17

Automotive applications

T. MATSUO, SCI-TEX, Japan

17.1 Introduction

It is estimated that about 25% of the total worldwide use of fibre in textiles is used for technical textiles but in advanced countries this figure increases to about 40%. In technical textiles, the largest user is the automotive sector as shown in Table 17.1, whose figures were obtained from statistics in 2003. This sector uses about 2000 kt. The table also shows that the average unit price of fibre for automotive use is comparatively high compared with the main technical-textile end-use fibres. The amount of fibre used for a standard passenger car is about 25 kg. This is now increasing because the requirements for the safety and comfort of passengers and for car weight reduction, which means an increase of reinforcing fibres for hard composites, are being intensified.

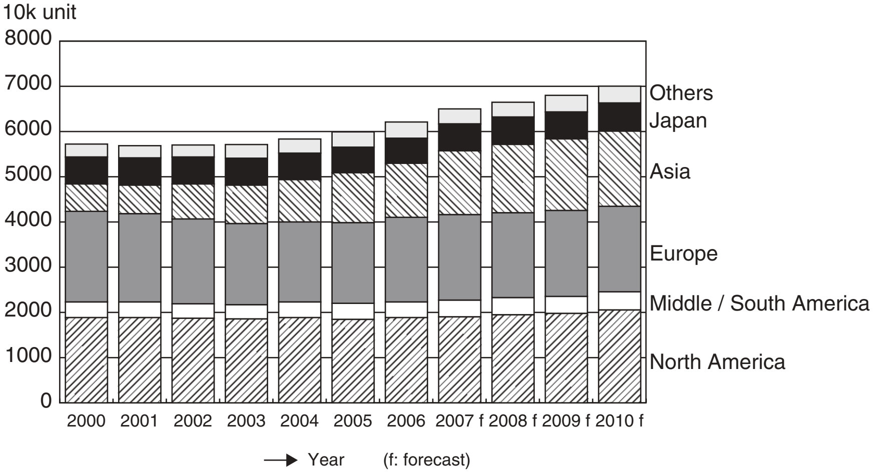
Furthermore, the worldwide demand for automobiles is growing, as shown in Fig. 17.1. Hence, the amount of automotive fibre being used is therefore increasing. These statistical facts indicate the industrial importance of automotive fibre in terms of end-use.

The selection criterion for automotive use materials is ‘performance/cost’ as with most other technical textile materials. In general it is more strictly applied to automotive use. For example, steel cord is usually used as a reinforcing material in tyre belt plies for passenger cars. The reason is that steel has the best value for ‘(tensile modulus)/cost’ of currently existing materials. But if car weight reduction becomes more important in the future, the selection criterion may become ‘(specific tensile modulus)/cost’ and then steel could be replaced by a high-performance fibre such as poly-ketone fibre.

Fibre is used for several kinds of parts in automobiles such as (a) tyres, driving belts, tubes and hoses, seat belts, air bags, seats, roof trims, floor coverings, noise control materials and cover sheets, (b) filters, and (c) mechanical parts, exterior body panels and bumper beams. In the near future, optical fibre for the information and driving control system, and

Table 17.1 Share in consumption amount and relative unit price by end-use field in technical textiles[1]

	Share (%)	Relative unit price
Transportation	25.3	3.5
Industrial	15.6	2.2
Sports	15.3	3.8
Living goods	7	1
Construction	7	1.3
Clothing goods	7	1.9
Sanitary, medical	6	1.2
Agriculture, fishery	6	1.4
Protection	6	8
Packaging	5	1
Civil engineering	1	1



17.1 Trend in the demand for automobiles in the world.[2]

reinforcing fibre for the fuel pressure vessel may also be widely used. The percentage use of automotive fibres for main parts is summarized in Table 17.2. Hard composites is the second largest user group but they are mostly reinforced by glass fibre through compression moulding and/or injection moulding. As described in Section 17.3.1, nylon tyre cord is preferable for use when driving on rough roads, especially in developing countries, because nylon is superior in toughness compared with PET. On the other hand, rayon fibre is preferred for use in run-flat tyres in Europe and North America, because it has better heat resistance than PET. With regard to the shares in the total amount of automotive fibres used, polyethylene

Table 17.2 The amount of automotive fibres by end-uses[3]

End-uses (main parts)	Share (%)
Rubber composites (tyre, driving belt)	36
Safety system (seat belt, airbag)	4
Car interiors (seat, door trim, roof trim floor covering)	17
Hard composites (body, mechanical parts)	30
Others (filter, etc.)	13

terephthalate (PET) fibre takes up about 42% and nylon 66 fibre about 26%.[4] They are mainly used in area (a) because they are fairly inexpensive and have comparatively good physical properties and dyeability. But in other areas such as area (c), glass fibre has a far superior 'performance/cost' value to them as a reinforcing fibre.

In this chapter, polyester fibres and polyamide fibres for automotive use are first described in terms of fibre performance requirements (Section 17.2). Then applications to rubber composites such as tyres, driving belts (Section 17.3), internal safety systems such as seat belts and air bags (Section 17.4), car interiors such as seats, roof trims and floor coverings (Section 17.5), and others such as exterior cover sheets and noise control materials (Section 17.6) are explained.

Sections 17.3, 17.4, 17.5 and 17.6 describe: (a) the particular part to which fibre is applied; (b) the application form of fibre material to the part in terms of fibre function; (c) the performance requirement of the fibre material; and (d) the fibre species and type used for the part.

17.2 Polyester and polyamide fibres for automotive use in terms of fibre performance requirements

17.2.1 PET, nylon 6 and 66 fibres

In Table 17.3, the main properties of PET, nylon 6 and nylon 66 fibres are shown compared with those of polypropylene (PP) and p-aramid fibres. In Table 17.4, the advantages and disadvantages of PET, nylon and PP fibres in terms of properties, cost, and energy consumption are summarized.

PP fibre is usually the most economical, lowest in energy consumption to produce fibre and lowest in specific gravity. But PET and nylon fibres have advantages in dyeability, high temperature resistance and dimensional stability over PP. It must be noted that the lower melting point of PP causes a limitation in the application of PP to temperature-sensitive parts. Compared with nylon fibre, PET fibre has a higher modulus, higher heat stability, higher resistance to colour change, higher durability for

Table 17.3 Properties of PET, nylon fibres comparing with PP and p-aramid fibres (standard type)

Fibres	Specific gravity	Melting point (˚C)	Glass transition temp (˚C)	Tensile strength (MP$_a$)	Breaking elongation (%)	Tensile modulus (GP$_a$)	LOI (%)	UV degradation	Colour-change by UV
PET	1.38	260	70	510–690	15–40	6–11	18–21	++	++
Nylon 66	1.14	260	35 (50%RH)	350–550	18–36	3.0–6.5	20–21	+	+
Nylon 6	1.13	220	20 (50%RH)	450–700	20–32	2.5–3.4	20–21	++	+
PP	0.91	160	–15	410	25–60	6.4	18–20	+*	+++**
p-Aramid	1.14	–	300	2760	3.3	58	29	++	–

Notes:
++: fairly good; +: good; +*: can be good by additive; +++*: very good by pigment colour; –: sensitive

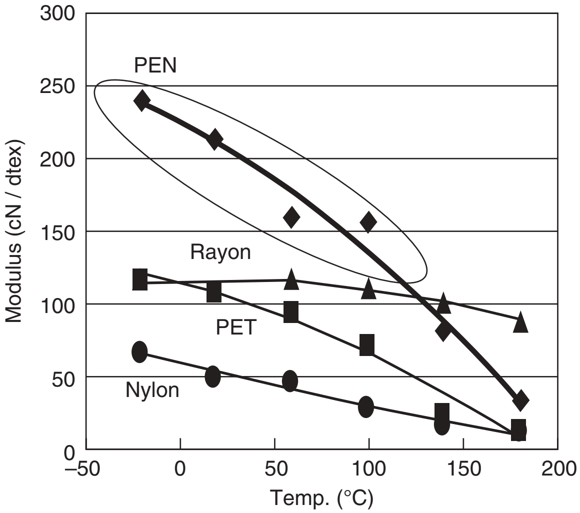
Table 17.4 Advantages and disadvantages in properties of PET and nylon fibres comparing with PP fibre

Fibres	Advantage, feature	Disadvantage
PET	Balanced in physical properties	Easy in hydrosis A little less in wearing resistance
Nylon	Excellent in toughness and wearing resistance Low in modulus Excellent in strain recovery	Easy in yellowing Fairly expensive as conventional fibres High in energy consumption for fibre production
PP	Excellent in chemical resistance Low specific gravity Low in energy consumption for fibre production	Very bad in dyeability Low in heat resistance High in creep and stress relaxation

sunlight degradation and is less expensive. In addition, the production of nylon fibre uses the most energy. But it has greater toughness, excellent tensile strain recovery and also excellent adhesiveness. With regards to nylon 6 and 66, the former has higher heat resistance but it is a little more expensive. Hence, nylon 66 is used for the end-uses requiring higher heat resistance. In these property and cost situations, PET fibre is usually used for the reinforcement of most rubber composite parts. But for tyres used on rough roads in developing countries, advantage is taken of the excellent toughness of nylon fibre. For seat belts, PET fibre is mainly used because of its higher modulus, higher glass transition temperature and higher durability for sunlight. On the other hand, nylon 66 fibre is used for air bags because of its higher foldability when it needs to be contained and higher resistance to small burning particles. For car interiors, PET fibre is mainly used because of its higher sunlight (colour change) resistance and higher heat resistance.

17.2.2 Other polyester fibres and polyamide fibres

Polyethylene naphthalate (PEN) is the other main type of polyester fibre which is now used in automotive materials. As shown in Fig. 17.2, PEN has a much higher tensile modulus and heat stability than PET because of the higher molecular stiffness caused by the naphthalene ring for PEN compared to the benzene ring for PET. Its cost is situated midway between PET and p-aramid. One example of its automotive applications is in tyre



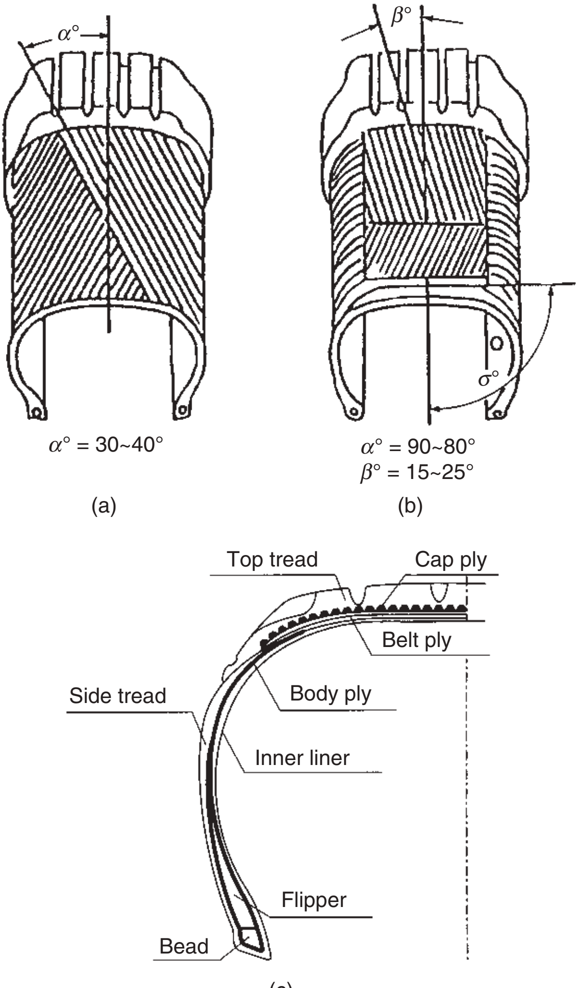
17.2 Changes in the modulus of PEN by temperature comparing with other fibres.[5]

cap plies because its high modulus can reduce the noise caused by the vibration of tyres in contact with the road. The fibre is also useful for the reinforcement of other automotive rubber composite parts such as brake hoses and driving belts. It should be noted that there are wholly aromatic polyesters and p-aramids other than PET, PEN and nylon 6 and 66. But all of them are generally too expensive to be widely used as automotive materials. Some high-class tyres and high-performance tyres use p-aramid fibre. One typical example of its use is as a cap ply in combination with nylon 66.

17.3 Rubber composite parts

17.3.1 Tyres

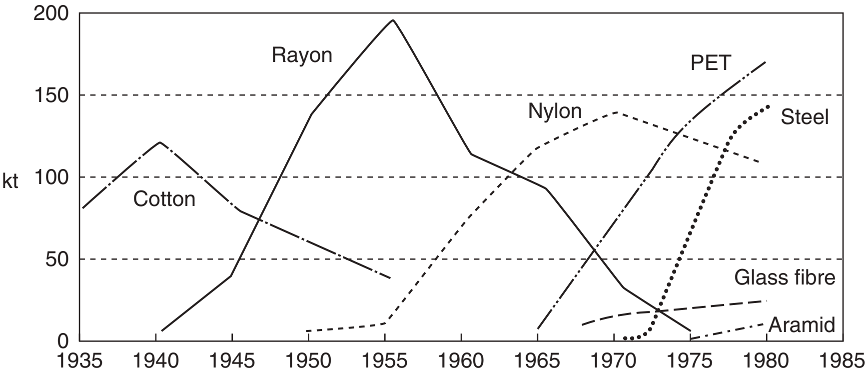
Tyre structures can be classified as bias tyres and radial tyres. These are illustrated in Fig. 17.3. A bias tyre has a higher energy absorption capacity, therefore it is more feasible to use it on rough roads. But it also has a lower wearing resistance. Hence it has been gradually replaced by the radial tyre with the increase in smoother road surfaces. In the bias tyre, nylon fibre is used for body ply cord because of its excellent toughness. In radial tyres for passenger cars, PET fibre is mainly used for body ply cord because its higher modulus can contribute to improved driving comfortability by the reduction of flat spotting. Nylon 66 fibre is mainly used for cap ply cord because of its higher strength and higher toughness. Figure 17.4 shows the changes by year in the amounts of several tyre cord materials used in USA,



17.3 Structures of tyre for a passenger car: (a) bias tyre; (b) radial tyre; (c) the cross-sectional structure of a radial tyre.[6]

which correspond to the historical changes of the bias tyre and radial tyre, as stated above.

A high modulus low shrinkage (HMLS) type of PET multi-filament is usually used for tyre cord, because a higher modulus and higher heat resistance in shrinkage are important requirements for tyre cord. But the most important property that needs to be improved for PET is its comparatively low adhesiveness to matrix rubber. As regards nylon, a high strength type of multi-filament is required for tyre cord. The properties of tyre cords made of several materials are summarized in Table 17.5 in which yarn



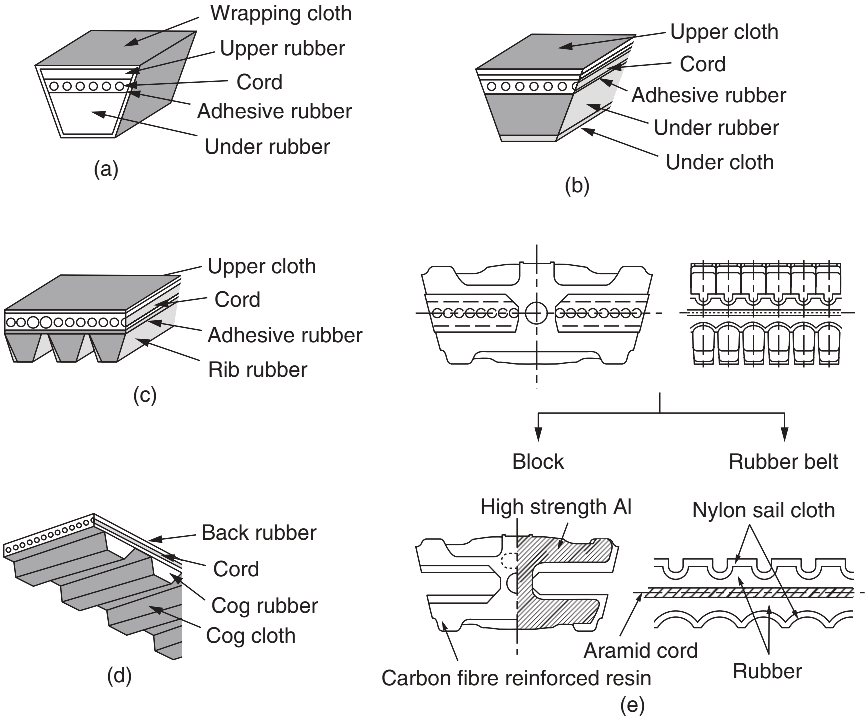
17.4 Changes by year in the amount of several tyre materials consumed in the USA.[7]

Table 17.5 Properties of nylon 66 and HMLS PET tyre cords comparing with other materials[8]

	Ny66	HMLS PET	PEN	Rayon super III	p-Aramid	Steel
Thickness	1400/2	1670/2	1670/2	1840/2	1670/2	–
Twist (T/10 cm)	39 × 39	39 × 39	39 × 39	47 × 47	32 × 32	–
Strength index of flat yarn	100	90	80	55	210	–
Elongation of flat yarn (%)	19	11	9	9	3.6	–
Therm. shrink. of flat y. (%)	5.5	3.0	1.5	≥0.3	≥0.3	–
Elongation at fixed load (%)	7.0	4.0	2.0	2.0	0.9	–
Creep index	100	50	–	70	10	–
Adhesiveness	good	fairly g.	fairly g.	good.	fairly g.	good
Specific gravity	1.14	1.38	1.36	1.52	1.44	7.81
Melting point (°C)	265	260	272	degrade	degrade	1450
Glass transition temp. (°C)	–	70	113	–	–	–

Notes:
Rayon super III: the third generation super tenacity rayon

thickness/number of ply is also shown. There are different methods for the fibre reinforcement of tyres other than by using cord. One is a direct blend of short fibres such as p-aramid with matrix rubber. Another example is the use of the composite made of p-aramid nonwoven and rubber which is inserted into the inner part of a truck/bus tyre to increase run-flat capability.



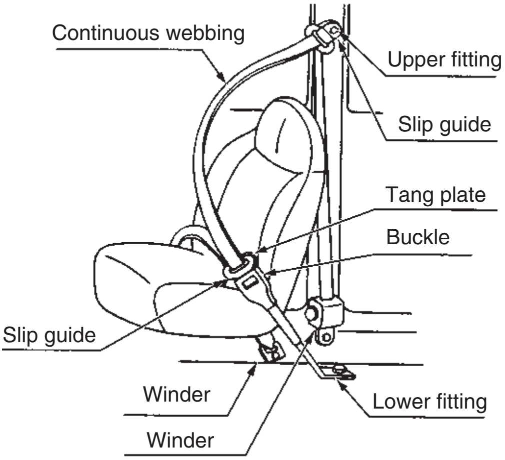
17.5 Structures of several kinds of driving belts:[9] (a) wrapped V-belt; (b) raw edge V-belt; (c) V-ribbed belt; (d) belt with cog; (e) composite V-belt.[10]

17.3.2 Driving belts

Driving belts can be generally classified as V-belts, V-ribbed belts, cogged belts and metal combined belts, which are shown in Fig. 17.5. For subsidiary automotive equipment such as air conditioners, a V-belt is used. Cogged belts and V-ribbed belts are used for engines. Recently a metal combined belt has been used for speed variation in small passenger cars. PET fibre is applied to the cord of V-belt and the cloth of its upper part. p-Aramid fibre is applied to the cords of V-belts, V-ribbed belts and metal combined belts.

17.4 Internal safety systems

Seat belts and air bags are very important as passive safety systems inside automobiles.



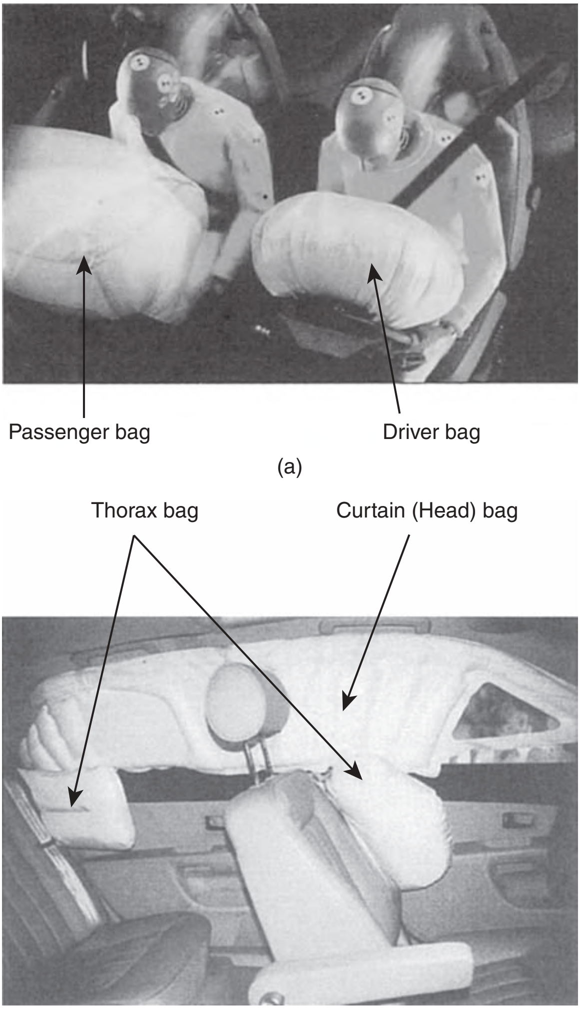
17.6 A typical example of sheet belt system.[11]

17.4.1 Seat belts

A seat belt is used to prevent a passenger in a car being thrown from their seat in an accident by fixing them to the seat and absorbing the impact shock. Figure 17.6 illustrates an example of a seat belt. PET woven fabrics are usually used for its webbing. As described in Section 17.2.1, PET is more suitable than nylon for the webbing, because PET has a higher impact energy absorbing capability and suffers less discoloration by sunlight. There are several standards for webbing such as the Federal Motor Safety Standard, Economic Commission for Europe and JIS. The main mechanical requirements in these standards are strength, width, elongation and energy absorption ratio. There are also requirements related to durability such as wearing resistance, cold and heat resistance, water resistance, light degradation resistance and colour fastness. Typical examples of specification values of PET fibre for this end use are: yarn thickness 1000–2500 dtex with 4–25 dtex of its mono-filament thickness, and strength 8–10 cN/dtex.

17.4.2 Air bags

The function of an air bag is to cushion a passenger from collision impact. The bag is instantly inflated by heated gas after a collision stronger than a certain limit. An air bag can be very effective as a passive safety system in combination with a seat belt. There are several kinds of air bags: driver bag, front passenger bag, thorax bag, curtain bag, rear bag and knee bag. Figure 17.7 shows photographs of several kinds of air bag. The base ma-



(a)

(b)

17.7 Examples of inflated airbags: (a) front airbags; (b) thorax bags and curtain bag.

terial of an air bag is nylon 66 weave because nylon is more suitable for use in an air bag than PET as described in Section 17.2.1. The thickness of nylon filament used for air bags ranges from 235 dtex to 700 dtex. The number of mono-filaments ranges from 70 to 220. A high strength type is needed. There are two types of base material: coated and non-coated. The coating material is now mainly silicone resin. The advantages of the coated type are: better non-gas-permeation, easier bag pressure control, greater heat resistance to burning particles. On the other hand, the non-coated type is lighter in weight, thinner, more flexible and less expensive. For non-coated cloth, some special products have been developed by weaving with an ultra-high yarn density, with a filament of lower mono-filament thickness, and with a filament whose fibre cross-section is flat.

17.5 Car interiors

The main interior components of an automobile are the seats, door trim, roof trim and floor covering.

17.5.1 Seat and door trim

Polyester fibre is used for most of the seat skin sheet, and for some seat cushion material. It is also used for some door trim skin material. There are several kinds of seat skin sheets such as pile weave, weave, tricot with raising, pile double raschel knit, and pile circular knit. General trends are towards an increase in knit fabrics (tricot, double raschel and circular knit) which are less expensive and have more formability than weave fabrics. Recently a suede fabric, using a PET nonwoven base material, has been introduced. Skin sheets containing phase change material have been also been developed, which can increase the temperature comfortability of the seat. The essential properties of seat skin sheets can be classified as aesthetic effect, physiological comfortability, strength/wearing durability, colour fastness, flame retardancy, heat resistance and non-volatile substance content. They are also often required to have some special functions such as anti-bacterial, deodorizable, anti-static and stain resistant properties. Pile or raising of these sheet fabrics is usually related to an increase in the values of tactile and visual aesthetic effects. An extremely high level of colour-fastness in sunlight is usually required, because automobiles can be used in high temperatures and strong sunlight.

Urethane foam is usually used for seat cushion material under the skin sheet. But some special PET nonwovens have recently been developed such as a fibre mass stabilized with elastomer fibre bonding, a folded web and stitch-bonded web, and a PET 3-dimensional knit fabric with super water absorbancy. One of the most important advantages of these fibrous materials over urethane foam is their moisture permeability for passengers' physiological comfort.

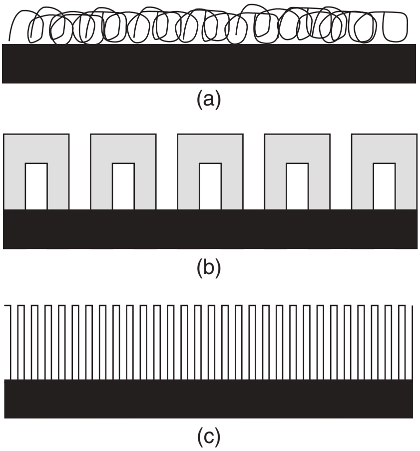
The material of door trim skins is usually made of plastic such as vinyl chloride and polyolefin. But textile sheets are also used for higher-class cars. In most cases, the textile material is the same as the seat skin fabric. However, the fabric needs to have high enough formability to be made into the complicated shape of a door trim. Its lower end is usually covered by the same carpet as the floor because the door often gets kicked.

17.5.2 Roof trims

PET nonwoven and tricot are used as roof trim skin sheets. The use of needle-punched nonwoven in particular has increased, and nonwoven patterned into velour by needling is especially common. But there are also spun-laced nonwovens and stitch-bonded nonwovens. They are usually formed into roof trim by integration with base materials. Pigment-dyed PET has been widely adopted. Sheets need to have colour-fastness for sunlight, heat resistance, mechanical durability, light durability, formability and non-volatile substance content and stain resistance in addition to lightness. Certain levels of sound absorbing capability and heat insulation are also needed. The base materials for roof trim can be mainly classified as polymer foam sheets and fibre-reinforced porous polymer sheets. Glass fibre is used for most of these sheets.

17.5.3 Floor coverings

Floor coverings can be mainly divided into liner coverings and optional coverings. Needle-punched nonwoven carpet and tufted carpet are used for liner coverings. The usage of nonwoven carpet has greatly increased because it is more economical and has better formability. There are three main kinds of surface pattern: plain, loop-like and velour-like, as schematically shown in Fig. 17.8. The latter two patterns can be made by the combination of specific needles and needling patterns. The surface material of these needle-punched carpets mainly consists of pigmented PET fibre and/or pigmented PET recovered from bottles. Its fibre thickness is reduced



17.8 The illustration of three main types of surface patterns for needle punched carpet: (a) plain; (b) loop-like; (c) velour-like.[13]

from 11 to 6 dtex to increase its covering factor. Quite attractive aesthetic effects can be achieved with needle-punched carpet by the specific patterning described above. The main performance requirements are: mechanical durability, sunlight durability, heat resistance, sunlight colour fastness, sound absorbability, sound insulation, anti-fogging, non-volatile substance content, flame retardancy, stain resistance and formability. With an increased requirement for weight reduction, sound absorbability has become more important than sound insulation.

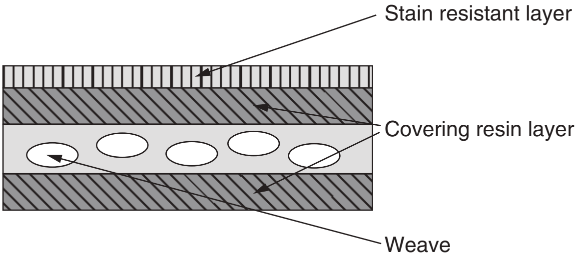
Tufted carpet has usually been used for optional carpets, where its aesthetic effect and appearance of high quality to the customer is of greater importance. Its weight ranges from 350 to 2000 g per m^2 based on the wide variety of customer requirements. Its surface material fibre is nylon, PET or PP. Of these, PP is increasing its usage share.

17.6 Others

17.6.1 Exterior cover sheets

There are two kinds of automotive exterior cover sheets. One type is a cover for protecting lorry cargo, which is further subdivided into covers for hood use and for plain covering use. The other type is for protecting passenger cars. PET spun yarn weave is mainly used for lorry cargo covers. Figure 17.9 shows its typical structure. Its coating layer is usually poly-vinyl chloride. The main specifications of cover sheets are also summarized in Table 17.6. Some PET filament weave is also used for truck cargo covers but filament weave is inferior in durability to spun yarn weave. The main performance requirements are: waterproof properties, water repellency, mechanical durability, weather resistance, dimensional stability, stain resistance, ability to be welded by radio frequency, and lightness.

Cover sheets for protecting passenger cars are usually made of PET filament weave, whose yarn thickness is about 250 dtex. Its weight is about 200 g per m^2. It is usually coated to make it waterproof. Some cover sheets



17.9 Cross-sectional structure of exterior cover sheet.[14]

Table 17.6 Specification of main synthetic sail cloth[15]

		No.		
		4	5	6
Width (cm)		92–103	92–103	92–103 183–184 203–204
Area density (g/m^2)		575–605	530–600	470–535
Tensile strength (kg/cm^2)	W	170–205	150–165	140–160
	F	140–170	125–170	105–130
Tearing strength (kg)	W	9–13	8–11	8–11
	F	13–14	9–13	7–11

Notes: W: warp direction; F: weft direction

contain aluminium powder for UV protection. Some other cover sheets are flame-retardant to protect cars from fire.

17.6.2 Boot mats

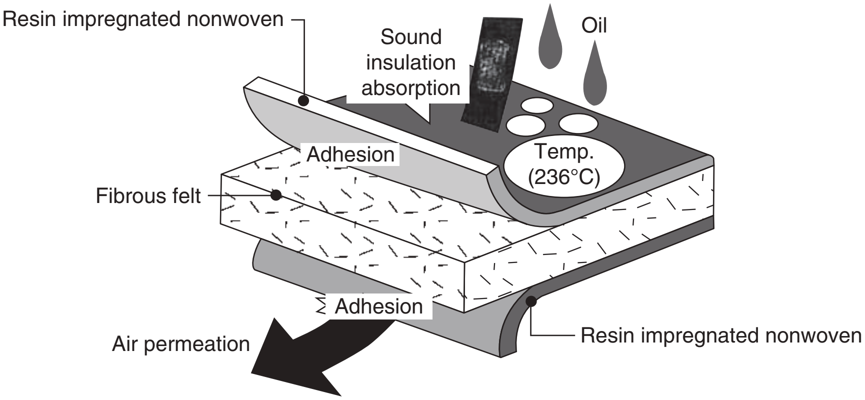
The performance requirements for a boot mat are not great enough to make it a particularly cost-sensitive automotive part. Needle-punched nonwoven is usually used for the mat. Felt made of recovered fibre is also used for the underlayer of the mat.

17.6.3 Noise control materials

The sound insulation capability of a sheet is generally proportional to its weight. For example, 10 kg per car is needed for a good sound insulation floor covering. In order to reduce car weight, the strategy for noise reduction within the cabin has been changed to adopting the use of parts having higher sound absorption capability instead of higher sound insulation. Interior parts such as floor covering and roof trim are typical targets in this strategy, as stated above. Multi-layered nonwovens are used for the engine silencer and sheet supporting spring to reduce unusual sounds in line with this strategy. Figure 17.10 is an example of such an engine silencer.

17.7 Conclusion

In the future, the need for eco-friendliness in cars will become more important. Weight reduction will be attempted for all kinds of automotive parts and for car structures. Trials on the structure of polymer material will be carried out for its ability to be recovered easily from scrapped cars.



17.10 An example of an engine silencer.[16]

The re-use of recovered materials for automobiles will be increased. Carbon neutral material such as poly-lactic acid and natural cellulose fibre may be gradually introduced into automotive parts. These factors might have positive impacts in some cases and negative in other cases on the automotive use of polyester fibres and nylon fibres. But it is most likely that the use of these fibres will not be particularly affected, at least in the near future. Therefore, the amounts of these fibres for automotive use will increase at least in proportion to the increase in car demand.

Many of the references in this chapter are unfortunately written only in Japanese. Hence the author would like to list some books written in English at the end of the following references for the convenience of readers.

17.8 References and bibliography

1. H. ISHIHARA; *Kakou gijutu*, **41**, 760 (2006)
2. T. MOTIMARU; *Automobile and Textiles*, Published by Sen-I Sha, p 5 (2004)
3. A. YONENAGA; private communication
4. A. YONENAGA; private communication
5. H. MORI; Extended Abstract of 10th Japan Sea Polymer Workshop, p 19 (2006)
6. K. KAWASAKI; *Automobile and Textiles*, Published by Sen-I Sha, p 153 (2004)
7. ibid, p 156 (2004)
8. K. KAWASAKI; *Sen-I Handbook*, Edited by The Soc. of Fiber Science and Technology, Japan, Published by Maruzen, p 660 (2004)
9. T. KINOSHITA; *Automobile and Textiles*, Published by Sen-I Sha, p 168 (2004)
10. S. MURASE; ibid, p 96 (2004)
11. A. YONENAGA; ibid, p 271 (2004)
12. H. ENDO; ibid, p 135 (2004)
13. H. SUZUKI; ibid, p 145 (2004)

14. H. SUZUKI; ibid, p 145 (2004)
15. A. HINATA; ibid, p 82 (2004)

Bibliography

W. FUNG; *Handbook of Technical Textiles*, Edited by A. R. Horrocks and S. C. Anand, Published by Woodhead Publishing Ltd. in association with Textile Institute (2000)

W. FUNG and J. M. HARDCASTLE; *Textiles in Automotive Engineering*, Published by Woodhead Publishing Ltd. (2000)

S. K. MUKHOPADHYAY *et al.*; Automotive textiles, *Textile Progress* vol. 29 Nos.1/2, Textile Institute Publication (1999)

18

Applications of polyesters and polyamides in civil engineering

R. FANGUEIRO, C. GONILHO PEREIRA
and M. DE ARAÚJO, University of Minho, Portugal

18.1 Introduction

A niche market for the textile industry is providing fibres and fabrics to the construction industry, as a potential substitute for more traditional building materials such as wood, concrete, masonry and steel. If in several applications this is the main goal of the textile industries, in other cases, textile materials are already considered traditional civil construction materials.

Fibre reinforced composites are gaining popularity within the civil construction sector. Applications like fibre-reinforced concrete, concrete retrofitting, concrete jacketing and composite concrete structures internal and external reinforcement are, among others, applications where fibres and fibrous structures play an important role. In these emerging applications fibres like AR-glass, carbon and aramid are of paramount importance due to their high strength, high modulus and to the possibility to compete with the conventional structural construction materials.

In applications related to the geotechnical and geoenvironmental applications, where properties beside mechanical ones are of paramount importance, fibres and textile structures are already commonly used materials. Examples like embankments and retaining walls, road construction and road overlaying, erosion control of steepened slopes, shore protection, construction of waste landfills, architectural membranes, offshore applications, among others, show that fibres and fibrous structures are the core construction materials. In these applications polyamide fibres and, especially, polyester fibres are used in an indiscriminate way.

18.2 Polyester and polyamide fibres and structures for civil construction applications

Depending on the applications envisaged, polyester and polyamide fibres are used in civil construction projects in several forms. If concrete internal reinforcement is the objective, polyester and polyamide fibres are used as micro- and macro-fibres, fibrillated fibres and monofilaments. Otherwise, if concrete external reinforcement is required, polyester and polyamide fibres are applied as woven fabric. Polyester and polyamide woven and knitted fabrics as well as needle punched nonwoven fabrics, are also available in geotextiles and geogrids. The combination of different types of structures – hybrid structures – is also common, and their impregnation in matrices, polymeric or cementitious, is usual.

18.2.1 Monofilaments, micro- and macro-fibres and fibrillated fibres

Polyester and polyamide fibres are available in several geometries and dimensions. Monofilaments, rovings (tows) and fibrillated fibres are specially used to reinforce cementitious or polymeric matrices. Monofilaments are single straight fibres usually made by drawing molten polymers. Such fibres are usually round in cross-section and are usually used in fibre-reinforced concrete applications. Many polymers are spun in the form of filaments whose diameters vary from 5 to 15 μm in diameter. Several thousand filaments are spun simultaneously, by drawing them from a single die and bundling together. Rovings are cut into short lengths in order to obtain micro- and macro-fibres. Dispersed rovings act as individual monofilaments. The geometry of a fibrillated fibre can be described in terms of a film thickness and the width of each filament.

18.2.2 Fibrous structures

Polyester and polyamide fibres are available in several fibrous structures. The most used polyester and polyamide fibrous structures are geotextiles and geogrids. Geotextiles can be woven, knitted or nonwoven structures. Geogrids can be produced with conventional weaving and/or knitting process, coated with copolymer resins.

Conventional woven fabrics are produced by orthogonal interlacing two sets of yarns: one called warp whose yarns are along the length of the fabric, while the other one is weft whose threads run along the width of the fabric. Both sets of yarns are mutually positioned under the angle of 90° (warp at 0° and weft at 90°). The warp and weft yarns can be interlaced in diverse ways presenting a regular pattern named woven weave structure. Plain weave is the simplest woven structure and it is characterized by the interlacement of warp and weft yarns, alternately over and under. This is a balanced structure, with good stability and reasonable porosity. However, it presents several disadvantages such as difficulty to drape and high level of fibre crimp leading to low mechanical properties.

Woven fabrics are usually dimensionally stable, but they present lower extensibility and porosity rather than other structures. The mechanical properties of woven fabrics are very important for technical textiles and they depend on different factors, namely raw materials, linear density of the warp and weft, yarn density and woven structure. The strength of a fabric is usually higher in the warp and weft directions, while in diagonal direction they present lower mechanical properties, higher elasticity and lower shear resistance.

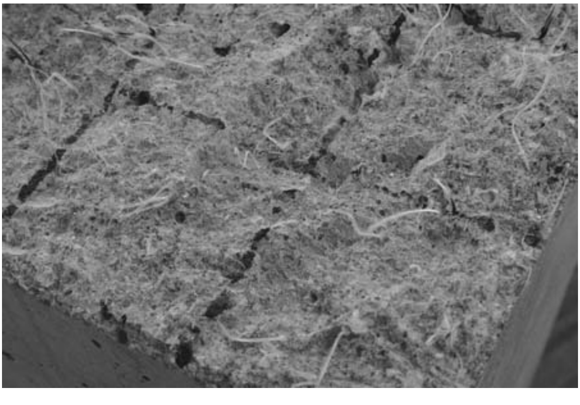
Knitted fabrics are textile structures characterized by the interlacing of loops. Two different basic textile technologies allow the manufacturing of knitted structures: weft and warp knitted technologies. Both types of knits produced by these technologies can have extensibility in one specific direction and by using straight yarns, which are not knitted, it is possible to design the stability in one direction, with deformability in the others [1]. All loops of a warp knitted fabric are formed from a separate yarn, called warp, mainly introduced in the longitudinal fabric direction. Therefore, neighbouring loops of one course are not produced from the same yarn. These structures have mechanical properties very similar to those of woven fabrics, are very flexible and, depending on the construction, can be elastic or inelastic. For the production of weft-knitted fabrics, a single yarn may lead to the formation of an entire course (horizontal row of loops). One important factor that influences the properties of weft knitted fabrics is the stitch length, that is the length of a yarn in a knitted loop. The weft-knitting technology presents great ability to produce complex shapes which is very important for technical applications.

Nonwoven is a very interesting production technique due to the wide variety of products that may be developed comparing to other textiles technologies. According to EDANA [2], nonwovens are sheets, webs or bats of natural and/or man-made fibres or filaments, that have not been converted into yarns, and that are bonded to each other by entangling fibre or filaments mechanically, thermally or chemically [2]. The process of nonwovens manufacture can be divided in two steps: the matt preparation (carding, air laying, wet laying or spun laying) and the bonding process itself. Needle-punched nonwoven geotextiles are entangled to form a complex structure by random fibres, accounting for its bulky nature, wide range of pore size distribution and good drainage.

Braided textiles structures are produced by intertwined yarns. There are three types of braided structures: diamond, regular and hercules. Diamond structure is obtained when yarns cross alternately over and under the yarns of opposite direction and, in this case, the rotation is one to one. But it is possible to modify this rotation to two by two and three by three obtaining, in this way, the other two structures. Among these structures, diamond is the most stable and hercules presents the least stability. Usually, braids are produced in a biaxial structure; however, if yarns are inserted (middle-end-yarn) and oriented longitudinally into the structure, a three axial braid is obtained. Also it is possible to insert in the middle of the tubular form fibre bundles, obtaining in this way a triaxial structure with axial fibres. The diameter of the braid is controlled by several factors namely, the number of fibres, the angle of the intertwining yarns, the number of intersections of fibre per unit length of the yarns and the linear density of the fibres. Braiding technology has been used for the production of hollow pieces with or without core. The braid structures have weak axial and compression stability and are conceived to have multidirectional conformability [1]. Nowadays, braids are the reinforcements with more variety of applications on the market, namely the rope and offshore industries.

18.3 Synthetic fibre-reinforced concrete

The term fibre-reinforced concrete is defined by ACI 116R, Cement and Concrete Terminology, as a concrete containing dispersed randomly oriented fibres (Figure 18.1) [3]. Fibre reinforced concrete can be described as a composite material consisting of a concrete phase and a small portion of discrete and discontinuous fibres distributed and oriented randomly within the concrete [4]. The development of steel fibre reinforced concrete may have begun around the early 1960s. Polymeric fibres came into commercial use in the late 1970s, glass fibres experienced widespread use in the 1980s, and carbon fibres attracted much attention in the 1990s [5, 6].



18.1 Synthetic fibre-reinforced concrete.

Inherently concrete is brittle under tensile loading and mechanical properties of concrete may be improved by randomly oriented short discrete fibres which prevent control initiation, propagation, or coalescence of cracks [3, 7, 8]. The major disadvantage of concrete may be thought to be the complexity of its structure, which results in many internal stress concentration zones [5]. Thus, some internal micro-cracks exist at cement paste-aggregate interfaces even prior to any load and environmental effects. Under externally imposed structural loads and environmental effects, concentration of tensile stresses occurs at the interfaces between aggregates and matrix, causing the growth of micro-cracks in size and number; propagation of interface micro-cracks into the matrix and eventual joining of micro-cracks yield large cracks and lead to the failure of the concrete. Cracks in concrete structures reduce safety and durability even during their life time [9]. After the formation of the first crack, brittle matrices, as plain mortar and concrete, lose their tensile load-carrying capacity almost immediately [10]. The cracks generally develop with time, thereby impairing the waterproofing properties and exposing the interior of the concrete to the destructive substances containing moisture, bromine and acid sulphate, among others. The exposure acts to deteriorate the concrete, with the reinforcing steel corrosion [11, 12].

Fibre-reinforcement is used to improve the brittle nature of cementitious composites [9]. Fibre-reinforced concrete is more ductile than unreinforced concrete. One way to quantify the increase of ductility is to measure the area under the load-deflection curve, which is defined as toughness. Fibres bridge cracks during loading and transfer the load, arresting the growth and coalescence of cracks. Fibre reinforcement has been shown to improve the ductility, toughness, flexural strength and shear strength of cementitious materials, to reduce shrinkage cracking and permeability and enhance fatigue and impact resistance. Fibres are added not only to improve tensile strength [5, 13]; recently, it has been found that a number of fibres can also improve the residual properties of concrete after exposure to elevated temperatures [14].

Synthetic fibres have become more attractive in recent years as reinforcements for cementitious materials. Synthetic fibres can provide effective, relatively inexpensive reinforcement for concrete and are alternatives to asbestos, steel and glass fibres. Recently, structurally efficient fibres have been developed, exhibiting increased toughness and/or loading carrying capacity after cracking [15, 16]. Fibre types that have been incorporated into cement matrices include polyethylene (PE), polypropylene (PP), acrylics (PAN), poly(vinyl alcohol) (PVA), aramid, carbon, polyamides (PA) and polyester (PES) [17]. The properties of synthetic fibres vary widely, in particular with respect to the modulus of elasticity, an important characteristic when fibres are used for producing composites. Besides physical and mechanical properties, durability of fibres used for fibre-reinforced concrete is also of paramount importance [6, 17].

To increase the strength of their composites, fibres must have a modulus of elasticity greater than the matrix. For cementitious materials, where the modulus of elasticity ranges from 15 to 30 GPa, this condition is difficult to meet with most synthetic fibres. Therefore, attempts have been made to develop fibres with a very high modulus of elasticity for cement reinforcement. However, both theoretical and applied research have indicated that, even with low modulus fibres, considerable improvements can be obtained with respect to the strain capacity, toughness, impact resistance and crack control of the fibre-reinforced concrete composites. In many applications, the enhancement of these properties is of much greater significance than the modest increase in tensile (flexural) strength. In some applications, the poor tensile strength of concrete can be enhanced by combining concrete with small diameter fibres, which can be synthetic fibres. It is usually assumed that the fibres do not influence the tensile strength of the matrix, and that only after the matrix has cracked do the fibres contribute by bridging the crack. Most of the current applications with fibre-reinforced concrete involve the use of fibres ranging around 1% by volume with respect to concrete. More recently, it has become possible to incorporate relatively large volumes (ranging up to 15%) of synthetic fibres into concrete. With such large volumes of fibres it has been noted that the fibres may substantially increase the tensile strength of the matrix.

18.3.1 Type of reinforcement

Synthetic fibres are usually used as primary reinforcement in thin sheet elements where conventional steel reinforcement is not feasible. These elements are prefabricated rather than cast-in-place. Most structural reinforcements have involved the use of steel, glass or carbon fibres. The development of high modulus synthetic fibres, such as polyaramid, allows the possibility of replacing steel or glass fibres, but at a high cost that makes current use of synthetic fibres for primary reinforcement an unfeasible alternative.

Secondary reinforcement is used to control cracking caused by intrinsic tensile stresses such as drying shrinkage, plastic shrinkage or temperature changes. The purpose of crack control is neither to eliminate cracking caused by intrinsic stresses, nor to increase the load-carrying capacity of the concrete; crack control replaces a random pattern of relatively large cracks with a more deliberately structured pattern of closely spaced fine cracks. Actually, this makes concrete less water permeable and hence more durable.

18.3.2 Effect of fibres on fresh and hardened concrete

Dispersion of fibres during mixing is an important concern in the production of fibre-reinforced concrete. Despite the benefits of fibre reinforcement, fibres can make cementitious materials difficult to work, in the fresh state, compromising hardened state properties [13]. The addition of fibres at high dosages, however, has potential disadvantages in terms of poor workability and increased cost [18, 19]. Micro-defects, such as voids, honeycombs and clumping or 'balling' of fibres can be a problem at high fibre contents [6]. A compromise to obtain good fresh concrete properties and good toughness of hardened concrete can be obtained by adding two different types of fibres, which can work individually at different scales to yield optimum performance and can reduce the overall cost of concrete production. The addition of non-metallic fibres such as glass, polyester, polypropylene, etc. results in good fresh concrete properties and reduced early age cracking. It is also important to have a combination of low and high modulus fibres to arrest the micro- and macro-crack, respectively. Another beneficial combination of fibres is that long and short fibres can control different scales of cracking [18, 19]. The beneficial effects of non-metallic fibres could be attributed to their high aspect ratios and increased fibre availability at a given volume fraction. Because of their low stiffness, these fibres are particularly effective in controlling the propagation of micro-cracks in the plastic stage of concrete. However, their contribution to post-cracking behaviour, unlike steel fibres, is not known to be significant [18, 19].

Synthetic fibres seem to perform better than glass or steel fibres. Plastic shrinkage cracking is caused by excessive loss of water from fresh concrete due to evaporation. The problem is most acute in the summer months when weather conditions may increase the rate of moisture evaporation so that it exceeds the rate of bleeding [19]. When it happens, local drying at the surface will result in plastic shrinkage cracking. Once the magnitude of tensile stresses needed to cause cracking is quite low, synthetic fibres have the potential to prevent his type of cracking in cases where inadequate preventive measures have been taken. Laboratory studies show that slabs with fibre reinforcement develop less plastic shrinkage cracking than slabs of control concrete [6].

Some studies have shown no significant improvements in tensile or compressive strength of concrete when low volumes of synthetic fibres are added to concrete. Other studies have shown a slight decrease in compressive strength, over unreinforced concrete control specimens. These apparent differences are attributed to changes in the water-to-cement ratio between control and fibre-reinforced concrete. Since the addition of fibres slightly decreases slump, additional water is often used to bring the slump back into the desired range. This small addition is sufficient to lower strengths by about 10% [6].

Several studies reported greater static flexural strength in concrete with added synthetic fibres than in unreinforced concrete. However, these increases were quite small when fibre contents were low. The static flexural strength of fibre-reinforced concrete increases after being subjected to fatigue loading, behaviour also observed in unreinforced concrete [17].

Fibre-reinforced concrete is expected to have a finer crack pattern than plain concrete. The crack spacing is directly related to the radius of the fibre for circular cross-section. The finer the fibre, the smaller the crack spacing. Another factor of paramount importance is the fibre-concrete interfacial bond strength. The reduction in crack width as the crack spacing is reduced will give fibre-reinforced concrete lower water permeability than unreinforced concrete.

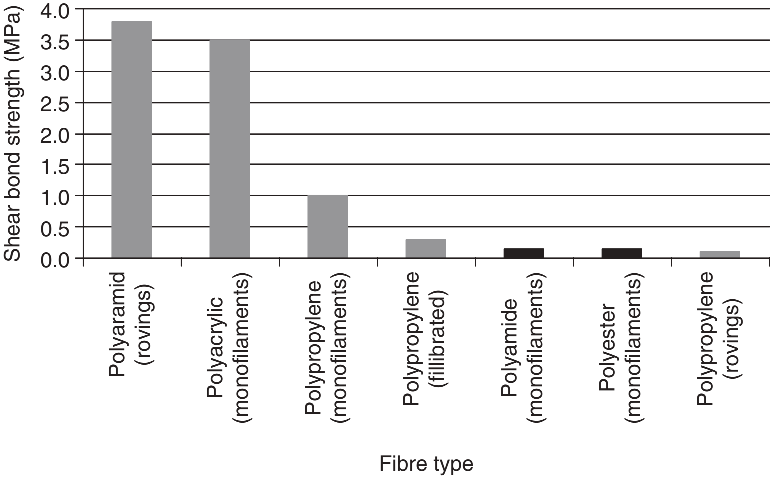
18.3.3 Properties of synthetic fibres

Several different kinds of polymers have been investigated for their suitability to use in concrete. In fibre properties evaluation, four aspects are of interest, namely, fibre geometry and dimension, mechanical properties, physical properties and chemical durability.

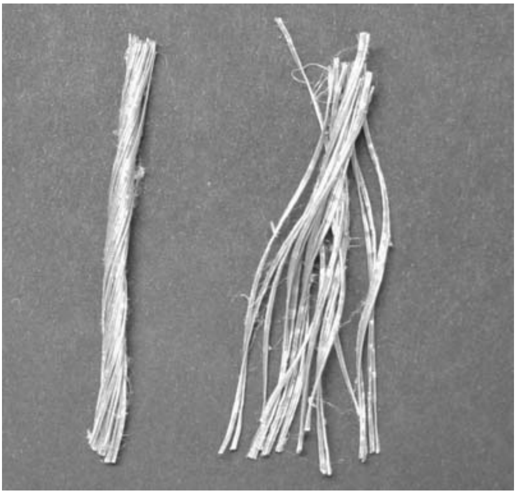
Fibre geometry and dimensions

A synthetic fibre can be described as a flexible, macroscopically homogeneous body, with a high length to thickness ratio (aspect ratio) and a small cross-section. All fibres have one particular structural feature in common: a preferential orientation of their elemental units with respect to the fibre axis [6].

Fibres are available in many different geometries and dimensions, such as monofilaments, rovings (tows) and fibrillated polymers. Monofilaments are single straight fibres usually made by drawing molten polymers. Such fibres are usually round in cross-section, ranging in diameter from 50 µm to 0.5 mm, being usually strong. However the smooth surface may result in a low interfacial bond strength, which limits the reinforcing capability of the fibre. Bond strength is primarily determined by nature of the polymer. If bond strength at the interface between fibre and matrix is too high, fibre ruptures after the first crack initiates. On the other hand, fibre is easily pulled out if the bond strength is too low. Bond strength may dominate the mechanical properties of fibre-reinforced concrete in this way and the combination of fibre and matrix needs to be selected prudently to get efficient bond strength [9]. Rovings of polyaramid present the highest bond strength, slightly higher than polyacrylic monofilaments. Polyamide and



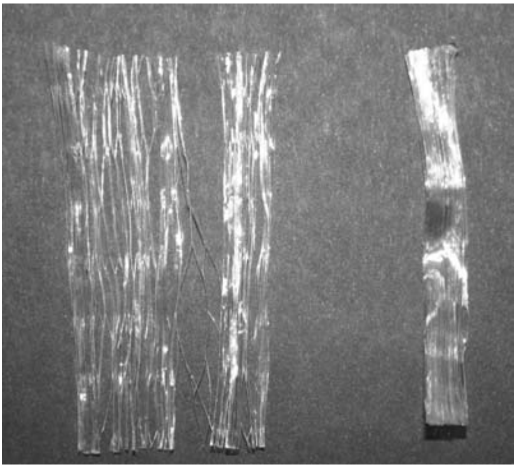
18.2 Fibre-concrete matrix bond strength.



18.3 Example of fibre geometry.

polyester monofilaments present one of the lowest bond strengths (Figure 18.2) [6].

Many polymers are spun in the form of filaments (fibrils) which vary from 5 to 15 μm in diameter. Several thousand fibrils are spun simultaneously, by drawing them from a single die and bundling together. Rovings are cut into short lengths when adding them to concrete. In the concrete, the yarn separates into individual fibrils which need to be dispersed efficiently during mixing. Dispersed rovings act as individual monofilaments within the cement matrix (Figure 18.3). The high surface-to-volume

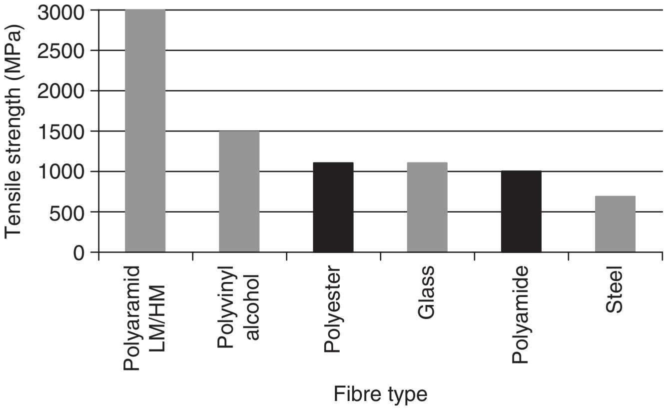


18.4 Examples of fibrillated fibre geometry.

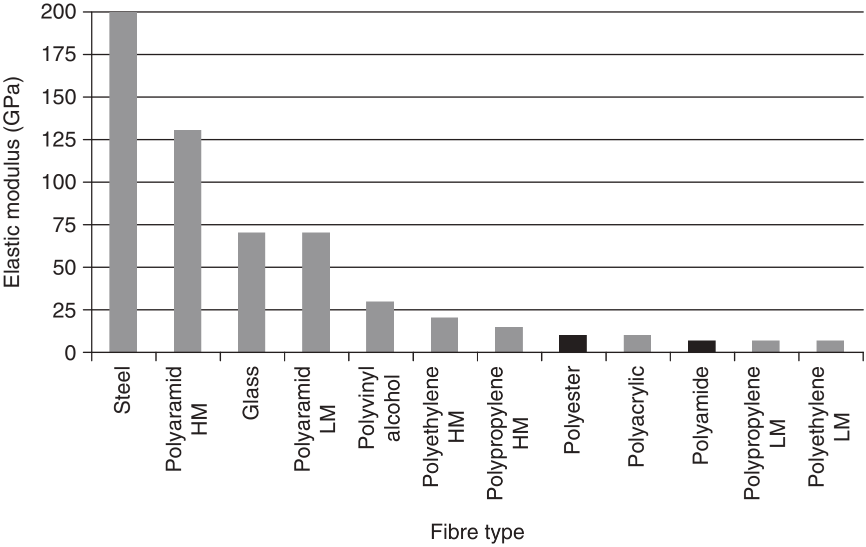
ratio should increase the effective interfacial bonding. The geometry of a fibrillated fibre can be described in terms of a film thickness (generally 15 to 100 μm) and the width of each fibril (100 to 600 μm). During mixing, the bundles are opened up by the aggregate to act as individual fibrils contributing, each one, to the reinforcing action (Figure 18.4). The fibres are easy to handling and to disperse uniformly within the concrete mix.

Mechanical properties

The fibre mechanical properties determine its potential as a concrete-reinforcing material. Commodity synthetic fibres are characterized by low modulus of elasticity and high elongation. Since the modulus of elasticity for most cementitious materials ranges from 15 to 30 GPa, the relatively low modulus of the fibres means that high strength composites are not achievable with synthetic fibres. Their advantage lies in increasing such properties as strain capacity, toughness, and crack control, properties that are more important for some applications. Polyamide fibres present a tensile strength of 1000 MPa, modulus of elasticity of 6 GPa and ultimate elongation of 10% (Figures 18.5, 18.6 and 18.7) [6]. Polyester fibres present a tensile strength of 1100 MPa, modulus of elasticity of 10 GPa and ultimate elongation of 24% (Figures 18.5, 18.6 and 18.7) [6].



18.5 Tensile strength of fibres used to reinforce concrete (LM: low modulus; HM: high modulus).

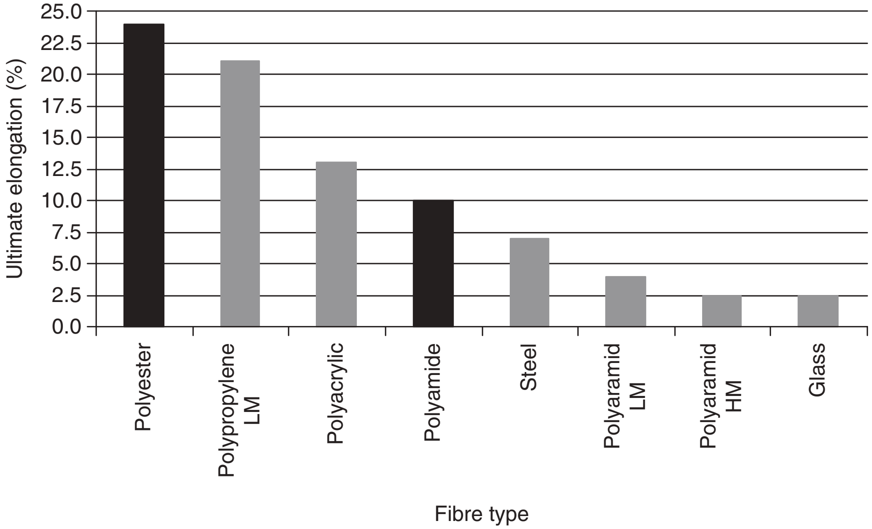


18.6 Elastic modulus of fibres used to reinforce concrete (LM: low modulus; HM: high modulus).

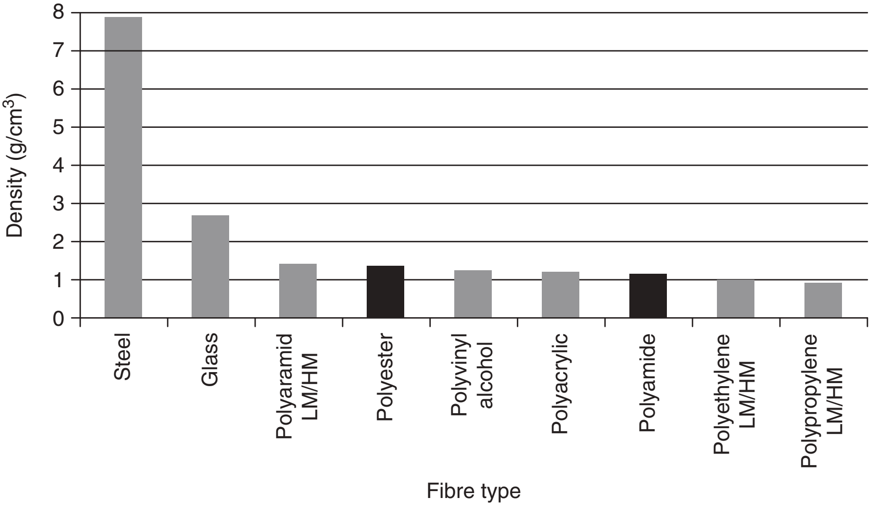
Physical properties

Fibres are characterized by low density so that a relatively low mass of fibres yields a high volume of fibres in concrete (Figure 18.8). The density of polyamide and polyester fibres are 1.14 and 1.35 g/cm^3, respectively [6].

Synthetic fibres are also very flexible; fibre breakage or mechanical distortion will not be a problem during concrete mixing. The relatively low

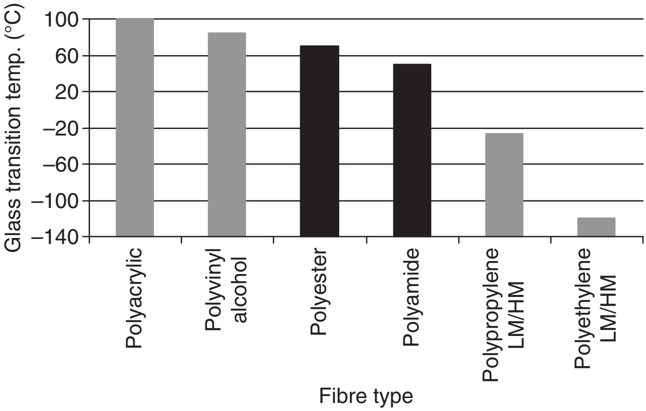


18.7 Ultimate elongation of fibres used to reinforce concrete (LM: low modulus; HM: high modulus).



18.8 Density of fibres used to reinforce concrete (LM: low modulus; HM: high modulus).

thermal stability of polymers could be a disadvantage. Melting points are generally below 300°C but service temperatures are considerably lower, since fibres start to soften and lose their tensile properties at temperatures considerably below melting point. This behaviour causes loss of reinforcing capabilities in structures exposed to high temperatures (e.g. fire), but in

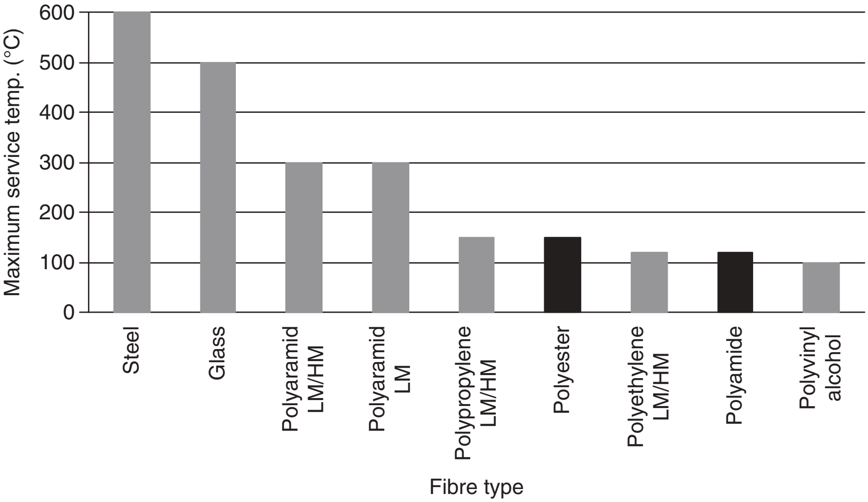


18.9 Glass transition temperature of fibres used to reinforce concrete (LM: low modulus; HM: high modulus).

normal environmental temperature fluctuations will not cause a problem. The glass transition temperature (T_g) which represents a change in consistency from rubbery to brittle as the temperature is lowered, should also be considered. Polyamide and polyester glass transition temperatures are 45 and 70°C respectively [6] (Figure 18.9). In most cases, glass transition temperature lies well outside service temperature fluctuations, but, if it lies just above maximum ambient temperature usually encountered in service, as in the case of polyamide, solar heating could cause the temperature in the concrete to exceed T_g. Maximum service temperature of polyamide and polyester fibres is 120 and 150°C respectively [6] (Figure 18.10).

Environmental durability and thermal resistance

Cement paste develops a moist alkaline environment detrimental to many organic materials. The minimum pH in a cement paste is about 12.3, which corresponds to a saturated calcium hydroxide solution. However, many types of cement have high alkali content, which can raise the pH to 13.5 or higher, when the cement is mixed with water. This very high pH will be detrimental to some polymers. Polyacrylics, polyesters and polyamides are particularly sensitive since they can undergo alkaline hydrolysis [6]. Hydrolysis may be slow at room temperature, but may be significantly accelerated at higher temperatures. Moreover, how much this phenomenon occurs depends on three factors: the degree of saturation of the concrete; the rate of hydrolysis; and the extent that hydrolysis will reduce the mechanical properties of the fibre. Synthetic fibres cannot withstand



18.10 Maximum service temperature of fibres used to reinforce concrete (LM: low modulus; HM: high modulus).

high temperatures. Most plastics soften and lose much of their tensile properties at temperatures in the range of 150 to 250°C [6].

18.3.4 Polyamide fibres

Polyamides (PA) are well known as nylons, and are defined as polymers which contain amide groups in the main chain. The commercial success of nylons 6 and nylon 6,6 is due to the outstanding properties of the polymers and an economical raw material base. Commercially, polyamide fibres are available in various lengths in single-filament form. These fibres exhibit low bonding with a cement matrix. Because polyamide fibre has a relatively high cost compared with polypropylene, its commercial potential may be somewhat limited.

Walton and Majumdar [17] demonstrated that the use of these fibres in small amounts substantially improves impact resistance of the composite but has very little effect on its tensile or flexural strength [11]. The high impact resistance of the composite containing nylon fibre is derived from the stretching and pulling-out of the fibres which occurs at large strains after the failure of the matrix and at a lower load. Balaguru [18] compared the load-deformation behaviour of rapid-hardening concrete reinforced with nylon 6 and steel fibres, and found that the post-peak drop is steeper for nylon than for steel fibre.

Song *et al.* analysed the strength properties of polyamide fibre reinforced concretes [11]. Compared to polypropylene reinforced concrete, the polyamide fibres claimed a slightly increased ability to distribute themselves throughout the concrete, thus distributing the unfavourable stresses within a greater volume of concrete and improving the concrete's properties in the plastic and hardened state. The compressive strength of the polyamide reinforced concrete improved by 12.4% over the unreinforced control concrete. Polypropylene reinforced concrete improved the compressive strength by 5.8%. The polyamide- and polypropylene reinforced concretes were 17.1% and 9.7% higher, respectively, than that of the unreinforced control concrete. The strength of the polyamide reinforced concrete posted a 5.9% increase, while polypropylene reinforced concrete registered 1.5%. The polyamide fibres performed better in reducing the incubating of early plastic shrinkage cracks because of their higher tensile strength resulting in a better load transfer across the cracks. Moreover the strength improvements achieved by the polyamide fibres overcome those achieved by polypropylene fibres.

Kurtz and Balaguru [18] studied the postcrack creep of synthetic fibre-reinforced concrete in flexure, comparing the behaviour of polypropylene fibrillated fibres and polyamide single filament (nylon 6). They concluded that both polypropylene and polyamide reinforced concrete can sustain only a small percentage of the postcrack strength. The maximum sustainable stress for the polypropylene represents only 24.9% of the average residual strength and for polyamide reinforced concrete this percentage is 38.3%. It was also concluded that polyamide reinforced concrete was found to creep considerably faster than the polypropylene reinforced concrete but for less time.

18.3.5 Polyester fibres

Polyesters (PE) are defined as polymers containing –CO–O– groups in the main chain. This definition excludes polymers of esters such as vinyl acetate and methyl methacrylate since in these polymers the ester groups reside in the side-chains and not in the polymer backbone. The physical and chemical properties of polyester fibres can be changed substantially by altering manufacturing techniques. Polyester fibres which have a higher modulus of elasticity can provide improvements in impact strength. Polyester fibres provide a higher strength at the beginning of ageing, but the values slightly decrease or remain about the same with accelerated ageing. Patel *et al.* studied the properties of polyester fibre-reinforced concrete and concluded that the addition of polyester fibre at 1% (by volume) of concrete increased the impact strength by 75%, the split tensile strength by 9%, the flexural strength by 7%, and the compressive strength by 5% [17]. There was no change in modulus of elasticity and shear strength. Polyester fibres are generally not resistant to strong alkalis. Wang *et al.* [17] studied polyester fibre in Portland cement concrete and observed that polyester fibres lose strength rapidly in the cement matrix. Therefore, polyester fibres are ineffective without surface treatment as reinforcement in Portland cement products due to their chemical degradation.

There have been several studies [18, 19, 20, 21] on the mechanical properties of various fibre reinforced systems, containing hybrid combinations of steel and non-metallic fibres (glass, polyester and polypropylene) and the plastic shrinkage cracking. Steel reinforced concrete and hybrid reinforced concrete present higher compressive strength than unreinforced control concrete. However, concretes with individual non-metallic fibres do not register any increase in strength compared to unreinforced control concrete. The difference in performance of the steel fibre-reinforced concrete and the hybrid fibre-reinforced concretes, with respect to compressive strength and modulus of elasticity, is not significant. Split tensile strengths of hybrid fibre concretes were found to be higher compared with unreinforced concrete control specimens and monosteel fibre-reinforced concrete. Compared with control concrete, all fibre-reinforced concretes showed a significant increase in flexural strength. The combination of steel and polyester showed the maximum flexural strength. All the fibre-reinforced concretes yield a higher flexural toughness compared with control concrete. The maximum crack width was observed in the case of plain control concrete. Compared with steel reinforced concrete, hybrid reinforced concrete showed better crack control features. The total crack area reduces with the increased addition of non-metallic fibres, where polyester and polypropylene fibres performed better than glass. Although the increase in non-metallic fibres results in a significant crack width reduction, it also causes a decrease in concrete workability. This negative effect restricts the maximum dosage of polypropylene and polyester fibres.

18.3.6 Applications

Polyester fibres are used in fibre-reinforced concrete for industrial and warehouse floors, pavements and overlays and pre-cast products [22, 23]. Polyester micro- and macro-fibres are used in concrete to provide superior resistance to the formation of plastic shrinkage cracks versus welded wire fabric and to enhance toughness and the ability to deliver structural capacity when properly designed, respectively. Polyester macro-fibres can be used as a true alternative to welded wire fabric, steel fibres and conventional light gauge steel reinforcing for pre-cast slabs on grad and shotcrete applications. Monofilament polyester fibres are used as secondary reinforcement thus controlling plastic shrinkage, reducing segregation, minimizing bleeding water, providing a three-dimensional reinforcement versus two-dimensional with welded wire fabric, reducing cracking, increasing the surface durability and reducing permeability [24]. The primary applications of monofilament polyester fibres are plain concrete (unreinforced concrete), in place of welded wire fabric reinforcement, flatwork, footings, foundations, walls and tanks, concrete pipes, burial vaults and pre-stressed beams.

18.4 Geotechnical and geoenvironmental applications

18.4.1 Geotechnical applications

Geosynthetics are thin polymeric materials that are widely used in civil engineering applications. There are numerous types of geosynthetics available for the design engineer to address the diverse range of applications, and each has a specific function. Functions can be hydraulic (drainage, filtration and waterproofing) or mechanical (protection, reinforcement and separation) [26, 27]. Geosynthetics are being increasingly used as reinforcement in engineering projects such as earth embankments, reinforced soil walls and roadways, among others [28]. Geotextiles are a core member of the geosynthetics family and may be applied as a woven, knitted or nonwoven structure [29].

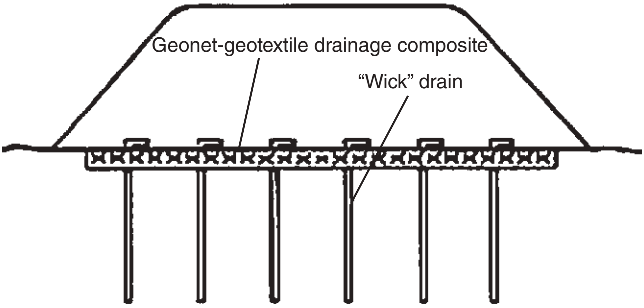
Among the different geosynthetics products, geotextiles present the widest range of properties. They can be used to fulfil most of the functions, except waterproofing. The use of nonwoven geotextiles for filtration or drainage purposes instead of coarse-grained soils is very attractive in applications such as paved and unpaved roads, landfill covers and lines, earth dams, embankments and retaining walls because of the relative ease of placement and gain in space [27].

Geogrids are classified into three types according to the manufacturing method and form: plastic (sheet extruded from olefin and punched and drawn); textile (high-tensile-strength yarn woven or knitted and then coated by resin) (Figure 18.11); and melting [30].

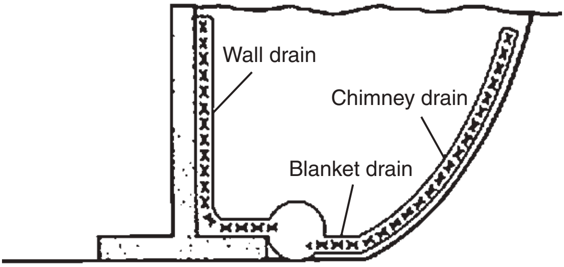
Mechanically stabilized earth walls: embankments and retaining walls

Mechanically stabilized earth walls have gained popularity over recent decades [32]. Embankments (Figure 18.12) and retaining walls (Figure 18.13) reinforced with geogrids and geotextiles are covered under this category [33]. Geotextiles have been extensively used as drainage and filter materials for the past 40 years. Although the designs of these applications have been based on empirical criteria, they have been overwhelmingly successful [34]. Physical and hydraulic properties of geotextiles are of utmost importance for the design of drains and filters [34]. The filtration

18.11 Knitted high tenacity polyester geogrids with UV stabilized saturation coating [31].



18.12 Mechanically stabilized earth walls: embankments [31].



18.13 Mechanically stabilized earth walls: retaining walls [31].

and drainage functions are especially attractive in the construction of soil structures such as retaining walls or embankments. Moreover, geosynthetics materials have strengthened their reputation as reliable reinforcing elements based on improved material characteristics and design practices [35].

There has been an increase of interest in the construction of reinforced soil retaining walls to supporting bridge abutments in place of traditional pile foundations. Two of the main reasons for the increased interest are the reduction in overall cost of the project and the reduction, or potential elimination, of 'bridge bumps' which arises from differential settlement between a traditional pile supported abutment and the approach rod [35]. Skinner *et al.* have studied the design and behaviour of geosynthetic reinforced retaining wall and bridge abutments on yielding foundations [36].

The beneficial effect of geosynthetic material is largely dependent on the form in which it is used as reinforcement. Same geosynthetic material when used in planar layers or discrete fibres will give different strength improvements in different forms. Horizontal geosynthetic layers improve the strength mainly by friction and interlocking between soil and the reinforcement, whereas the randomly oriented fibres improve strength friction and coiling around soil particles [37]. Latha *et al.* studied relative efficiency of these two forms of reinforcement, i.e. planar and discrete fibre, in improving the shear strength of sand [37].

Two important characteristics of the geotextile must be considered as they relate to their applications: one is the ability to percolate water through the geotextile, generally expressed by the fabric permeability coefficient; the other is the particle retention capacity, expressed by geometrical ratios between characteristic particle dimensions of the soil to be retained and a characteristic opening of the fabric [38]. The particle retention capacity of geotextile has direct relation with its structure, features of the soil to be preserved, as well as conditions of the flowing water in site. The development of the geotextile water retention curves is of great importance to model the transient water flow in earthen systems containing geotextiles where unsaturated conditions may prevail such as in reinforced embankments and retaining walls [39].

Also textile geogrids, made with high tenacity polyester filament, using a conventional weaving and/or knitting process, coated with copolymer resins, are commonly used as reinforcement material in embankments, slopes and retaining walls, among other structures [40]. Typical properties of a polyester geogrid for road, embankments and riverside stabilization applications are presented in Table 18.1 [41].

The required service lifetime of geogrids used for reinforcement of embankment and slopes varies according to the sensitivity of the environmental conditions and required safety factor. Typical lifetimes for slopes and embankments are 50–100 years. Usually, the lifetimes of geogrids are assessed as the long-term creep behaviour which causes shape deformation and collapse of the slopes and embankments [40]. Palmeira *et al.* studied the drainage and filtration properties of polyester nonwoven geotextiles under confinement. He has concluded that polyester geotextile permitivity

Table 18.1 Technical data of polyester geogrid [41]

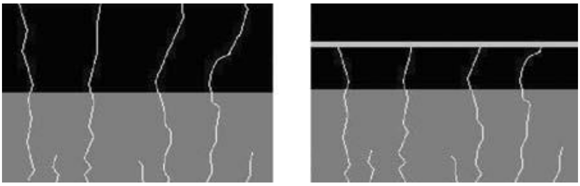
Properties		Unit	ZHGQ 60/30A	ZHGQ 80/30A	ZHGQ 100/30A	ZHGQ 150/30A	ZHGQ 60/30B	ZHGQ 80/30B	ZHGQ 100/30B	ZHGQ 150/30B
Material		–			High tenacity polyester yarn					
Coating		–			PVC coating					
Process		–			Knitting					
Tensile strength	MD	kN/m	≥60	≥80	≥100	≥150	≥60	≥80	≥100	≥1500
	CD	kN/m	≥30	≥30	≥30	≥30	≥30	≥30	≥30	≥30
Extension	MD	%	≤13	≤13	≤13	≤13	≤13	≤13	≤13	≤13
	CD	%	≤13	≤13	≤13	≤13	≤13	≤13	≤13	≤13
Length		m			≤100					
Width		m			≤5					

and transmissivity depend on the geotextile thickness [34]. Jeon *et al.* also analysed the drainage performance of geotextile composites under confined loads [42]. According to Jeon *et al.*, textile geogrids made from polyethylene terephtalate (PET) high performance yarn coated by resin (polyvinyl chloride or acrylic) are recognized as an important synthetic construction material because PET has high tensile strength and excellent creep properties although it has weak chemical stability. Jeon *et al.* studied the stability to chemical conditions in the application of textile geogrids to soil retaining wall systems [42].

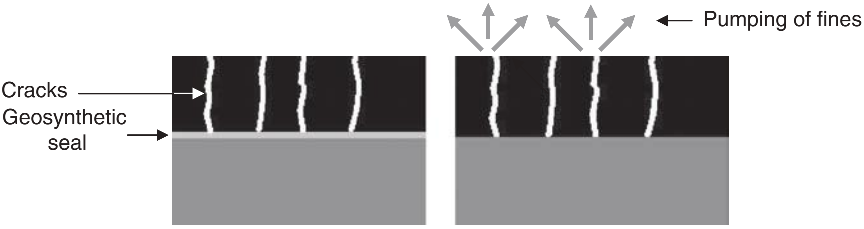
Road construction, reinforcement and overlaying

Roads and highways are of the utmost importance to the development of any country. Due to systematic traffic of heavy vehicles, climate conditions and mechanical properties of the materials in their constructions, road and highway pavements may last considerably less than expected [43]. The design philosophy of a pavement system depends fundamentally on layers of materials, its rigidity, thickness and resistance to stresses [44].

A good pavement must provide a smooth riding profile, withstand large traffic volumes and transmit the stresses efficiently to the underlying subgrade support. But after a certain number of years, pavement defects (cracking) appear at the surface due to repeated traffic loading, local environmental distress and ageing. The traditional flexible pavement rehabilitation using the overlay method is expensive and rarely provides a durable solution as the cracks rapidly propagate through the new asphalt layer forming the so-called ‘reflective cracks’ (Figure 18.14). Flexible pavements are constructed of bituminous and granular materials. But advent of modern synthetic polymers of increasing thermal resistance has created a growing interest on their applications on pavements. Geosynthetics have been used for unpaved roads on subgrade to fulfil one or more of the basic functions: reinforcement, separation, filtration and drainage [44]. Geosynthetics can be effectively used to: reduce or avoid reflective cracking (Figure 18.14); work as a barrier to avoid pumping of soil fines (Figure 18.15); reduce the pavement thickness by reducing the asphalt cap thickness (Figure 18.16); and increase the lifetime of the pavement.



18.14 Pavement reflective cracking (adapted [43]).



18.15 Pavement pumping of fines (adapted [43]).

18.16 Pavement reduced thickness by reducing the asphalt cap thickness (adapted [43]).

Geotextiles have been successfully used for reinforcement of unpaved roads of soft subgrade to improve the performance of a reinforced fill layer placed on soft ground [45]. The inclusion of geotextiles and geogrids has the potential to extend pavement life by reinforcing and inhibiting reflective crack-up. The high tensile strength of a reinforced pavement will have significant influence on the behaviour of the pavement surface under traffic loading and environmental movements. Gurung [44] concluded that the use of geosynthetic inclusions increases the tensile strength of the pavement and, when comparing the use of geotextiles and geogrids, he concluded that the tensile peak strength of a pavement reinforced with a geogrid was higher than with a geotextile.

18.4.2 Geoenvironmental applications

Erosion control of steepened slopes

Soil erosion along degraded hill slopes has been a problem of serious concern throughout the world. In India, about 5330 million tonnes of soil are being lost every year [46]. Failure of natural slopes is mostly associated with human intervention either for urbanization or for other development activities. Denudation of slopes frequently leads to serious problems of downstream sediment. Denuded slopes are often difficult to revegetate and may become unsightly. Better erosion control methods are needed for construction site slopes, so that the soil movement after shaping will be minimized and subsequent reshaping will be unnecessary [47]. Unscientific measures of slope protection and improper design of structures will always have a consequence on the stability of slopes. A small initial movement in an unstable slope can trigger further soil water movement resulting in soil erosion and consequences landslides.

A dominant factor affecting runoff and erosion of bare soils is the seal formation on the soil surface due to the disintegration of soil aggregates at the soil surface by impacting drops and the compaction of the disintegrated particles into a thin and very compact sealing layer. To control this process, protection of the soil surface against impacting drops is required, as well as the reinforcement of aggregates at the soil surface. M. Agassi [47] studied the stabilization of steep slopes with geomembranes. Geomembranes are used extensively by soil engineers, e.g., as an interface between compacted and uncompacted soil layers. Geotextile membranes placed to cover the soil surface can absorb raindrop impacts and so control crust formation and reduce the consequent runoff and erosion.

Several materials may be used in steep slopes denuded by erosion to reduce surface soil erosion, but usually they will not yield the vegetation growth. Natural vegetation for sustainable erosion control and slope protection is a proven choice of soil conservation along hilly terrain [46]. The use of geotextiles in steep slopes serves the purpose of protecting the soil and the seeds in the initial stage of vegetation growth [46].

Natural geotextiles made of coir, jute, etc. are preferred to synthetic fibres considering the fact that the material is environmentally friendly and ecologically compatible as it gets degraded with the soil. In an age of growing environmental awareness, synthetic geotextiles present some disadvantages [46].

Geosynthetics for shore protection

In recent years, traditional forms of river and coastal structures have become very expensive to build and maintain, because of the shortage of natural rock. As a consequence, the materials used in hydraulic and coastal structures are changing from traditional materials and systems to cheaper ones [48]. Geosynthetic structures for shore protection have demonstrably lower construction and lifetime costs than those of hard structures. Therefore, alternative shore protection structures, especially for sandy coasts, that include geotextile solution are of interest to replace traditional materials and systems, such those constructed from rock or concrete blocks [49].

Recently, woven geotextiles in the form of tubes and bags have been successfully used in various environmental protection facilities, such as underwater breakwater, river dyke improvement, stream bank erosion control and erosion control of seashores [50]. One of these applications is the use of geotextile tube technology. Geotextile tube technology is mainly used for flood and water control, but it is also used to prevent beach erosion, and for shore protection and environmental applications. Woven, nonwoven and composite synthetic fabrics, i.e. geotextiles, have been used for various types of containers, such as small hand-filled sandbags, three-dimensional fabric forms for concrete paste, large soil, and aggregate-filled geotextile gabion, prefabricate hydraulically filled containers, and other innovative systems involving containment of soils using geotextiles [48].

One innovative system is a geotextile wrap-around revetment which is a sand slope that is reinforced with a geosynthetic: the material is wrapped and encapsulated with geotextiles to create a flexible revetment. A layer of geotextile is first placed at the site and sand is placed on top of it to produce this system. Loose ends of the geotextile are then folded back and inserted into the fill. A second geotextile layer is laid on top and the procedure is repeated until the layers reach the designed height. The finished system is covered with sand to give it a natural appearance. The geotextile encapsulates the sand and adds tensile strength to it through increased confinement [49].

Waste landfills

Geosynthetics have been increasingly used in environmental protection works and in the case of waste disposal areas their functions range from barriers to fluids or gases to reinforcement of earth works and slopes [51]. When disposed in excavations, the volume of waste to be stored can be maximized with the use of steeper slopes, however keeping the appropriate safety margins required in this type of work. The use of geosynthetics in such slopes, as barriers or drainage materials, poses important considerations regarding the stability conditions of the cover soil and adherence between soil and geosynthetics and between different types of geosynthetics [51]. Geosynthetics are modern engineering materials that can be used in this type of problem to work as barriers or in liquid collection systems [52]. They have been increasingly used in liquid collection systems. They are easy and quick to install and, being manufactured, they can be subjected to rigid quality control to guarantee their properties. Among the geosynthetics types, a geotextile can function as drainage or filter layer in a liquid collection system. To perform well as a filter, prolonging the service life of the drainage materials, the geotextile layer has to retain particles from the waste, while maintaining a sufficient permeability to allow the passage of fluid during the entire contaminating lifespan of the landfill [52]. Moreover, besides drainage and filtration nonwoven geotextiles are widely used in waste landfills as materials having the functions of protection and separation, among others. In general polyester or polypropylene geotextiles are the most important geosynthetic materials that are installed above the geomembranes for protection and drainage. These geotextiles are exposed to chemicals such as acidic or alkaline solutions, especially leachate solutions, until the reclamation of waste is completed [53]. Leachate is a very complex and variable liquid and can bring solid particles in suspension; microbiological activities are intense, biological and physical clogging can occur and leachate flow can be intermittent for most of the disposal area lifetime [52].

Gas drainage layers comprising either natural materials or geocomposites are specified in most modern and recent landfills. Because of the large gas fluxes generated in these landfills, the use of geocomposites or natural material is well indicated to relieve gas pressure underneath the hydraulic barrier in the cover system and allow the collection of gas and its transmission to point outlets. However, for abandoned or uncontrolled old landfill sites, which in most cases generate very low quantities of gas, a nonwoven geotextile can be used as gas collection layer below the hydraulic barrier. Thiel indicated that limited testing of nonwoven needle punched geotextiles showed that these materials may be acceptable for gas relief [54]. A nonwoven geotextile, in general, has relatively large pore sizes compared to most soils, and consequently its gas transmissivity behaviour may be expected to be similar to a coarse soil. Furthermore, its low capillary rise potential, high breakthrough head for saturation and low water retention capacity make it more attractive than conventional coarse-grained soils. Gains in space, cost and construction time are other advantages [54]. Jeon studied eight types of polypropylene and polyester nonwoven geotextiles/geotextile composites.

18.5 Textile architectural applications

Architectural engineering is one of the many areas of civil engineering. It is the engineering discipline responsible for the planning, analysis, design, construction, maintenance and renovation of building systems considering always their impact on the surrounding environment [55, 56].

Textile architecture is not a new branch of architecture. Its technological potential is continuously leading to new developments and applications [57]. In order to produce new materials for architectural applications, the research leads to the development of production techniques as well as of opportunities for material applications. Nowadays, designers and engineers are facing an incredible demand for higher efficiency, not only in building construction, but also by the relationship between the construction and the environment [58].

Several textile materials can be used in this area. The continuous development of synthetic fibres allowed the development and the growing of high performance fabrics with excellent properties, suitable for architectural applications, namely, good mechanical resistance, rot and fungus resistance, hydrophobic behaviour, among others [59].

18.5.1 Textile architectural membranes

Since the 1950s, membrane development for building purposes led to new materials with considerable strength and resistance [60]. Textile architectural membranes or tensile membrane structures are normally a woven structure based material, which are often coated or laminated on both sides, in order to improve the mechanical and/or environmental resistance. The main purpose of the coating is to confer a higher durability and impermeability to the fabric and to maintain together all the constituent parts of the membrane. During the coating process, the adhesion stage is extremely important because it will be the indicator of the seam strength. A good adhesion will result in a woven fabric able to carry significant loads. There are several types of coatings. The most common used are polyvinyl chloride (PVC), polytetrafluoroethylene (PTFE or Teflon as commercially known) and silicones. However, for special applications, coating is not applied, but a foil is laminated into the fabric. Lamination process consists in the application of a vinyl film on the woven or knitted structure. Most fabrics used in architecture have a topcoating applied to their exterior coating. The main function of the topcoating is to improve the cleanability of the membrane. Acrylic, polyurethaneacrylic, polyvinyl fluoride (PVF) film lamination or polyvinylidene (PVDF) coatings, are examples of topcoats [59, 60, 61, 62].

In textile architecture, three types of membrane can be used: films, nets and fabrics. Films are polymers in sheet structure without any coating or laminating, including vinyl, polyester and polyethylene. When compared to fabrics, films are cheaper but have low mechanical resistance. Nets consist of a porous fabric, for example polyester fabric, lightly coated with vinyl. They are usually are used for sun and wind protection, but they do not protect from rain. Knitted nets are produced with high density polyethylene and polypropylene or acrylic fibres. The third type of membrane, are fabrics that are widely used. In fabric structures, the materials used are meshes, nettings and films. The mesh consists of a porous fabric with open spaces between the yarns and is produced with several types of fibre. One of the meshes comprises polyester weaves lightly coated with vinyl which have mechanical resistance, present lower water absorption, easy dying and are an inexpensive material. Polyamide fibres are frequently used for industrial applications due to their properties, such as, high strength and chemical resistance, although they have high water absorption and are more costly than polyester. Netting can use polyester, polyamide or polypropylene filaments or spun yarns which are knitted or knotted in order to produce the fabric. Each of these fibres presents advantages and disadvantages. For instance, polyester holds better than polyamide, it is not so easy to coat and is more expensive. Polyamide is easier to coat but has a higher water absorption rate than polyester and does not hold the dye as easily. Regarding films, they are transparent polymers extruded in sheet form without any supporting substrate. Some examples are vinyl, polyester or polyethylene. Although they are not as expensive as textile structures, they have several drawbacks, namely less strength and durability and more elasticity than textile structures, making them not a very suitable option for several applications [59, 61].

For architectural applications, fabrics need to have special properties and special forms that cannot be chosen randomly. Thus, the production of textile architectural membranes is divided into two phases: the conceptual design and analysis of the structures and the use of advanced geometry in the production of the built form. These fabrics present a totally different behaviour than the traditional ones, being characterized by non-linear, anisotropic and non-elastic behaviour. The fabrics are also resistant to abrasion and mechanical degradation, impermeable to water, air and wind and resistant to the sun and acid rain degradation when exposed during long periods of time. The fibres are resistant to deformations and extensions under loads, characteristically obtained by the shape given to the fabric. The fabrics should have sufficient curvature to enable the tensile forces applied. They need also to be lightweight, flame resistant, present a long life service and be translucent. The low mass and the translucency are two properties which contribute to thermal comfort inside the building system [59, 63, 64].

To obtain a good textile architectural structure that works according to the requirements, it is necessary to select the right material, the proper design, engineering, production and installation. Most textile structures use fabrics rather than meshes or films. In tensile membrane structures, the most important material is obviously the fabric.

Several fibres can be used in membranes, being their selection made according to the membrane end use. Some fibres present the appropriate properties having the potential to be applied; however, the high costs prevent their wide utilization. From all the synthetic fibres, the most used for membranes are polyester, glass fibre and aramid; other types of fibres are used in very specific applications, such as polyamide and cotton. Table 18.2 presents some of the properties of the mentioned fibres [60, 61, 62].

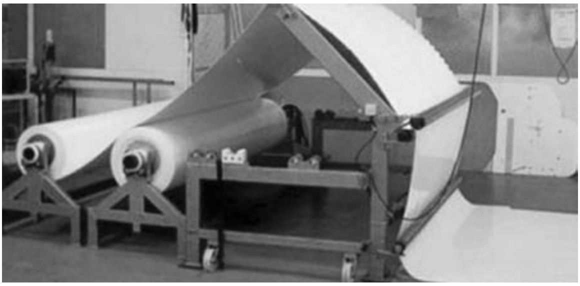
Table 18.2 Properties of fibres used in textile architectural membranes

Fibre	Tensile strength (N/mm²)	Tensile strain (%)	Elasticity (N/mm²)	Other properties
Polyamide 6.6	Until 1000	15–20	5000–9000	• When exposed to light only average resistant to ageing; • Swelling when exposed to moisture • Only little importance to textile architecture
Polyester	1000–1300	10–18	10000–15000	• Widely spread • Standard product
Glass fibre	Until 3500	2.0–3.5	70000–90000	• When exposed to moisture, reduction of breaking strength • Brittle fibres • Standard product
Aramid	Until 2700	2.0–4.0	130000–150000	• Special fibre for high-tech products • Costly

Polyamide is not preferred for this application due to its poor resistance against UV light and, when wet, polymide swells in length direction, reducing its interest to textile architecture. Polyamide textile structures could be laminated with vinyl films resulting in a stronger product and more durable than polyester; however a high cost and stretch are major drawbacks. For these reasons, polyamide textile structures should only be used for specific applications [62, 63].

Polyester fibre is considered as a standard product in this area, and together with glass fibre, is the most common fibre in textile architecture. The main reason for its wide use is directly related to its advantages, such as, good tensile strength, high durability, low cost, stretch, elasticity, and allows small corrections during installation. However, when exposed to sunlight polyester mechanical properties decrease over time. Polyester fabrics are usually coated or laminated with PVC films resulting in a cheaper product (Figure 18.17).

The Austrian Company Sattler Ag is one of many companies manufacturing products for textile architectural applications using polyester yarns for base material. Their textiles structures are used for pavilions for international trade fairs and exhibitions, halls and tents (e.g. for events and family parties), leisure centres, inflatable structures (tennis, pools and golf) and tailor-made structures. Some of the characteristics of Sattler's material are presented in Table 18.3. According to Sattler Ag, the excellent



18.17 Plastic-coated polyester fabric [65].

material used presents greater rigidity than steel, low maintenance, tear, ageing and weather resistance combined with lightness and elegance [66].

As far as the laminating is concerned, vinyl is applied to the woven or knitted polyester meshes, usually known as scrims or substrates. Normally, the textile structure base used is characterized by a high count and high tensile. The laminate provides extra strength. One of the production methods of polyester textile structures allows the coating during its production. All process consists in the production of the fabric that is placed under tension before and during the coating process. The result is a fabric with good dimensional stability once the yarns, in warp and weft directions, present similar characteristics. Depending on the fabric characteristics, it is possible to have different applications. For instance, usually lighter fabrics are used for acoustic and thermal insulation liners suspended beneath a structure's envelope. However, if the application is for exterior, demanding a long service lifetime, heavier fabrics are most suitable. In this case, above the coating is applied a layer named topcoating, for instance, polyvinyl fluoride (PVF) or polyvinylidene (PVDF). Both types of topcoatings provide a protective finish to withstand environmental degradation. To prevent the hardening and the degradation by sunlight and fungus attacks and to provide fire retardancy, several additives are added to the material. An acrylic and PVDF finish are two types of additives. The first provides a better service life and the second an improvement to the soil behaviour [61, 63, 64, 65].

PVC coated polyester membranes present the following characteristics [67, 68, 69]:

- one of the least expensive;
- design life between 15 and 20 years;
- robust and durable;
- easier to ship and erection can be mountable;

Table 18.3 Sattler products characteristics. Examples [66]

Characteristics	Unit	Type I	Type VI	745	787 114	787 181
Product	–	648	717	Uni	Antiwicking	Opaque
Material	–	Pes-Lowick	Pes-Lowick	Pes	Pes	Pes-Lowick
Coating	–	Acrylic/PVDF	Acrylic/PVDF	Acrylic/PVDF	Acrylic/PVDF	Acrylic/PVDF
Weave	–	L 1:1	L 3:3	L 1:1	L 1:1	L 1:1
Yarn	dTex	1100	1670	1100	1100	1100
Ends/picks	–	9/9	14/14	7/7	8/8	8/8
Total weight	g/m^2	700	1350	590	670	750
Tensile strength	N/5 cm	3300/3000	7500/7000	2100/2300	3000/2800	3000/2800
Flame retardency	–	✓	✓	✓	✓	✓

- translucency can reach up to 20% depending on the thickness of the material;
- wide range of possible colours;
- flame retardant;
- easily cleaned;
- good tensile strength and dimensional stability.

This kind of coating allows the use of different chemical additives that guarantees the leakage proofness, light transmission, UV resistance and abrasion resistance, among others. With these features it is possible to have properties like resistance to fungus and bacteria, temperature resistance and antistatic properties [65].

Vinyl-coated polyester membranes are usually used for producing flexible structures, like awnings, canopies, walkways, tent halls, smaller air-supported structures and light member-framed structures. This membrane presents a polyester scrim, a bonding or adhesive agent and an exterior PVC coating. The polyester scrim is made of high tenacity multifilament yarns which confer to the membranes excellent dimensional stability allowing bending without losing any tensile properties. The function of the polyester scrim is to support the coating and provide the tensile and tear strength, elongation and the dimensional stability of the final fabric. Polyester fibres are bonded to the coating by an adhesive agent. The adhesive agent, besides the bonding function, prevents the wicking of moisture into the fibres. Properties such as, water resistance, mildew resistance, flame retardancy, different levels/degrees of translucency (from high levels of light transmission to completely opaque) and a wide range of colours, characterize the vinyl-coated polyester.

Polyester mesh fabric produced by Jiangsu Jiuding New Material Company is a reinforcement, which is an industrial fabric made by a warp knitted using polyester yarn. This product is used as base fabrics for vinyl laminated fabrics and coated fabrics. Applications are usually tent and structural material and awning and canopy material among others. Polyester mesh fabrics present properties such as, high tensile strength and weight, extensibility, conformability, long-term dimensional stability and can be widely used, which make them excellent products for the applications previously mentioned. Some of the products available are listed in Table 18.4 [70].

Awnings, tents and low tension frame structures are applications where vinyl-laminated polyester can be used. Laminated fabrics consist normally in two or more layers of fabric or films bonded together with the help of an adhesive agent by a heat or pressure process. A good bonding is required once it is necessary to have the proper seam strength and to prevent delamination. The use of an open-weave scrim, for instance a mesh, makes

Table 18.4 Characteristics from Jiangsu Jiuding New Material Co. Ltd products [70]

Style	Yarn (dTex)	Density (count/inch)
PNW90 (9 × 9)	1000 × 1000	9 × 9
PNW180 (18 × 16)	1000 × 1000	18 × 16
PNW145 (9 × 9)	500 × 500	9 × 9
PNW80 (18 × 12)	500 × 500	18 × 12
PNW110 (12 × 12)	1000 × 1000	12 × 12
PNW60 (12 × 12)	500 × 500	12 × 12

these fabrics more economical. But if colour, UV resistance, abrasion resistance are required, then the product final price will be high. Vinyl-laminated polyester is a good option for backlighting [61].

A membrane is a unique structure, lightweight and flexible, that presents higher strength/weight ratio when compared with concrete or steel. It is environmentally friendly and in most cases, the fabrics are recycled, and can be designed for almost any condition. All these features are advantages for the textile structures. The low rigidity of these structures could be a problem, thumb spans greater than 15 m should be avoided, loss of tension can result in failure of the structure, there are thermal limits, and in an open system the water control is difficult and thus needs special attention.

18.5.2 Applications

With fabrics made of high tensile coated polyester, a whole new application comes up in the field of building. Due to its unique properties like high flexibility, high tensile strength, the lightweight and the high light transmission ratio of the material it is possible to apply this structure to, 'roof large without trusses, to design spaces flooded with light, structurally realise completely new form, to generate attention by design and colour, to establish temporary structures and to set them up again at another location, to build in a resources-saving manner and to develop completely new building areas' [65].

The applications of textile architectural membranes for building include a wide range of areas, such as, sports and leisure, arts and culture, travel and transportation, business and commerce, and agriculture and environmental industries. Some examples of those applications are [65, 69]:

- Public event building: using temporary or permanent roofing and also enclosed building forms for exhibitions, shows, among others (Figure 18.18).

18.18 Public event architectural membranes [65].

18.19 Tourism and catering architectural membranes [65].

- Tourism and catering: usually used for sun, wind and rain protection providing a comfortable environment; also their lightness and expanse are attractive characteristics (Figure 18.19).
- Parks and landscape spaces: protect the visitors from the weather conditions and are generally suited to the natural environment (Figure 18.20).
- Open-air theatres: during this type of event protection against the weather is required (Figure 18.21).
- Sports buildings: the main function is the weather protection; one of the most important features is the high light transparency of the membranes (Figure 18.22).
- Entrance and walkway areas: besides the technical function (provides protections against weather conditions) also works as a decorative element (Figure 18.23).

18.20 Park architectural membranes [65].

18.21 Open-air theatre architectural membranes [65].

18.22 Sports building architectural membranes [65].

18.23 Entrance and walkway areas architectural membranes [65].

18.24 Shopping centres and exhibition spaces architectural membranes [65].

- Shopping centres and exhibition spaces: exceptional membrane architecture supports marketing concepts which make shopping experience-oriented (Figure 18.24).
- Railway and bus stations: the main function, in this case, the protection although aesthetic function is also an aspect which is usually considered (Figure 18.25).

In addition, there are classical applications and others that can be done with different functions, such as:

- for heat- or noise-insulating purposes, a multilayered membrane is used;
- for light protection, i.e. opaque membranes for specific requirements like cinema halls and some greenhouses where the light should not enter in the building;

18.25 Railway and bus stations architectural membranes [65].

18.26 Flexible bulk containers [65].

- for textile secondary structures for shading sails;
- for interior architecture as a decorative element;
- for applications that only requires demountable, temporary structures for short-term.

Ceno Tec is an Austrian company that offers other innovative applications, such as: flexible bulk containers like big bags (Figure 18.26), protective cloth/hoods and oil retentions/cascade separators (Figure 18.27).

Textile architectural membranes are widely used and for many and different reasons. Their unique properties allow them to have the flexibility to improve and lead them to innovative technologies. Further developments in membranes will be related to the materials development and its application. New applications and materials development ensures the use of membranes in the architecture of the future [58].

18.27 Cascade separators [65].

18.6 Ocean engineering applications

Besides the previous applications, namely concrete reinforcement, geotechnical, environmental and textile architectural, polyester and polyamide fibres are also used in a specific area of civil engineering field, ocean engineering.

18.6.1 Civil engineering in the ocean

Civil engineering embraces a wide variety of technical areas in both theoretical and experimental research. It deals with different areas such as, planning, design, construction, repair, maintenance and management of physical infrastructure networks [71, 72].

One of the civil engineering branches is ocean engineering, a hybrid technical area, which is a relatively young and remarkably exciting field of engineering. It is the application of basic engineering to the analysis, design, construction and management of systems that operate in the ocean environment. Some of the areas which are covered and included in this discipline are: Offshore Engineering; Naval Architecture; Marine Structural Mechanics; Safety and Reliability; Materials; Cable; Mooring, Buoy Technology; Underwater Technology; etc. [73].

According to the Society of Naval Architects and Marine Engineers, 'ocean engineers study the ocean environment to determine its effects on ships and other marine vehicles and structures' [74]. Ocean engineers may design and operate stationary ocean platforms, or manned or remote-operated sub-surface vehicles used for deep sea exploration. They have petroleum engineering tasks such as underwater oil or gas exploration, or they might design structures such as offshore drilling platforms, harbour facilities, and underwater machines [75].

One of the most important aspects of ocean engineering concerns how environmental conditions such as, wind and wave climate, currents, seawater, hydrostatic pressure and earthquakes, affect the different types of civil structures including the equipment used, and how the structures, their foundations, and equipment respond to these factors [72].

18.6.2 Fibre ropes for construction engineering in the ocean

Rope technology has begun with organic fibre material which was spun and twisted into a larger more useful form without any binding element [76, 77]. Rope modernization started with the development of polyamide fibres (nylon) in 1938, followed later with the introduction of other synthetic fibres, such as polyester [76]. In recent decades advances have been made in this field which greatly influenced civil engineering in the oceans during this century. Fibre technology innovations led to the development of new fibres with different properties and performances for a wide range of applications. One of those applications includes the construction and reinforcement of ropes and cables, widely used in this field of civil engineering [78]. Thus, for conventional rope-making, the most common fibres are polyester, polyamide and polypropylene. Table 18.5 presents the general properties of fibres used in the production of ropes as well steel wire [79].

Conventional steel wire mooring systems present several problems as water depth increases, namely, lower restoring efficiency, high proportion

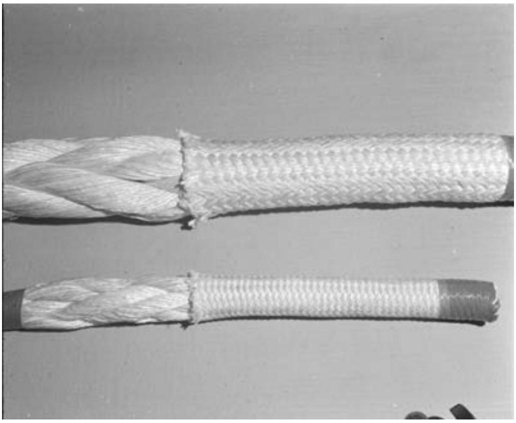
Table 18.5 General fibre properties

Fibre	Specific modulus (N/tex)	Specific strength (N/tex)	Other characteristics
Polyamide	4	0.84	• 10–15% wet strength loss • Poor wet internal abrasion resistance • Moderate creep
Polyester	10	0.84	• Good wet internal abrasion resistance
Polypropylene monofilament	8	0.73	• Lighter than water • Moderate creep • Low strength
Polypropylene multifilament	3.5	0.66	• Lighter than water • Moderate creep • Low strength
Steel wire	26	0.18	• Typical properties • Corrodes

of tether strength is consumed by the vertical components of line tension, reduced pay-load of the vessel, large mooring radius and sea-floor foot print, costly to maintain, mechanically complex, relatively inflexible and it is too heavy. All these disadvantages prompted engineers to find a substitute material. Thus, fibre ropes seem to be an interesting alternative once they can solve some of those problems [80, 81]. Synthetic fibre mooring ropes are lightweight (20% compared with wire rope) and more flexible, thus being much easier to handle. Synthetic fibre ropes do not corrode with the salt-water environment; have high tensile strength and adequate axial stiffness similar to wire ropes. However, they are much more susceptible to damage than steel wire. The ropes' elasticity allows them to absorb the energy of the movements under adverse environmental conditions (i.e. excessive wave and winds), and they possess excellent resistance to abrasion, wear, creep and thermal degradation [76, 82, 83]. Generally synthetic fibres can be used in mooring systems, in anchoring and in logging applications [82, 84, 85].

There are three types of rope construction which can be used: plaited, twisted and braided. The rope design and construction are important issues since rope performance depends on them. Each construction provides different properties [86, 87]:

- plaited: resists rotation; does not kink or twist; has good strength and elongation; good weight;
- twisted: offers good strength; easy handling; tendency to 'unravel' when placed under load; may cause failure;
- braided: higher in strength and durability; lower in elongation; very pliable and easy to handle; more difficult to splice; higher cost; single and solid – braided types are more reliable than double-braided (Figure 18.28).



18.28 Braided rope type (Cordoaria Oliveira Sá, Portugal).

Polyamide fibre has been used in marine mooring since the 1950s approximately. This fibre is characterized by low modulus presenting the lower value from all quoted fibres, and is the strongest one when dry. However, when wetted, it loses 10% of its strength although that value can go up to 20%. In these conditions, polyamide also suffers strength loss due to creep and internal abrasion during cyclic tensile loading. All these disadvantages, along with the short service life, make polyamide ropes, in a general way, unsuitable for permanent deep water moorings.

Notwithstanding that fact, nowadays there are excellent ropes made of polyamide yarns. For instance, Enka®Nylon is a high-tenacity polyamide yarn used for mooring ropes with the ability of high shock absorbance and long time reliability. The wide range of high-tenacity polyamide yarns with Enka®Nylon is used in several fields of technical applications where safety and reliability are key requirements. One of those areas is ocean engineering. Enka®Nylon 140HRT and Enka®Nylon 142HRT are two types of polyamide yarns usually used for the production of mooring ropes. Some of their characteristics are described in Table 18.6 and Table 18.7 [88]:

Table 18.6 Enka®Nylon 140HRT characteristics [88]

High-tenacity polyamide 6.6 filament yarn					
Linear density (nominal dTex)	Number of filaments (nominal)	Linear density (dTex)	Breaking strength (N)	Breaking tenacity (mN/Tex)	Extension at break (%)
700	108	716	60.7	848	19.5
940	140	942	79.5	844	17.9
1400	210	1405	118.6	844	18.9
1880	280	1895	159.2	840	19.5
2100	280	2105	175.1	832	19.8

Table 18.7 Enka®Nylon 142HRT characteristics [88]

Super high-tenacity polyamide 6,6 filament yarn					
Linear density (nominal dTex)	Number of filaments (nominal)	Linear density (dTex)	Breaking strength (N)	Breaking tenacity (mN/Tex)	Extension at break (%)
940	140	938	90.0	960	16.9
1400	210	1407	133.4	950	18.4

Due to polyester fibres' advantages, ropes made from these fibres are replacing polyamide ropes in many critical conventional marine applications. Technological innovation allowed the development and production of high quality polyester fibres enabling the production of strong polyester ropes with relatively high modulus. Very durable in cyclic tensile fatigue loading, stronger than polyamide in dry conditions, keeping strength and generally stronger than polyamide when wetted, are advantages which make polyester a good candidate for deep water mooring systems. On some occasions, polyester fibres are combined with polypropylene fibres because, although they present similar strength and stiffness properties to those of all polyester ropes, they have lower weight and cost, have great resistance to surface abrasion and heat build-up than all polypropylene ropes [79]. Nowadays, technology allows the production of high tech polyester yarns which can be used in ocean engineering in several operations. Marlow Ropes Ltd is a British company which produces several types of ropes for different areas, namely for marine applications like mooring and anchor lines. Three strand polyester is a rope made of high tenacity polyester yarns possessing special features. No strength loss when wet, good abrasion resistance, flexible and soft handle and easy splice are some of them. However, they present other properties which make them suitable for the applications mentioned, such as, UV resistance (50% strength retention after three years) and good resistance to acids and alkalis. Tables 18.8 and 18.9 show some of the characteristics of the three strand polyester rope.

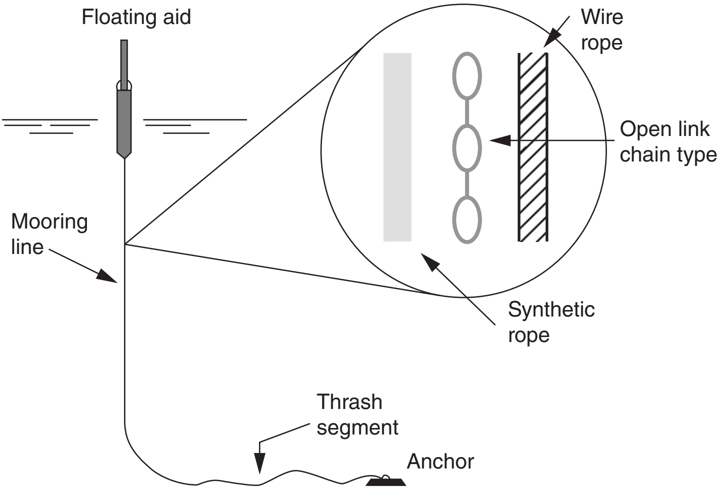
The traditional practice of mooring with ropes, for thousands of years, remained unchanged till recently. A mooring system can be defined as a compliant, usually tensile structure, which restrains a vessel against the forces of the sea and the movements generated by natural forces such as wind, wave and currents. The mooring consists of a fixed mooring system

Table 18.8 Technical data of three strand polyester [89]

Three strand high-tenacity polyester rope	
Fibre	High tenacity polyester
UV resistance	50 % strength retention after three years
Standard lengths	100–200 m reels
Recommended splice	Easily spliced using three strand method
Chemical resistance	Good resistance to acids and alkalis
Colours	White, black and navy blue
Sheave diameters	10:1 or ten times rope diameter
Working loads	Maximum loads should not exceed 50% of the breakload published Normally exceed 20–30% of the break load published
Relative density to H_2O	1.38 g/cm^3
Critical temperatures	Melts at 260°C

Table 18.9 Technical data of different types of three strand polyester [89]

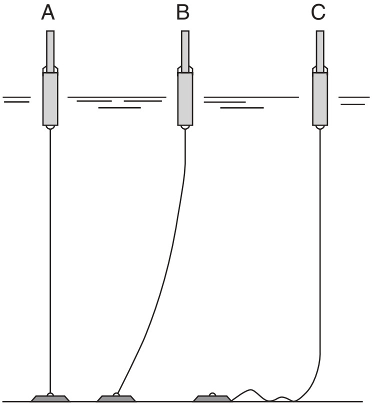
High-tenacity polyamide 6.6 filament yarn			
Diameter (mm)	Average breaking load (kg)	Minimum breaking load (kg)	Weight (kg/100m)
4	529	300	1.24
6	968	560	2.91
8	1920	1020	5.10
10	2740	1590	8.05
12	3170	2270	11.06
14	4380	3180	15.70
16	4540	4060	20.50
18	7270	5080	26.00
20	7770	6350	31.90
24	11210	9130	46.00
28	14640	12330	62.80
32	18840	15700	82.00



18.29 Scheme of a mooring system [84].

that can be platforms, cells, spuds and bollards, a pile system, and a mooring line system which includes natural or synthetic fibre rope, wire rope and mooring chains (Figure 18.29). As can be seen in Figure 18.30, floating mooring systems can be installed in three different ways: tension leg (A), taut leg (B) and catenary (C) [90, 91].

The best structural concept for synthetic fibre moorings is the taut leg system. This allows polyester rope to be deployed from the platform at



18.30 Installation types of mooring systems: tension leg (A); taut leg (B); and catenary (C) [84].

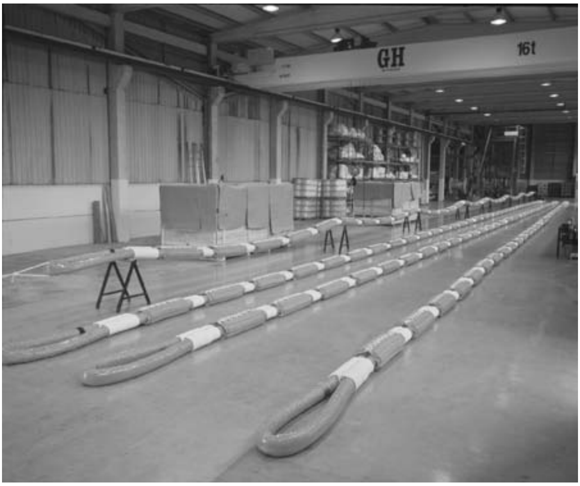
approximately 45° from vertical and placed under tension. Many are the advantages in using the mooring design taut leg for polyester fibres, namely [76, 80, 82, 85]:

- low creep and good creep rupture resistance;
- good fatigue performance;
- low sensitivity to alternate tension compression;
- low hystereses;
- elasticity of synthetic line provides the restoring force, i.e., there is a favourable force vector to restore the platform to its neutral position;
- reduction of mooring line weight hence better vessel payload;
- more efficient system allowing a smaller footprint in the ocean;
- lower cost;
- due to its lower tensile stiffness an extreme reduction is visible/verified in line dynamic tension;
- very low rate of hydrolysis;
- corrosion resistance;
- easy handling and subsequent simpler and better installation techniques;
- in most cases lower vessel offset.

Fibre ropes have been used for more than 30 years in offshore and ocean industry, but polyester ropes in permanent moorings are relatively new. However, they have been extensively studied and tested in field and laboratories and, nowadays, polyester ropes seem to be well established in deepwater moorings [82]. There are several possible failures in ropes, categorized as: environmental, surface, wear tensile and structural failures (like tensile overload or torque effects) and fatigue. One of the huge problems with steel is the corrosion due to the sea-water, but the same occurs in polyester ropes because of hydrolysis, although less significant. Environmental effects like UV and microbiological attack are not a concern since polyester has an excellent resistance to both [76]. Rope installation needs to be done carefully because most of the damage occurs by mishandling during this stage, in which ropes can be cut, crushed or suffer abrasions against objects [76, 82]. Tensile overload should not occur if the rope is properly designed, although severe twisting or flexion should be avoided. In polyester fibres, the fatigue due to transverse crack growth, under cyclic loading, is not a failure mechanism as it is for steel. According to Hearl *et al.*, there are five types of fatigue effects which need to be considered for ropes: tensile fatigue, hysteresis heating, creep rupture, internal abrasion and axial compression. The tensile fatigue, which should be up to 20% minimum load at 70% maximum, is almost nonexistent in polyester fibres. The same happens regarding creep rupture that occurs under static and dynamic cyclic load; it would be necessary to produce it over many thousands of years. Hysteresis heating is not significant for strain amplitudes less than ±0.5%, however this could be a problem with larger amplitudes which may occur in shallow water moorings. For polyester fibres, internal abrasion only takes effect after millions of load cycles due to reduced relative fibre movement, but it is a serious problem for highly twisted polyamide ropes in wet conditions. Due to its low modulus, axial compression fatigue, according to Flory [79], is not likely to be a problem for polyester fibres, being necessary for a large number of cycles to occur. Also they can support thousands of very low trough load cycles or a complete relaxation without losing significant loss.

Based on the studies already undertaken in yarn fatigue mechanisms, one can conclude that polyester ropes designed according to current standards and planned lifetimes, give no reason to expect failures, which make them a very good option for mooring systems. Due to absence of corrosion and of metal fatigue, polyester rope performance should be better than steel ropes. Besides, if well designed, axial compression fatigue does not occur and internal abrasion appears to be the cause of the loss of strength after millions of cycles. However, the fatigue performance of polyester ropes depends on different factors like, fibre quality, rope construction, termination design and on cycle load history [76, 78, 82, 86, 92].

The key to a successful anchoring system is the structure which attaches the vessel to the anchor. Two options are available to anchor, wire ropes and natural or synthetic ropes. The first option presents two distinct advantages, brute strength and its weight. However, the absence of elongation, the difficulty in handling it due to its weight and the transmission of heavy shock-loads to the vessel and the anchor make them not very good for this operation. Regarding natural fibre ropes, there are several drawbacks



18.31 Rope for anchor applications (Cordoaria Oliveira Sá, Portugal).

namely: low elongation, high weight and high bulk, no resistance to the effects of rot, sun damage and shipboard vermin. They also transmit heavy-shock loads to vessel and anchor [85].

When synthetic ropes were introduced in the ocean industry, polyamide was one of the fibres which were used for anchoring applications (Figure 18.31). By that time, its uses gave a new dimension to the sector, becoming extremely important because polyamide performance was better than wire and natural fibre ropes. Polyamide ropes are strong, resistant to sun and rot damage and, above all, they have elasticity allowing stretching without breaking and absorbing a part of the load applied on the anchoring system, for instance winding and wave action, maintaining the anchor in the right position. One of the most common construction methods of ropes using polyamide is called three-strand nylon anchorline, usually used to anchor a vessel in an adequate way being characterized by a reduced diameter rope.

Comparing polyester fibre with polyamide, the latter absorbs a considerable amount of water leading to significant changes in their properties. After wetting and once the polyamide fibres become dry, their handling becomes very difficult with resistance to flaking or coiling. Moreover, polyamide presents an aliphatic linear structure while polyester has an aromatic ring which gives a higher stiffness to the fibre [79, 85]. After many cycles of dynamic loads, a decrease in physical strength is observed in polyamide fibres which can lead to failure. Due to the twisting given during production to typical three-strand polyamide rope, they have tendency to kink or hackle especially when used with mechanical winches.

18.32 An example of three-strand rope and 150 ft (46 m) of Yale [84].

Yale Cordage developed a new manufacturing rope with polyamide fibre, eight-strand rope, with the same strength and abrasion resistance to the polyester version, which can solve many of the above mentioned problems [84] (Figure 18.32). This unique construction process allows that less storage is required, lower pull-out force due to superior energy absorption, superior performance in power windlasses and non-hackling and torque-balanced performance.

According to Lee *et al.* [81], considering all possible materials and production techniques that can be used for rope production there is not enough experience to determine which is the best for mooring systems and other applications. Since synthetic fibre rope properties will influence the system performances, it is necessary to consider the design and the system analysis, rope design, rope specification and testing, rope production and quality assurance, rope handling and installation and in-service inspections and maintenance of the ropes applied in the ocean industry [81, 85].

18.7 References

1. ARAÚJO, M.; FANGUEIRO, R.; HONG, H.; 'Têxteis Técnicos. Materiais do Novo Milénio'; Vol. 3, IMIT, Braga, (2000).
2. EDANA – European Disposables and Nonwovens Association (EDANA).
3. SAHMARAN, M.; YAMAN, I. O.; 'Hybrid Fibre Self – Compacting Concrete With A High-Volume Coarse Fly Ash'; *Construction and Building Materials*, 21, (2007), 150–156.
4. JUÁREZ, C.; VALDEZ, P.; DURÁN, A.; SOLOLEV, K.; 'The Diagonal Tension Behavior of Fibre Reinforced Concrete Beams'; *Cement and Concrete Composites*, 29, (2007), 402–408.
5. AYDIN, A. C.; 'Self Compactability of High Volume Hybrid Fibre Reinforced Concrete'; *Construction and Building Materials*, 21, (2007), 1149–1154.
6. LUDIRDJA, D.; YOUNG, J. F.; 'Synthetic Fiber Reinforced for Concrete'; USACERL Technical Report FM – 93/02; November; 1992.

7. ZHANG, J.; LI, V. C.; 'Simulation of Crack Propagation in Fiber-Reinforced Concrete by Fracture Mechanics'; *Cement and Concrete Research*, 34, (2004), 333–339.
8. KURTZ, S.; BALAGURU, P.; 'Postcrack Creep of Polymeric Fibre-Reinforced Concrete in Flexure'; *Cement and Concrete Research*, 30, (2000), 183–190.
9. KAWAMATA, A.; MIHASSHI, H.; KANEKO, Y.; KIRIKOSHI, K.; 'Controlling Fracture Toughness of Matrix for Ductile Fiber Reinforced Cementitious Composites'; *Engineering Fracture Mechanics*, 69, (2002), 249–265.
10. FISHER, G. A.; LI, V. C.; 'Effect of Fiber Reinforcement on the Response of Structural Members'; *Engineering Fracture Mechanics*, 74, (2007), 258–272.
11. SONG, P. S.; HWANG, S.; SHEU, B. C.; 'Strength Properties of Nylon – And Polypropylene-Fiber-reinforced Concretes'; *Cement and Concrete Research*, 35, (2005), 1546–1550.
12. AHMED, S. F. U.; MIHASHI, H.; 'A Review on Durability Properties of Strain Hardening Fibre Reinforced Cementitious Composites (SHFRCC)'; *Cement and Concrete Composites*, 29, (2007), 365–376.
13. SANTHANAM, M.; SIVAKUMAR, A.; 'A Quantitative Study on the Plastic Shrinkage Cracking in High Strength Hybrid Fibre Reinforced Concrete'; *Cement and Concrete Composites*, (2007).
14. KUDER, K. G.; OZYURT, N.; MU, E. B.; SHAH, S. P.; 'Rheolagy of Fibre – Reinforced Cementitious Materials'; *Cement and Concrete Research*, 37, (2007), 191–199.
15. POON, C. S.; LAM, S. L.; 'Compressive Behavior of Fiber Reinforced High-Performance Concrete Subjected to Elevated Temperatures'; *Cement and Concrete Research*, 34, (2004), 2215–2222.
17. OH, B. H.; PARK, D. G.; KIM, J. C.; CHOI, Y. C.; 'Experimental and Theoretical Investigation on the Postcracking Inelastic Behavior of Synthetic Fibre Reinforced Concrete Beams'; *Cement and Concrete Research*, 35, (2005), 384–392.
18. SIVAKUMAR, A.; SANTHANAM, M.; 'Mechanical Properties of High Strength Concrete Reinforced with Metallic and Non-Metallic Fibres'; *Cement and Concrete Composites*, (2007).
19. OH, B. H.; PARK, D. G.; KIM, J. C.; CHOI, Y. C.; 'Fracture Behavior of Concrete Members Reinforced with Structural Synthetic Fibers'; *Engineering Fracture Mechanics*, 74, (2007), 243–257.
20. ZHENG, Z.; FELDMAN, D.; 'Synthetic Fibre-Reinforced Concrete'; *Prog. Polym. Sci.*, 20, (1995), 185–210.
21. ZHANG, J.; 'Modelling of the Influence of Fibers on Creep of Fiber Reinforced Cementitious Composite'; *Composites Science and Technology*, 63, (2003), 1877–1884.
22. THE EUCLID CHEMICAL COMPANY – Expert Solutions Using Fiber Reinforced Concrete; 'Synthetic Fibers'.
23. THE EUCLID CHEMICAL COMPANY – Successful Applications of Structural Synthetic Fibers; 'TUF – STRAND SF'.
24. THE EUCLID CHEMICAL COMPANY – 'FBERSTRAND 200–Polyester Fiber Reinforcemnt'; www.euclidchemical.com
25. THE EUCLID CHEMICAL COMPANY – 'FBERSTRAND N–Nylon Fiber Reinforcement';www.euclidchemical.com

26. CARTAUD, F.; TOUZE-FOLTZ, N.; DUVAL, Y.; 'Experimental Investigation of the Influence of a Geotextile Beneath the Geomembrane in a Composite Liner on the Leakage Through a Hole in the Geomembrane'; *Geotextiles and Geomembranes*, 23, (2001), 229–328.
27. BOUAZZA, A.; FREUND, M.; NAHLAWI, H.; 'Water Retention of Nonwoven Polyester Geotextiles'; *Polymer Testing*, 25, (2006), 1038–1043.
28. BAKEER, M. R.; ABDEL-RAHMAN, A. H.; NAPOLITANO, P. J.; 'Geotextile Friction Mobilization During Field Pullout Test'; *Geotextiles and Geomembranes*, 16, (1998), 73–85.
29. RAWAL, A.; ANANDJIWALA, R.; 'Comparative Study Between Needlepunched Nonwoven Geotextile Structures Made from Flax and Polyester Fibres'; *Geotextiles and Geomembranes*, 25, (2007), 61–65.
30. JEON, H. Y.; CHO, S. H.; MOK, M. S.; PARK, Y. M.; PARK, J. W.; 'Assessment of Chemical Resistance of Textile Geogrids Manufactured with PET High-Performance Yarn'; *Polymer Testing*, 24, (2005), 339–245.
31. STRATA SYSTEMS, INC.; www.geogrid.com
32. TAN, S. A.; CHEW, S. H.; NG, C. C.; LOH, S. L.; KARUNARATNE, G. P.; LOKE, K. H.; 'Large-Scale Drainage Behaviour of Composite Geotextile and Geogrid in Residual Soil'; *Geotextiles and Geomembranes*, 19, (2001), 163–176.
33. SOONG, TE-YANG; KOERNER, R. M.; 'On the Required Connection Strength of Geosynthetically Reinforced Walls'; *Geotextiles and Geomembranes*, 15, (1997), 377–393.
34. PALMEIRA, E. M.; GARDONI, M. G.; 'Drainage and Filtration Properties of Non-Woven Geotextiles under Confinement Using Different Experimental Techniques'; *Geotextiles and Geomembranes*, 20, (2002), 97–115.
35. TUPA, N.; PALMEIRA, E. M.; 'Geosynthetic Reinforcement for the Reduction of the Effects of Explosions of Internally Pressurised Buried Pipes'; *Geotextiles and Geomembranes*, 25, (2007), 109–127.
36. SKINNER, G. D.; ROWE, R. K.; 'Design and Behaviour of a Geosynthetic Reinforced Retaining Wall and Bridge Abutment on a Yielding Foundation'; *Geotextiles and Geomembranes*, 23, (2005), 234–260.
37. LATHA, G. M.; MURTHY, V. S.; 'Effects of Reinforcement Form on the Behavior of Geosynthetic Reinforced Sand'; *Geotextiles and Geomembranes*, 25, (2007), 23–32.
38. LIU, L. F.; CHU, C. Y.; 'Modelling The Slurry Filtration Performance of Nonwoven Geotextiles'; *Geotextiles and Geomembranes*, 24, (2006), 325–330.
39. NAHLAWI, H.; BOUAZZA, A.; KODIKARA, J.; 'Characterization of Textiles Water Retention Using a Modified Capillary Pressure Cell'; *Geotextiles and Geomembranes*, 25, (2007), 186–193.
40. KOO, HYUN-JIN.; KIM, YOU-KYUM; 'Lifetime Prediction of Geogrids for Reinforcement of Embankments and Slopes'; *Polymer Testing*, 24, (2005), 181–188.
41. ZHEJIANG HAILIDE NEW MATERIAL CO, LTD; www.hailide.com.cn
42. JEON, H. Y.; KIM, S. H.; CHUNG, Y. I.; PARK, Y. M.; CHUNG, C. G.; 'Analysis of the Drainage Performance of Geotextile Composites Under Confined Loads'; *Polymer Testing*, 23, (2004), 239–244.
43. PALMEIRA, E. M.; 'Geosynthetics in Road Engineering'; www.geosynthetics-society.org

44. GURUNG, N.; 'A Laboratory Study on the Tensile Response of Unbound Granular Base Road Pavement Model Using Geosynthetics'; *Geotextiles and Geomembranes*, 21, (2003), 59–68.
45. LEKHA, K. R.; 'Field Instrumentation and Monitoring of Soil Erosion in Coir Geotextile Stabilised Slopes – A Case Study'; *Geotextiles and Geomembranes*, 22, (2004), 399–413.
46. AGASSI, M.; 'Stabilizing Steep Slopes with Geomembranes'; *Soil Technology*, 10, (1997), 225–234.
47. SHIN, E. C.; OH, Y. I.; 'Coastal Erosion Prevention by Geotextile Tube Technology'; *Geotextiles and Geomembranes*, 25, (2007), 264–277.
48. YASUHARA, K.; RECIO-MOLINA, J.; 'Geosynthetic – Wrap Around Revetments for Shore Protection'; *Geotextiles and Geomembranes*, (2007), doi:10.1016/j.geotexmem.2007.02.004
49. HUANG, C. C.; TZENG, Y. S.; LIAO, C. J.; 'Laboratory Tests for Simulating Abrasion Damage of a Woven Textile'; *Geotextiles and Geomembranes*, 25, (2007), 293–301.
50. BERGADO, D. T.; YOUWAI, S.; HAI, C. N.; VOOTTIPRUEX, P.; 'Interaction of Nonwoven Needle-punched Geotextiles Under Axisymetric Loading'; *Geotextiles and Geomembranes*, 19, (2001), 229–328.
51. PALMEIRA, E. M.; VIANA, H. N. L.; 'Effectiveness of Geogrids as Inclusions in Cover Soils of Slopes of Waste Disposal Areas'; *Geotextiles and Geomembranes*, 21, (2003), 317–337.
52. JUNQUEIRA, F. F.; SILVA, A. R. L.; PALMEIRA, E. M.; 'Performance of Drainage Systems Incorporating Geosynthetics and Their Effect on Leachate Properties'; *Geotextiles and Geomembranes*, 24, (2006), 311–324.
53. JEON, H. Y.; 'Chemical Resistance and Transmissitivity of Nonwovens Geotextiles in Waste Leachate Solutions'; *Polymer Testing*, 25, (2006), 176–180.
54. BOUAZZA, A.; 'Effect of Wetting on Gas Transmissivity of Non-Woven Geotextiles'; *Geotextiles and Geomembranes*, 22, (2004), 531–541.
55. ARCHITECTURAL ENGINEERING: BASIC INFORMATION; http://www.princetonreview.com/
56. ARCHITECTURAL ENGINEERING; http://en.wikipedia.org/wiki/architectural_engineering; 8 June 2007.
57. 'Creating Space and Structure Using Textiles – Application/Use'; http://www.al-mirkaz.com/textile_architecture.php
58. JOHNSTON, S.; 'Innovative Applications of Architectural Membranes'; *Journal of Undergraduate Research*, 6(3), November 2004.
59. ARAÚJO, M.; FANGUEIRO, R.; HONG, H; 'Têxteis Técnicos. Materiais do Novo Milénio'; Vol. 2, IMIT, Braga, (2000).
60. HEBBELINCK, S.; MOLLAERT, M.; HAASE, J.; 'From Small Parts to Large Structures'; *Bauen mit Textilien Heft* 4/2001.
61. 'Getting Down to Basics: Fabric Facts that All Designers Should Know'; *Fabric Architecture*, March/April, 2007; www.fabricarchitecture.info
62. HOUTMAN, R.; ORPANA, M.; 'Materials for Membrane Structures'; *Bzuen mit textilien Heft*, 4/2000.
63. ENOS, R.; 'A Technical Guide to Special Structures'; *MoonBurst Structures 2002–2004*; www.moonburststructures.com

64. GOSLING, P.; WILKINSON, S.; 'A Pragmatic Approach to Determination of the Mechanical Behaviour of Structural Fabrics'; PhD Projects 2007; www.ceg.nlc.ac.uk
65. TEXTILE CONSTRUCTIONS – Textile Architecture; http://www.ceno-tec.de
66. SATTLER A. G.; www.sattler-europe.com
67. 'How to Design a Tensile Structure Membrane'; www.fabricarchitecture.com/
68. ADVANCED STRUCTURES DIVISION; www.taivokogvo.co.jp 1995–2002
69. *Tensile Membranes, Stadium Covers*; Graboplan Kft; www.graboplan.hu
70. JIANGSU JIUDING NEW MATERIAL CO., LDT; www.tech-fabric.com/
71. www.usna.edu/NAOE/eoe/brief2.htm
72. http://en.wikipedia.org/wiki/Ocean_engineering
73. FIELDS OF OCEAN ENGINEERING; www.elsevier.com/wps/find
74. www.engineeringk12.org/
75. SMITH, B.; WILLIAMS, J. G.; 'Direct measurement of Large Strains Synthetic Fiber Rope Moorings using Polymeric Optical Fibers'; 2002 Offshore Technology Conference; Houston, Texas, USA; 6–9 May 2002.
76. HAGENBUCH, B.; 'The Story of Rope'; *Rope Cord News*, VX(1), Spring 2006.
77. BUNSELL, A. R.; DAVIES, P.; PIANT, A.; 'Mechanical Behaviour of Polyethylene Terephthalate and Polyethylene Naphthalate Fibres Under Cyclic Loading'; *J Mater SCI* 41, (2006), 1745–1756.
78. VECCHIO, C.; MENICONI, L. C.; 'Deep Water Mooring System Using Fiber Rope'; *Composite Materials for Offshore Operations* – 2, pp 255–264.
79. FLORY, J. F.; MCKENNA, H. A.; PARSEY, M. R.; 'Fiber Ropes for Ocean Engineering in the 21st Century'; Presented at the Civil Engineering in the Oceans Conference, American Society of Civil Engineers, 1982.
80. ADVANCED DESIGN CONSULTING INC.; 'Making it Stronger Than Steel: US Navy Awards Synthetic-rope Research Contract to Advanced Design Consulting'; ADC Press Release, NY, 28 June 2002.
81. LEE, MING-YAO *et al.*; 'Development of API RP 2SM for Synthetic Fiber Rope Moorings'; 2000 Offshore Technology Conference; Houston Texas, USA; 1–4 May 2000;
82. SYNTHETIC ROPES DEVELOPMENT, TECHNOLOGIES; Synthetic Rope Development 2007 Advanced Design Consulting USA, Inc.; www.adc9001.com
83. GARLAND, J. J. *et al.*; *Synthetic Rope Used In Logging: Some Potentials*; Oregon State University, Corvallis.
84. YALE CORDAGE; *Anchoring Technology*, September 2005; www.yalecordage.com
85. LEE, MING-YAO; GROVE, T.; 'Use of Synthetic Ropes in Deepwater Moorings: ABS Guidance Notes'; pp. 257–268.
86. NOAA COASTAL SERVICES; Glossary: A; Center Updated on 3 January 2007; www.csc.noaa.gov
87. CANADIAN COAST GUARD – Aids to Navigation Program: 'An Owner's Guide to Private Aids to Navigation 2001 Edition'; www.ccg-gcc.gc.ca
88. POLYAMIDE HIGH PERFORMANCE PMBH; www.polyamide-hp.com
89. MARLOW CORDAGE; www.marlowropes.com

90. TTE-6755 Port Planning and Design; Lecture 15, 'Moorings'; *Port Planning and Design*, L. Prieto-Portar, January 2007.
91. BANFIELD, S. J.; FLORY, J. F.; HEARL, J.W. S.; OVERINGTON, M. S.; *Comparison of Fatigue Data for Polyester and Wire Ropes Relevant to Deepwater Moorings*; Tension Technology International Inc.
92. BANFIELD, S.; CASEY, N.; *Evaluation of Fibre Rope for Offshore Mooring*, Tension Technology International Inc.