see manufacturers striving to engineer costs downwards and develop global economies of scale in production and product development. Technical textiles will become better ‘value for money’ than ever before and this should open the way towards further applications as existing end-uses mature.

Individual companies will become less defined by the technologies and materials they use than by the markets and applications they serve. Table 1.5 summarises some of the key market areas and the functions which technical textiles perform, with examples of individual products in each category. It does not pretend to be an exhaustive list which would run into many thousands of products and would constantly be changing.

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2

Technical fibres

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2.1 Introduction

A number of definitions[1–3] have been used to describe the term 'technical textiles' with respect to their intended use, functional ability and their non-aesthetic or decorative requirements. However, none of these carefully chosen words include the fundamental fibre elements, technical or otherwise, which make up the technical textile structures. The omission of the word 'fibre' may indeed be deliberate as most technical textile products are made from conventional fibres that are already well established. In fact over 90% of all fibres used in the technical sector are of the conventional type.[4] Specially developed fibres for use in technical textiles are often expensive to produce and have limited applications.

Historically, utilisation of fibres in technical capacities dates back to the early Egyptians and Chinese who used papyrus mats to reinforce and consolidate the foundations respectively of the pyramids and the Buddhist temples.[5,6] However, their serious use in modern civil engineering projects only began after the floods of 1953 in The Netherlands in which many people lost their lives. The event initiated the famous Delta works project in which for the first time synthetic fibres were written into the vast construction programme.[7] Since then, geotextiles in particular have matured into important and indispensable multifunctional materials.

Use of silk in semitechnical applications also goes back a long way to the lightweight warriors of the Mongolian armies, who did not only wear silk next to their skin for comfort but also to reduce penetration of incoming arrows and enable their subsequent removal with minimal injury. Use of silk in wound dressing and open cuts in web and fabric form also dates back to the early Chinese and Egyptians.

In light of extensive utilization of conventional fibres in the technical sector, this chapter initially attempts to discuss fibres under this category highlighting their importance and the scope of their versatility. The discussion covers concisely an outline of fibre backgrounds, chemical compositions and their salient characteristics. It then introduces other fibres which have been specially developed to perform under extreme stress and/or temperature; ultrafine and novel fibres are also discussed. Finally, the chapter concludes by identifying areas of application and the roles that selected fibres play in fulfilling their intended purpose.

Table 2.1 presents the complete range of fibres available to the end-user and some of their mechanical properties.

2.2 Conventional fibres

2.2.1 Natural fibres

Cotton accounts for half of the world's consumption of fibres and is likely to remain so owing to many of its innate properties and for economical reasons[8] that will not be discussed here. Cotton is made of long chains of natural cellulose containing carbon, hydrogen and oxygen otherwise known as polysaccharides. The length of the chains determines the ultimate strength of the fibre. An average of 10000 cellulosic repeat or monomeric units make up the individual cellulose chains which are about 2 μm in length. The linear molecules combine into microfibrils and are held together by strong intermolecular forces to form the cotton fibre. The unique physical and aesthetic properties of the fibre, combined with its natural generation and biodegradability, are reasons for its universal appeal and popularity. Chemical treatments such as Proban[9] and Pyrovatex[10] are two examples of the type of durable finishes that can be applied to make cotton fire retardant. High moisture absorbency, high wet modulus and good handle are some of the more important properties of cotton fibre.

Wool, despite its limited availability and high cost, is the second most important natural fibre. It is made of protein: a mixture of chemically linked amino acids which are also the natural constituents of all living organisms. Keratin or the protein in the wool fibre has a helical rather than folded chain structure with strong inter- and intrachain hydrogen bonding which are believed to be responsible for many of its unique characteristics. Geographical location, the breeding habits of the animals, and climatic conditions are some of the additional variables responsible for its properties. The overall high extensibility of wool, its natural waviness and ability to trap air has a coordinated effect of comfort and warmth, which also make it an ideal insulating material. The sophisticated dual morphology of wool produces the characteristic crimp which has also been an inspiration for the development of some highly technical synthetic fibres. Wool is inherently fire retardant, but further improvements can be achieved by a number of fire-retardant treatments. Zirconium- and titanium-treated wool is one such example which is now universally referred to as Zirpro (IWS) wool.[11]

Flax, jute, hemp and ramie, to name but a few of the best fibres, have traditionally taken a secondary role in terms of consumption and functional requirements. They are relatively coarse and durable, and flax has traditionally been used for linen making. Jute, ramie and to a lesser extent other fibres have received attention within the geotextile sector of the fibre markets which seeks to combine the need for temporary to short-term usage with biodegradability, taking into account the regional availability of the fibres.

Silk is another protein-based fibre produced naturally by the silkworm, *Bombyx Mori* or other varieties of moth. Silk is structurally similar to wool with a slightly

able 2.1 Fibres available to the end-user and associated mechanical properties

onventional fibres	High strength high modulus organic fibres	High chemical and combustion-resistant organic fibres	High performance inorganic fibres	Ultrafine and novelty fibres
atural g. cotton, wool, silk, jute, etc. egenerated g. viscose, acetates tencel, etc. ynthetics g. polyamide, polyester, polyacrylics, polyurethanes, polyolefins, etc.	*Para*-aramids e.g. Kevlar (Du Pont) and Twaron (Acordis) Polybenzobisthiazole (PBT) Ultra-high molecular weight polyethylene e.g. Dyneema (DSM) and Spectra (Allied Signal)	*Meta*-aramids e.g. Nomex (Du Pont) and Conex (Teijin) Kermel (Rhodia) Kynol (Kynol) Oxidised acrylic fibres, e.g. Panox (SGL) Others: Aromatic polymers; Polyether ether ketone, PEEK (Victrex and Zyex) Polyether ketone, PEK Poly *p*-phenylene sulphide, PPS, e.g. Ryton (Phillips) polytetrafluoroethylene, PTFE, e.g. Teflon (Du Pont) (Inspec formerly Lenzing) P84	Carbon Ceramics Boron Tungsten Alumina (e.g. Saffil) High modulus silicon Carbide & silicon nitride etc.	Microfibres; (linear density <0.5 dtex) Solar energy absorbing fibres (solar alpha) Heat-sensitive fibres (thermochromics) Scented fibres Antibacterial fibres (aseptic chlorofibres) Hollow fibres Antistatic fire-retardant fibres; etc.
enacity: 1–0.5 N tex^{-1} odulus: -18 N tex^{-1} Elongation: 2–7	Tenacity: 1.5–3 N tex^{-1} Modulus: 25–150 N tex^{-1} % Elongation: 1–8 LOI[a]: 0.20–0.40	Tenacity: 1–2 N tex^{-1} Modulus: 15–25 N tex^{-1} % Elongation: 1–4 LOI: 0.23–0.55	Tenacity: 0.5–2 N tex^{-1} Modulus: 70–220 N tex^{-1} % Elongation: 0–1.5	Tenacity: 0.1–0.4 N tex^{-1} Modulus: 2–15 N tex^{-1} % Elongation: 2–17

LOI: limiting oxygen index = minimum fraction of oxygen in nitrogen necessary to sustain burning.

different combination of amino acids which make up the protein or the fibroin, as it is more appropriately known. Silk is the only naturally and commercially produced continuous filament fibre which has high tenacity, high lustre and good dimensional stability. Silk has been and will remain a luxury quality fibre with a special place in the fibre market. However, its properties of biocompatibility and gradual disintegration, as in sutures, have long been recognised in medical textiles.

2.2.2 Regenerated fibres

Viscose rayon was the result of the human race's first attempts to mimic nature in producing silk-like continuous fibres through an orifice. Cellulose from wood pulp is the main constituent of this novel system, started commercially in the early 1920s. Thin sheets of cellulose are treated with sodium hydroxide and aged to allow molecular chain breakage. Further treatment with carbon disulphide, dissolution in dilute sodium hydroxide and ageing produces a viscous liquid, the viscose dope, which is then extruded into an acid bath. The continuous filaments that finally emerge are washed, dried and can be cut to staple lengths. The shorter cellulose molecules in viscose and their partial crystallisation accounts for its rather inferior physical properties relative to cotton. Further development and refinement of the manufacturing technique have created a whole range of fibres with improved properties. High tenacity and high wet modulus viscose compare in all but appearance to cotton in both dry and wet conditions. Chemically altered regenerated cellulose di- and triacetates do not burn like cotton and viscose to leave a fluffy black ash, but melt and drip instead. This characteristic enables them to be shaped or textured to enhance their visual and aesthetic appeal. Hollow viscose modifications give enhanced bulk and moisture absorbency and have an improved cotton-like feel.

Fire-retardant (FR) viscose was first introduced in the 1960s. A major example is produced by Lenzing in Austria by incorporating organophosphorous compounds into the spinning dope prior to extrusion. The additive is reasonably stable and has no chemical interaction with the cellulose molecules. It is also unaffected by bleaching, washing, dry cleaning, dyeing and finishing processes.[10] Early in the 1990s Kemira (now Sateri Fibres) of Finland introduced an alternative version of FR viscose known as Visil in which polysilicic acid is present. The fibre chars upon heating leaving a silica residue.

Lyocell,[12] is the latest addition to this series of fibres, commercially known as Tencel (Acordis), has all the conventional properties of viscose in addition to its much praised environmentally friendly production method. The solvent used is based on non-toxic *N*-methyl morpholine oxide used in a recyclable closed loop system, which unlike the viscose process avoids discharge of waste. Highly absorbent derivatives of Tencel, known as Hydrocell are establishing a foothold in wound dressing and other medical-related areas of textiles.

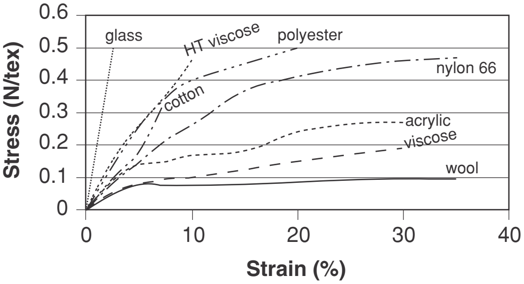
2.2.3 Synthetic fibres

All synthetic fibres originate from coal or oil. The first synthetic fibre that appeared on the world market in 1939 was nylon 6.6. It was produced by DuPont and gained rapid public approval. A series of nylons commonly referred to as polyamides now exists in which the amide linkage is the common factor. Nylon 6.6 and nylon 6 are most popular in fibre form. They are melt extruded in a variety of cross-sectional shapes and drawn to achieve the desired tenacity. They are well known for their high extensibility, good recovery, dimensional stability and relatively low moisture absorbency. Nylon 6.6 in particular soon became a popular household carpet fibre and was developed into fibres commonly known as Antron[13] manufactured by DuPont. Antron fibres of various generations use additives, varied cross-sectional shapes and modified surface characteristics to enhance the aesthetic and visual appeal of carpets as well as improving their resilience and dissipating static charges.

Nylon was later surpassed by the even more popular fibre known as polyester, first introduced as Dacron by DuPont in 1951. Polyester is today the second most used fibre after cotton and far ahead of other synthetics both in terms of production and consumption. Polyethylene terephthalate or polyester is made by condensation polymerisation of ethylene glycol and terephthalic acid followed by melt extrusion and drawing. It can be used in either continuous form or as short staple of varying lengths. The popularity of polyester largely stems from its easycare characteristics, durability and compatibility with cotton in blends. Its very low moisture absorbency, resilience and good dimensional stability are additional qualities. Many manufacturers across the world produce polyester under different commercial names with almost tailor-made properties. A high glass transition temperature of around 70 °C with good resistance to heat and chemical degradation also qualifies this polymer for most technical textile applications. These will be discussed in greater detail later. Flame-retardant Trevira CS and Trevira high tenacity, both polyesters developed and marketed by Trevira GmbH in Germany, are examples of the many varieties available today.

Wool-like properties are shown by polyacrylic fibres which are produced by the polymerisation of acrylonitrile using the addition route into polyacrylonitrile. They can then be spun into fibres by dry or wet spinning methods. Orlon[14] was produced by DuPont. It had a distinctive dumbbell shaped cross-section and was extruded by the dry process in which the solvent is evaporated off. Acrilan[15] produced by Monsanto and Courtelle produced by Acordis are spun by the wet extrusion technique and have near circular cross-sections. Acrylic fibres now also appear in bicomponent form with wool-like characteristics. Chemically modified acrylics, principally the modacrylics, include chlorine atoms in their molecular structure which are responsible for their low burning behaviour and, unlike acrylics, have the ability to self-extinguish once the source of ignition has been removed. A selected fibre in terms of fibre chemistry is Oasis,[16] a superabsorbent fibre made by the collaborative efforts of Acordis and Allied Colloids, based on crosslinking copolymers of acrylic acid. This fibre is claimed to absorb moisture many times its own weight and holds it even under pressure. Its application in hygiene and medical care in different forms is being pursued.

Polyolefin fibres include both polyethylene and polypropylene made by addition polymerisation of ethylene and propylene and subsequent melt extrusion, respectively. Polyethylene has moderate physical properties with a low melting temperature of about 110 °C for its low density form and about 140 °C for its high density form which severely restricts its application in low temperature applications. Polypropylene has better mechanical properties and can withstand temperatures of up to 140 °C before melting at about 170 °C. Both polymers have a density less than that of water which allows them to float as ropes, nets and other similar applications. The availability, low cost and good resistance to acid and alkaline environments of polypropylene has greatly influenced its growth and substantial use in geotextile applications.



2.1 Stress/strain behaviour of some common fibres.

Finally, elastane fibres[17] are synthetic-based elastomeric polymers with at least 85% segmented polyurethane in their structure. They have rubber-like properties, which means they can be extended up to six or more times their original length. They are used in combination with most natural and synthetic fibres in knitted and woven materials. They were initially produced by DuPont in 1959 under the now well-known trademark of Lycra.

Figure 2.1 presents typical stress/strain behaviour for most conventional fibres. Tenacity, modulus and percentage elongation ranges for most conventional fibres are also given at the bottom of Table 2.1.

2.3 High strength and high modulus organic fibres

Keller's much-published[18] contribution to the understanding of crystal growth in 1957 and confirmation of the tendency of polymers to form folded-chain crystals, provided the insight and inspiration for development of high strength, high modulus organic fibres that would surpass conventional fibres. During crystallisation, long chains of molecules fold back on themselves to form folded-chain crystals which only partly unfold during normal drawing. In the Netherlands in the 1970s DSM developed a super drawing technique known as *gel spinning*, which uses dilute solutions of ultra-high molecular weight polymers such as polyethylene to unfold the chains further and thus increase both tensile strength and fibre modulus. Ultra-high molecular weight polyethylene (UHMWPE) fibres, Dyneema or Spectra, are today the strongest fibres known, with tensile moduli in excess of 70 GN m^{-2}. Weight for weight this fibre genus is claimed to be 15 times stronger than steel and twice as strong as aromatic polyamides such as Kevlar.[19] It is also low in density, chemically inert and abrasion resistant. It, however, melts at around 150 °C and thermally degrades at 350 °C which restrict its use to low temperature applications.

To achieve even better performance characteristics at higher temperatures, other means of fibre production were explored in the 1960s. One successful approach eventually led to the advent of liquid crystalline polymers. These are based on polymerisation of long stiff molecules such as *para*-phenylene terephthalamide achieving molecular weights averaging to around 20 000. The influence of the stiff aromatic rings, together with hydrogen-bonding crosslinks, combines the best features of both the polyamides and the polyesters in an extended-chain configuration.[18–20] Molecular orientation of these fibres is brought about by capillary shear along the flow of the polymer as it exits from the spinneret thus overriding the need for subsequent drawing. Kevlar by DuPont and Twaron by Akzo (now Acordis) were the first of such fibres to appear in the early 1970s. There now exists a series of first, second and third generations of *para*-aramids. Kevlar HT for instance, which has 20% higher tenacity and Kevlar HM which has 40% higher modulus than the original Kevlar 29 are largely utilised in the composite and the aerospace industries. *Para*-aramids generally have high glass transition temperatures nearing 370 °C and do not melt or burn easily, but carbonise at and above 425 °C. All aramid fibres are however prone to photodegradation and need protection against the sun when used out of doors. These will be discussed later.

Other high tenacity and high modulus fibres include the isotropically spun Technora (Teijin) and Supara, based upon *para*-aramid copolymers, with slightly lower maximum strength and modulus values than Kevlar. Several other melt-spinnable liquid crystalline polymers are also available.[21]

2.4 High chemical- and combustion-resistant organic fibres

The fibres discussed in the previous section were developed following earlier observations that aromatic polymer backbones yielded improved tensile and heat resistance compared with conventional fibres. However, if the polymer chains have lower symmetry and order, then polymer tractability and textile fibre characteristics are improved. Solvent-spun Nomex and Conex were the first so-called *meta*-aramids made from poly(meta-phenylene isophthalamide) and were produced by DuPont in 1962 and by Teijin in 1972, respectively. The *meta*-phenylene isophthalamide molecule is identical in all but the position of its —NH— and —CO— groups to *para*-phenylene terephthalamide (or Kevlar) molecules. The different positioning of these groups in *meta*-aramids creates a zig-zag molecular structure that prevents it from full crystallisation thus accounting for its relatively poorer tensile properties. However, Nomex is particularly well known for its resistance to combustion, high decomposition temperature prior to melting and high limited oxygen index (LOI), the minimum amount of oxygen required to induce ignition.

Melt-spinnable aromatic fibres with chains containing paraphenylene rings, like polyether ether ketone (PEEK),[23] polyether ketone (PEK) and poly(*p*-phenylene sulphide) (PPS),[22] also have high melting points but, since their melting points occur prior to their decomposition temperature, they are unsuitable for fire-retardant applications. However, their good chemical resistance renders them suitable for low temperature filtration and other corrosive environments.

The polyheterocyclic fibre, polybenzimidazole or PBI, produced by Hoechst-Celanese has an even higher LOI than the aramids. It has excellent resistance to both heat and chemical agents but remains rather expensive. P84, initially produced by Lenzing and now produced by Inspec Fibres, USA, comprises polyimide groups that yield reasonably high resistance to fire and chemical attack. The acrylic copolymer-based fibre produced by Acordis known as Inidex (although now no longer produced) unlike many aramid fibres has high resistance to UV (ultraviolet) radiation and a fairly high LOI at the expense of much reduced tenacity and rather low long-term exposure resistance to heat.

Oxidised acrylic fibre, best known as Panox (SGL, UK) is another crosslinked, high combustion-resistant material produced by combined oxidation and pyrolysis

Table 2.2 LOI and tenacity range of some high chemical- and combustion-resistant organic fibres

Fibres brand name	Manufacturer	LOI (%)	Tenacity (GPa)
Nomex	Du Pont	29	0.67
Conex	Conex	29	0.61
Kermel	Rhone-Poulenc	31	0.53
Inidex	Courtaulds	43	0.12
PBI	Hoechst-Celanese	41	0.39
PAN-OX	RK Textiles	55	0.25
PEEK		42	
PEK			
PPS	Phillips	34	0.54

of acrylic fibres at around 300 °C. Although black in appearance, it is not classed as carbon fibre and preserves much of its original non-carbonaceous structure. In addition, it does not have the graphitic or turbostratic structure of carbon fibres. It retains a sufficiently high extension-at-break to be subjected to quite normal textile processes for yarn and fabric formation.[24] Panox has a very high LOI of 0.55. Fully carbonised, or carbon fibres with even higher tensile properties, are achieved by full carbonisation of these oxidised precursor fibres or by the melt spinning of liquid crystalline mesophase pitch followed by their oxidation and pyrolysis. These are discussed again in the section on inorganic fibres.

Table 2.2 shows the LOI and tenacity range of some of the better known high chemical- and combustion-resistant organic fibres.

2.5 High performance inorganic fibres

Any fibre that consists of organic chemical units, where carbon is linked to hydrogen and possibly also to other elements, will decompose below about 500 °C and cease to have long-term stability at considerably lower temperatures. For use at high temperatures it is therefore necessary to turn to inorganic fibres and fibres that consist essentially of carbon.[25]

Glass, asbestos and more recently carbon are three well-known inorganic fibres that have been extensively used for many of their unique characteristics. Use of glass as a fibre apparently dates back to the ancient Syrian and Egyptian civilisations[26] which used them for making clothes and dresses. However, the very high modulus or stiffness displayed by these fibres means that they are quite brittle and can easily be damaged by surface marks and defects. They are, therefore, best utilised by embedding in matrix forms where the fibres are fully protected. Epoxy resins, polyester and other polymers, as well as cement, have commonly been used both to protect and to make use of their contributory strength. Glass-reinforced boat hulls and car bodies, to name but two application areas of such composites, reduce overall weight and cost of fabrication as well as eliminating the traditional problems of rotting wood and rusting metals associated with traditional materials. Their good resistance to heat and very high melting points have also enabled them to be used as effective insulating materials.

Asbestos[27] is a generic name for a variety of crystalline silicates that occur naturally in some rocks. The fibres that are extracted have all the textile-like properties of fineness, strength, flexibility and more importantly, unlike conventional fibres, good resistance to heat with high decomposition temperatures of around 550 °C. Their use as a reinforcement material has been found in clay-rich prehistoric cooking pots discovered in Finland.[28] In more recent times they have been extensively used to reinforce brittle matrices such as cement sheeting, pipes, plastics[29] and also as heat insulators. However, with the discovery of their carcinogenic hazards, their use has gradually declined and alternative fibres have been developed to replace them totally.

High purity, pyrolysed acrylic-based fibres are classified as carbon fibres. The removal of impurities enhances carbon content and prevents the nucleation and growth of graphite crystals which are responsible for loss of strength in these fibres. Carbon fibres with different structures are also made from mesophase pitch. The graphite planes in PAN-based fibres are arranged parallel to the fibre axis rather than perpendicular as is the case with pitch-based carbon fibres.[28] Their high strength and modulus combined with relatively low extensibility means that they are best utilised in association with epoxy or melt-spinnable aromatic resins as composites.

Increasing demand in the defence and aerospace industries for even better performance under extreme conditions led, within the last quarter of the 20th century, to yet another range of new and rather expensive metal oxides, boron and silicon-based fibres. These are often referred to as ceramic fibres and will now be briefly discussed.

Aluminosilicate compounds are mixtures of aluminium oxide (Al_2O) and silicon oxide (SiO_2); their resistance to temperature depends on the mixing ratio of the two oxides. High aluminium oxide content increases their temperature tolerance from a low of 1250 °C to a maximum of 1400 °C. However, despite their high temperature resistance, these fibres are not used in high stress applications owing to their tendency to creep at high temperatures.[29] Their prime applications are in insulation of furnaces and replacement of asbestos fibres in friction materials, gaskets and packings.[30] Both aluminium oxide or alumina fibres and silicon oxide or silica fibres are also produced. Pure boron fibres are too brittle to handle but they can be coated on tungsten or carbon cores. Their complex manufacturing process makes them rather expensive. Their prime application is in lightweight, high strength and high modulus composites such as racket frames and aircraft parts. Boron fibre use is limited by their thickness (about 16 μm), their relatively poor stability in metal matrices and their gradual loss of strength with increasing temperature.[31] Boron nitrides (BN) are primarily used in the electronic industry where they perform both as electrical insulators and thermal conductors.

The most outstanding property of silicon carbide (SiC) is the ability to function in oxidizing conditions up to 1800 °C with little loss of mechanical properties. Silicon carbide exceeds carbon fibre in its greater resistance to oxidation at high temperatures, its higher compressive strength and better electrical resistance. SiC fibres containing carbon, however, lose some tensile properties at the expense of gaining better electrical conductivity.

Finally, many of the inorganic fibres so far referred to are now also produced in microcrystalline or whisker form and not in the more normal textile-fibre form. Whiskers have extremely good mechanical properties and their tensile strength is usually three to four times those of most reinforcing fibres. They are, however, costly to produce and their inclusion into composite structures is both difficult and cumbersome.

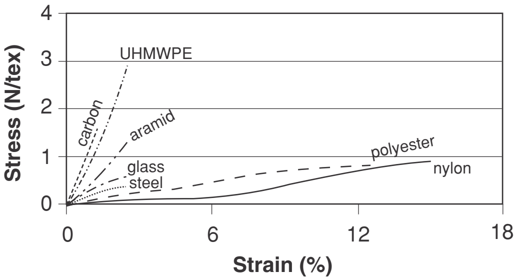
2.6 Ultra-fine and novelty fibres

Ultra-fine or microfibres were developed partly because of improved precision in engineering techniques and better production controls, and partly because of the need for lightweight, soft waterproof fabrics that eliminate the more conventional coating or lamination processes.[32] As yet there are no universal definitions of microfibres. *Textile Terms and Definitions*[2] simply describes them as fibres or filaments with linear densities of approximately 1.0 dtex or less. Others[33,34] have used such terms as fine, extra-fine and micro-fine corresponding to linear densities ranging from 3.0 dtex to less than 0.1 dtex. They are usually made from polyester and nylon polymers, but other polymers are now being made into microfibres. The Japanese first introduced microfibres in an attempt to reproduce silk-like properties with the addition of enhanced durability. They are produced by at least three established methods including island-in-sea, split process and melt spinning techniques and appear under brand names such as Mitrelle, Setila, Micrell, Tactel and so on. Once in woven fabric form their fine diameter and tight weave allows up to 30 000 filaments cm^{-2}, making them impermeable to water droplets whilst allowing air and moisture vapour circulation. They can be further processed to enhance other characteristics such as peach-skin and leather-like appearances. The split technique of production imparts sharp-angled edges within the fibre surface, which act as gentle abraders when made into wiping cloths that are used in the optical and precision microelectronic industries. Microfibres are also used to make bacteria barrier fabrics in the medical industries. Their combined effect of low diameter and compact packing also allows efficient and more economical dyeing and finishing.

Finally, constant pressure to achieve and develop even more novel applications of fibres has led to a number of other and, as yet, niche fibrous products. In principle, the new ideas usually strive to combine basic functional properties of a textile material with special needs or attractive effects.

For example, Solar-Aloha, developed by Descente and Unitika in Japan,[35] absorbs light of less than 2 μm wavelength and converts it to heat owing to its zirconium carbide content. Winter sports equipment made from these materials use the cold winter sun to capture more than 90% of this incident energy to keep the wearer warm. Another interesting material gives rise to thermochromic fabrics made by Toray which have a uniform coating of microcapsules containing heat-sensitive dyes that change colour at 5 °C intervals over a temperature range of –40 °C to 80 °C creating 'fun' and special effects.

Cripy 65 is a scented fibre produced by Mitsubishi Rayon (R) who have enclosed a fragrant essence in isolated cavities along the length of hollow polyester fibres. The scent is gradually released to give a consistent and pleasant aroma. Pillows and bed linen made from these materials are claimed[32] to improve sleep and sleeping disorders. The effect can also be achieved by printing or padding microcapsules containing perfumes into fabrics which subsequently burst and release the perfume. With careful handling, garments made from these materials are said to maintain this



2.2 Stress/strain curves of range of available fibres.

property for up to two years. Infrared-emitting and bacteria-repelling fibres are some of the other emerging novel fibres.

Figure 2.2 shows stress/strain values for a selected range of the fibres discussed.

The remainder of this chapter focuses on the vast application areas of fibres giving examples in each category with respect to their functional requirements, limitations and means of optimising their effectiveness.

Table 2.3 summarises applications into five major areas.

2.7 Civil and agricultural engineering

Natural fibres such as flax, jute and ramie can be used for most temporary applications where, for instance, soil erosion is the problem. The geotextiles made from these natural polymers help to prevent the erosion of soils by allowing vegetative growth and their subsequent root establishment. Once the purpose is served, the geotextile material gradually disintegrates into the soil.

In most medium to long term applications however, where physical and chemical durability and dimensional stabilities are of prime concern, synthetic fibres are preferred. There are currently at least six synthetic polymers considered suitable for this purpose; they include:

- polypropylene
- polyester
- polyethylene
- polyvinyl chloride
- polyamide
- aramids.

Polypropylene is by far the most utilised geotextile, followed by polyester, the other three trailing behind with polyamide as the least used synthetic polymer. *Para*-aramids are only used where very high creep resistance and tolerance to prolonged heating are required.[36]

Generally, geosynthetics must have lifetimes which are defined and relate to their function. Durability, therefore, is mainly determined by the resistance offered by the component fibre and its assembled structure to the degrading species that causes a reduction in the tensile and mechanical properties.[37] At least three main degrading mechanisms have been identified that ultimately determine the durability and life of the contending polymer; they include:

able 2.3 Applications of technical textiles

ivil & agricultural Engineering	Automotive & aeronautics	Medical & hygiene	Protection & defence	Miscellaneous
pplication				
eotextiles, geomembranes and geocomposites g. oil reinforcement eparation ltration rainage rosion control aterproofing oil stabilization for vegetative growth nderground hoses (used for irrigation & addition of fertilisers and pesticides)	Tyre reinforcement Seat belting Air bags Carriage interiors Bumpers Wings Engine reinforcement Flexible container carriers Balloons Parachutes, etc.	Wound care Bandages Barriers to bacteria Sterile wraps Disposable blood filtration (dialysis) valves Replacement ligaments Artificial arteries Synthetic sutures, etc.	Barriers to: chemical compounds, heat, moisture, flame and acoustics. Insulation Workwear Body armour e.g. Vests, Helmets, Gloves, etc.	Marine engineering Electronics Filtration industry Food processing Sports & leisure e.g. Ropes, Belts, Boat Building Sails Cables Clean room suits Gas & liquid filters Purifiers Tennis rackets Tents, etc.
orm of application				
onwoven, woven, warp knitted, grids, composites, three-dimensional network structures, etc.	Nonwoven, woven, knitted (warp/weft), composites (plastic or metal resins), etc.	Nonwoven, woven, knitted (warp/weft), braided, etc.	Nonwoven, woven, knitted (warp/weft), composites, network structures, etc.	Nonwoven, woven, knitted (warp/weft), braided, composites, etc.

- physical degradation
- chemical degradation
- biological degradation.

Physical degradation is usually sustained during transport or installation in one form or another. Initiation of cracks is normally followed by their subsequent propagation under environmental or normal stress. In the first instance, polymer susceptibility to physical degradation depends on such factors as the weight of the geotextile; generally lightweight or thin geotextiles suffer larger strength losses than thick and heavy materials. Secondly, woven geotextiles suffer slightly larger strength losses than nonwovens, owing to their greater stiffness and, finally, the generic nature of the polymer itself plays an important role. Polyester, for instance, suffers greater strength losses than polyolefin fibres owing to its high glass transition temperature of around 70 °C. Under normal soil conditions, the polymer is relatively brittle and therefore susceptible to physical damage.[38] Polypropylene with its glass transition averaging at about –10 °C is much more pliable under these conditions but suffers from the rather critical phenomenon of extension with time or creep.

Chemical degradation is the next mechanism by which chemical agencies, often in combination with ultraviolet light or/and heat, attack the polymer whilst in use or being stored. The presence of energy starts off a self-destructing chain of events that ultimately renders the polymer ineffective. Ultraviolet radiation normally attacks the surface of the polymer and initiates chain breakage or scission which leads to embrittlement and eventual failure of the polymer. Generally, chemical degradation is a function of polymer type, thickness and availability of stabilizers. The type, quantity, and distribution of stabilizers[39] also controls the degree of resistance to degradation. Polyolefins are particularly susceptible to ultraviolet degradation and need protection using light-stabilising additives. Oxidation due to heat operates similarly by weakening the polymer thus causing rapid degradation. A range of antioxidants are often included in the polymer during manufacture and processing to minimise this harmful effect.

Biological degradation can result from at least three types of microbiological attack: direct enzymatic attack, chemical production by microorganisms which may react destructively with the polymer, and attack on the additives within the polymer.[40,41] High molecular weight polymers are much more immune to biological attack than low molecular weight polymers because microorganisms cannot easily locate the molecular chain endings. However, some microorganisms can permeate less digestible polymers in order to gain access to food.

2.8 Automotive and aeronautics

Mechanical functionality has increasingly become an almost secondary requirement for travel safety, weight efficiency, comfort and material durability of the transporting medium. From bicycles to spacecraft, fibres in one form or another fulfil these important requirements. Carbon fibre reinforcement of the frame of a bicycle ridden in the 1992 Olympics was the first of its kind to allow a comfortable win ahead of its competitors.[41] The one-piece, light, fibre-reinforced composite structure and design of the bike have since become an earmark of this industry. In the simplest terms, composites utilise unique fibre properties such as strength, stiffness and elasticity whilst incorporating the compression resistance, and torsion and bending characteristics of the matrix used.[42] Glass fibres have been traditionally used for the manufacture of boat hulls and car bodies. UHMWPE, aramids and carbon-reinforced composites in a variety of matrix materials are now routinely produced and utilised in low to very high temperature applications.

Reinforcement of tyres is another area where the transport industry has benefited from fibres and where rapid temperature change and changing weather conditions demand effective response and durability. High tenacity viscose and polyester yarns built into the internal structure of tyres now address these needs adequately. In addition to all the obvious upholstery materials used in the interior of cars, trains and aeroplanes, fibres are now used in one form or another in such parts as the engine components, fan belts, brake pads, door panels, seat skeletons, seat belts and air bags. Fire-retardant additives or inherently fire-retardant fibres are today standard requirements in the public sector use of all transport in order to improve safety.

2.9 Medical and hygiene applications

Fibres used in relation to health care and surgery may be classified depending on whether they are natural or synthetic, biodegradable or non-biodegradable. All fibres used, however, must be non-toxic, non-allergenic, non-carcinogenic and must be able to be sterilised without imparting any change in their physical or chemical characteristics.[43]

Traditionally, natural fibres such as cotton, silk and later viscose have been extensively used in all areas of medical and surgical care. One such area of application is on the wound, where moisture and liquid that exude from the wound are absorbed by the fibrous structure to promote healing in relatively dry conditions. However, upon healing, small fibrous elements protruding from the wound dressing are usually trapped in the pores of the newly formed tissues which make their removal distressing to the patients.

Research work[44] in the early 1960s showed that wounds under ‘moist conditions’ would in fact heal better and faster, which would also remove the problem of fibres being trapped in the healing wound. The concept of moist healing has since been responsible for the development of many fibres which have vastly improved wound management techniques and patient care. Alginate fibres[45] are one such example where naturally occurring, high molecular weight carbohydrates or polysaccharides obtained from seaweeds have found use in the medical textiles. Chemically, alginate is a copolymer made from α-L-guluronic acid and β-D-mannuronic acid. It is made into fibres by extruding sodium alginate into a calcium chloride bath where calcium alginate filaments precipitate. The filaments are then drawn, washed and dried. Upon contact with wound fluid, these fibres are partially converted to a water-soluble sodium alginate that swells to form a gel around the wound, thus keeping the wound moist during the healing period. They can then be easily removed once the treatment is complete. Artificial polymers based on a crosslinking copolymer of acrylic acid have been developed which are claimed[16] to have superior absorption properties to alginates particularly when used under pressure. Hydrocel, a derivative of Acordis’s environmentally friendly Lyocell, is also claimed to be more absorbent than calcium alginate, taking up to 35 times its own weight of water whilst remaining intact.

Chitin[46,47] is another polysaccharide which, after cellulose, is the most abundantly available natural polymer. It is found in the outer shells of shrimps and crabs in combination with protein and minerals. Medicinal and medical use of this polymer has been realised seriously since the early 1970s. High purity chitin, from which protein, heavy metals and pyrogens have been removed, can be used for a range of applications from food additives for controlling cholesterol levels in blood to artificial skins into which tissues can safely grow. A derivative of chitin, chitosan has better processability and is now extensively available in fibre form. The particular appeal of both chitin and chitosan within biomedical applications is due to their being:

- natural and biodegradable
- compatible with most living systems
- versatile in their physical form, i.e. powder, aqueous solutions, films, shaped objects, fibres and sponges, and
- vehicles for transporting and delivering drugs.

Finally, collagen, a protein-based polymer that is collected from bovine skin and has traditionally been used in hydrogel or gelatine form for making jellies and sausage casings, is now available in fibre form. It is very strong and completely biodegradable.

Besides wound care, fibre-based structures in synthetic or natural form are used in extracorporeal devices that may be used to purify blood in kidneys, create artificial livers and function as mechanical lungs,[47] as well as finding use in suture materials, artificial ligaments and cartilages and cardiovascular implants. In general, healthcare and hygiene products, have applications that cover a wide spectrum from disposable items to surgeons uniforms and hospital bedding and all are becoming increasingly important across the world as the need to produce efficient and effective medical care increases.

2.10 Protection and defence

In textile terms, protection and defence can be a passive response in which the textile product receives and absorbs the impending impact or energy in order to protect the underlying structure. Ballistic garments are obvious examples, where the assembled fibrous material is deliberately designed to slow down and reduce the penetration of an incoming projectile. But they may also have a more active role, where the fibres show positive response by generating char or protective gases, shrinking or expanding to prevent penetration of moisture or vapour and so on. In each scenario, the protection of the underlying structure is the common objective.

In the early days, leather and metal mesh garments were used to protect the body against sword and spear attacks, but with the passage of time development of new materials occurred and, for example, early in the 1940s, nylon-based flack jackets[48] were introduced. They were a considerable improvement on the leather and metal garments but were still rather heavy and uncomfortable to wear. With the advent of *para*-aramids in the early 1970s, advanced fibres were for the first time used to make much more acceptable protective gear. In these garments, Kevlar or Twaron continuous filament yarns are woven into tight structures and assembled in a multilayer form to provide maximum protection. Their high tenacity and good energy absorption combined with high thermal stability enables these garments to receive and neutralise a range of projectiles from low calibre handguns, that is 0.22 to 0.44 inch (5.6–11.2 mm) to military bullets within the 5.56–7.62 mm range.[49] In the latter case, the fabric will require facing with ceramic tiles or other hard materials to blunt the tips of metal-jacket spitzer-pointed bullets.

To strike a better balance between garment weight, comfort and protection an even stronger and lighter fibre based on ultra-high molecular weight polyethylene (see Section 2.3) was developed and used in the early 1990s, which immediately reduced average garment weight by 15%.[50,51] UHMWPE, commercially known as Dyneema (DSM) and in composite form as Spectra Shield by Allied Signal, is now used to make cut-resistant gloves and helmets, as well as a wide range of protective garments. However, unlike Kevlar, with a fairly low melting temperature of 150 °C, it is best suited to low temperature applications.

Fire is another means by which fatal and non-fatal injuries can be sustained. No textile-based material can withstand the power and ferocity of a fire for sustained periods of greater than 10 min or so. However, if the fire ignition point could be increased or the organic structure converted to a carbonaceous char replica and its spreading rate delayed, then there may just be enough time gained to save an otherwise lost life. This is in essence the nature and objective of all fire-retardant compounds. Such treatments give fibres the positive role of forming char, reducing the emission of combustible volatile gases and effectively starving the fire of oxygen or providing a barrier to underlying surfaces.

In contrast, water-repellent fabrics may shed water by preventing water droplets from physically passing through them owing to their fine fibre dimensions and tight weaves, as is the case with ventile fabrics[52] or perforated barrier inlays such as Goretex,[53] whose tiny holes allow water vapour to pass through them but not water droplets. Wax and chemically treated fabrics reduce water/fabric surface tension by allowing water to roll off but do not allow permeation of moisture and air, so compromising comfort.

2.11 Miscellaneous

It is not possible to categorise fully all disciplines within which textile-based materials are increasingly being applied. The spectrum of fibre utilisation has already grown to include anything from conventional ropes and industrial belts to sophisticated two- and three-dimensional composite structures. The industries they cover, other than those already discussed, include wet/dry filtration, sports and leisure gear, inland water and marine applications, food processing, purifiers, electronic kit, clean room suits and many more. It will not be long before each area develops into its own major category.

2.12 Conclusions

Conventional fibres dominate the technical fibre market and are likely to do so for a long time to come. The rate of growth in consumption of fibres destined for technical applications, however, is now faster than those going to the traditional clothing and furnishing sectors. It was estimated that the world's technical fibres share of the market would have reached the 40% mark by the year 2000.[1] Much of this growth will depend on greater realisation of the technological and financial benefits that fibre-based structures could bring to the traditional and as yet unyielding sectors of engineering. Issues such as environment, recycling and biodegradability, which are increasingly subjects of concern for the public, will further encourage and benefit the growth and use of technical textiles.

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