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Textiles in filtration

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13.1 Introduction

The separation of solids from liquids or gases by textile filter media is an essential part of countless industrial processes, contributing to purity of product, savings in energy, improvements in process efficiency, recovery of precious materials and general improvements in pollution control. In fulfilling their tasks, the media may be expected to operate for quite lengthy periods, frequently in the most arduous of physical and chemical conditions. As performance is crucial to the success of an operation, fabric failure during use could result in heavy penalties, for example, owing to loss of product, maintenance and lost production costs and possibly environmental pollution costs.

The final products of processes which involve filtration by textile filter media may ultimately find their way into our everyday lives, some examples being edible products such as sugar, flour, oils, fats, margarine, beer and spirits, and other products such as dyestuffs and pigments (as used in clothing, furnishings and paints), viscose rayon fibres and films, nickel, zinc, copper, aluminium, coal, cement, ceramics, soaps, detergents, fertilisers and many more. In addition to assisting in the refinement of products for our general everyday use, textile filter media are also engaged in the purification of both industrial and domestic effluents, thereby contributing to a cleaner environment.

The purpose of this chapter is to provide the reader with a general introduction to the more common types of solid–gas (dust collection) and solid–liquid filtration mechanisms, the raw materials, polymers, fibres and different types of fabric construction which are employed in media manufacture and some typical fabric finishing processes.

13.2 Dust collection

13.2.1 Introduction

Gas-borne dust particles arise wherever solid materials are handled. Examples include conveyors, smelting processes, hopper filling, pulverising processes, combustion processes, milling operations, bag filling and so on. The dusts may create environmental pollution problems or other control difficulties caused by their toxicity, flammability and possibly risk of explosion. The particles in question may simply require removal and be of no intrinsic value or alternatively may constitute part of a saleable product, for example sugar or cement. Typically in the range 0.1–25 μm they may be collected by one of several techniques, viz. settling chambers, cyclones, granulate filters, electrostatic precipitators and fabric collectors. Of these, arguably the most efficient and versatile is the fabric collector, especially when processing very fine particles, which are slow to settle and, by virtue of their greater light scatter, more visible to the naked eye.

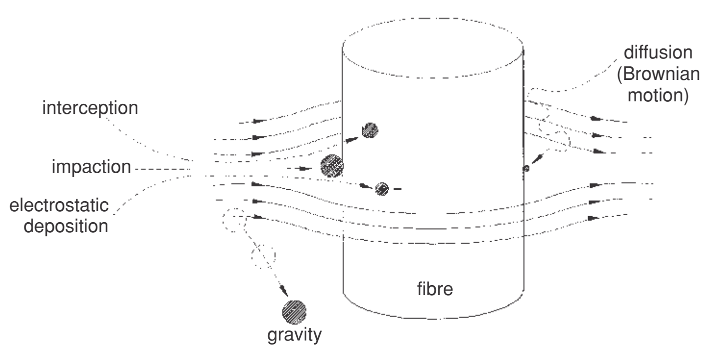
13.2.2 Dust collection theory and principles

Much has been written on the various mechanisms by which particles are arrested by unused filter media.[1] These are normally explained in terms of the effect of a spherical particle on a single fibre and may be summarised as gravitational, impaction, interception, diffusion (Brownian motion) and electrostatic. These mechanisms are shown diagrammatically in Fig. 13.1.

The theories behind these mechanisms notwithstanding, it has been argued[2] that although they may be valid for certain air filtration applications where total particle capture is vital, for the purposes of industrial dust collection, they are of limited value. A sieving mechanism is probably more appropriate wherein the size of the apertures in the medium assumes a more dominant role, at least until the fibres have accumulated a layer of dust which then takes over the sieving action.

13.2.3 Practical implications

In operation, fabric dust collectors work by drawing dust laden gas through a permeable fabric, usually constructed in the form of tubular sleeves, longitudinal envelopes or pleated elements. As the gas passes through the fabric, the particles in



13.1 Particle collection mechanisms.

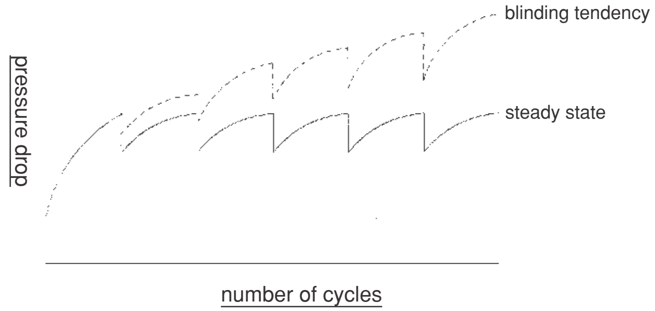
the gas stream are retained, leading to the formation of a layer of dust on the surface. This is normally referred to as a 'dust cake'. After a period of time, the accumulated dust leads to a reduction in the permeability of the material, and creates an increased pressure drop on the outlet side of the fabric. Consequently the fabric must be cleaned at appropriate intervals to return the pressure drop to a more acceptable level. Dust is then again collected and the filter continues through cycles of dust accumulation and cleaning. This mechanism is shown graphically in Fig. 13.2.

From the graph it will be observed that, after cleaning, the pressure drop does not return to the original level. This is because the fabric still retains a fraction of dust that actually assists in filtration by forming a porous structure that bridges the apertures in the fabric. It is this bridged structure that determines the filtration efficiency for subsequent filtration periods. The graph also shows that the pressure drop after each cleaning cycle continues to rise until a steady state condition develops. Were this not to occur (broken lines), the pressure drop would continue to rise to the point where more power would be required to pull the gas through the system than the fan can produce. This would result in a reduction in flow rate, possible fabric damage and ultimately system shut down.

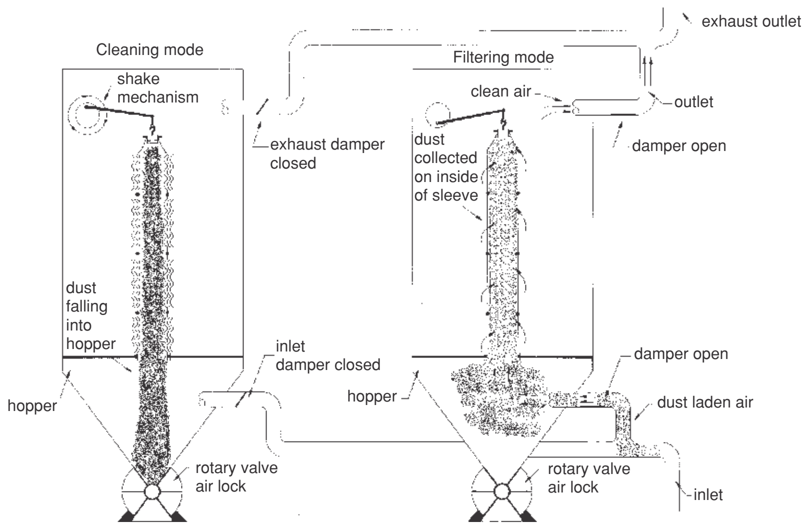
It follows from the above that, in steady state conditions, the amount of dust that is removed during cleaning is virtually equal to the amount that accumulates in the filtration phase. In reality a small, almost imperceptible increase in pressure drop may take place, resulting in a condition that will ultimately necessitate fabric removal. However, since this increase is typically less than 1 mm WG (water guage) per month, it is normally several months at least before this replacement becomes necessary.

13.2.4 Cleaning mechanisms

Fabric dust collectors are usually classified according to their cleaning mechanism, these being shake, reverse air and jet pulse. Whichever is employed it is important that a programme is devised to provide an optimum level of dust removal. In other words the cleaning should not be so excessive as to destroy the porous structure formed by the dust, which could lead to emission problems, but not so ineffective as to lead to an unacceptable pressure drop.



13.2 Resistance across filter medium.



13.3 Shake collector.

13.2.4.1 Shake cleaning

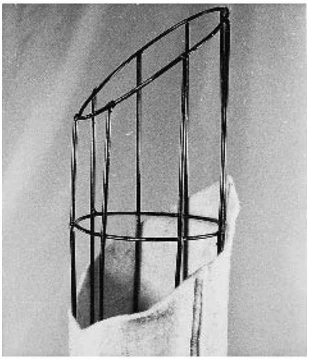
Shake cleaning, as the name implies, involves switching off the exhaust fan and flexing the filter elements (or sleeves) with the aid of a shaking mechanism, either manually, as in traditional units, or automatically. In both cases the effect is to release the dust, which then falls into a hopper for collection and removal (Fig. 13.3). In this type of collector the filter sleeves, which may be up to 10 m in length, are suspended under controlled tension from the arm of a flexing mechanism which effects the cleaning action.

13.2.4.2 Reverse air cleaning

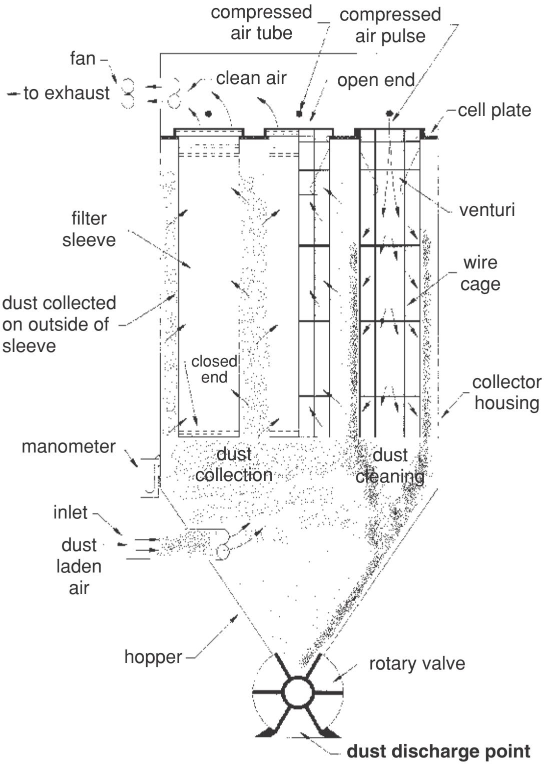
With this mechanism, cleaning is achieved again by switching off the exhaust fan but this time followed by reversing the airflow from outside to inside of the sleeves. There are two basic styles of reverse air collector. The first causes the sleeve to inflate during the collection phase and partially collapse during low pressure reverse air cleaning, whereas in the second, involving a higher cleaning pressure, the sleeves are prevented from total collapse by means of a number of metal rings inserted at strategic intervals along the length of the sleeve during fabrication. In some cases, reverse air cleaning may also be combined with a shake mechanism for enhanced performance.

13.2.4.3 Pulse jet cleaning

Compared with the mechanisms described so far, which normally involve dust collection on the inside of the sleeves, pulse jet collectors operate by collecting dust on the outside. On this occasion the sleeves, typically 3 m in length and 120–160 mm in diameter, are mounted on wire cages (Fig. 13.4). In operation, removal of the collected dust is effected by a short pulse of compressed air, approximately 8–14 litres in volume and 6 bar pressure, which is injected into a venturi tube located at the opening of the elements. This transmits a shock pulse that is sufficient to overcome the force of the exhaust fan and also to cause a rapid expansion of the filter sleeves. The dust is thus made to fall from the sleeves and to be collected in the hopper



13.4 Section of filter sleeve on cage.



13.5 Pulse jet dust collector.

(Fig. 13.5). Of the three types of mechanism described, the pulse jet is the most widely used.

13.2.5 Fabric design or selection considerations

The primary factors which determine the selection of a fabric for a particular application may be summarised as:

- thermal and chemical conditions
- filtration requirements
- equipment considerations, and
- cost.

13.2.5.1 Thermal and chemical conditions

The thermal and chemical nature of the gas stream effectively determines which type of fibre is to be used. Table 13.1 identifies the more common types which are used in dust collection and also their basic limitations. For example, if the temperature of the gas stream is higher than can be sustained by the fibre, and cost considerations preclude the possibility of gas cooling prior to dust collection, then alternative means of collection – perhaps by means of ceramic elements – will have to be sought.

Depending on the duration of exposure, high temperatures may have several effects on the fibre, the most obvious of which are loss in tenacity due to oxidation and less effective cleaning due to cloth shrinkage.

From Table 13.1, the maximum operating temperature for each fibre may appear quite low, especially when compared with the respective melting points. Suffice it to say that, whilst the fibres may withstand short surges at 20–30 °C higher than the temperatures indicated, experience has shown that continuous operation above the temperatures listed will lead to a progressive reduction in tenacity.

The presence of moisture in the gas stream, which above 100 °C will be present in the form of superheated steam, will also cause rapid degradation of many fibres through hydrolysis, the rate of which is dependent on the actual gas temperature and its moisture content. Similarly, traces of acids in the gas stream can pose very serious risks to the filter fabric. Perhaps the most topical example is found in the combustion of fossil fuels. The sulphur that is present in the fuel oxidises in the combustion process to form SO_2 and in some cases SO_3 may also be liberated. The latter presents particular difficulties because, in the presence of moisture, sulphuric acid will be formed. Hence, if the temperature in the collector were allowed to fall below the acid dew point, which could be in excess of 150 °C, rapid degradation of the fibre could ensue. Polyaramid fibres are particularly sensitive to acid hydrolysis and, in situations where such an attack may occur, more hydrolysis-resistant fibres, such as produced from polyphenylenesulphide (PPS), would be preferred. On the debit side, PPS fibres cannot sustain continuous exposure to temperatures greater than 190 °C (and atmospheres with more than 15% oxygen) and, were this a major constraint, consideration would have to be given to more costly materials such as polytetrafluoroethylene (PTFE).

Because a high proportion of fabric dust collectors are not faced with such thermal or chemical constraints, the most commonly used fibre in dust collection is of polyester origin, this being capable of continuous operation at a reasonably high temperature (150 °C) and is also competitively priced. On the debit side, polyester is acutely sensitive to hydrolysis attack and, were this to pose a serious problem, fibres from the acrylic group would be the preferred choice.

13.2.5.2 Filtration requirements

Failure to collect dust particles efficiently will inevitably lead to atmospheric pollution, which will at least be undesirable if not positively harmful. It is important therefore that, in the first instance, the fabric is designed to capture the maximum number

Table 13.1 Chemical and abrasion resistance of fibres

Generic type	Examples	Max working temperature (°C)	Abrasion resistance	Acid resistance	Alkali resistance	Some damaging agents
Polyester	Dacron Trevira	150	VG	G	P	Quicklime, conc. mineral acids, steam hydrolysis
Polyaramid	Nomex Conex	200	VG	P	VG	Oxalic acid, mineral acids, acid salts
Polyimide	P84	260	VG	P	VG	Oxalic acid, mineral acids, acid salts
Cellulose	Cotton Viscose	100	G	P	VG	Copper sulphate, mineral acids, acid salts, bacteria
Silicate	Fibreglass	260	P	F	F	Calcium chloride, sodium chloride, strong alkalis
Homopolymer acrylic	Dolanit Zefran Ricem	140	G	G	F	Zinc and ferric chloride, ammonium sulphate, thiocyanates
Copolymer acrylic	Dralon Orlon	120	G	G	F	As above for homopolymer
Polypropylene	Moplefan (Trol)	90 (125)	G	E	E	Aluminium sulphate, oxidising agents, e.g. copper salts, nitric acid
PTFE	Teflon Rastex	260	F	E	E	Fluorine
Polyamide	Nylons	100	E	P	E	Calcium chloride, zinc chloride, mineral acids
Polypeptide	Wool	110	G	G	P	Alkalis, bacteria
Polyphenylene-Sulphide	Ryton Procon	190	G	VG	E	Strong oxidising agents
PEEK	Zyex	250	VG	G	G	Nitric acid

E = Excellent, VG = Very Good, G = Good, F = Fair, P = Poor, PEEK= polyetheretherketone.
[a] Can be improved by special finishing treatments.

of particles present. The particle size and size distribution will be of great importance to the media manufacturer since these will determine the construction of the fabric. If the particles are extremely fine this could lead to penetration into (and possibly through) the body of the fabric, plugging of the fabric pores, ineffective cleaning and a prematurely high pressure drop. The fabric would become 'blind'. The skill therefore will be to select or design a fabric, which will facilitate the formation of a suitable dust pore structure on or near the surface and will sustain an acceptable pressure drop over a long period.

The particles may also present a challenge according to their abrasive nature, this giving rise to internal abrasion that will be further aggravated by the flexing actions to which the sleeve will be subjected. Conventional textile abrasion test methods will be of marginal value in predicting performance unless a mechanism for introducing the actual dust being processed can be introduced.

The particles that are conveyed to the collector may also possess an electrostatic charge,[3] either preapplied or acquired en route that, if carried into the collection compartment, could accumulate with potentially explosive consequences. Such a case, involving white sugar dust handling systems, is the subject of a paper by Morden.[4] As static electricity is essentially a surface effect, were it likely that the accumulation of such a charge will pose a serious risk, then consideration would have to be given to constructing the filter fabric with antistatic properties, for example by means of a special surface treatment or through the inclusion of antistatic fibres such as stainless steel or carbon-coated polyester (epitropic). Provided the media are properly earthed, such inclusions will enable the charge to dissipate readily.

Assessment of a fabric's antistatic properties can be made relatively easily by measurement of surface resistivity (Ω) between two concentric rings placed on the surface of the fabric, each carrying a potential difference of 500 V.[5]

Conversely, by constructing the filter medium with a blend of fibres of widely contrasting triboelectric properties, it is claimed by a fibre manufacturer[6] that superior collection efficiency can be obtained. It is further claimed that, by virtue of this enhanced efficiency, a more open structure can be used with consequent advantages in respect of the reduced power consumption required to pull the dust-laden air through the collector. However, although this effect has been used to some advantage in clean air room filtration applications, considerably more research is necessary if the triboelectric effects in industrial dust collection are to be fully understood and exploited.

Yet another problem which may confront the engineer is the presence of very hot particles. Whether from a combustion, drying or other process, these particles have been known to be carried with the gas stream into the filtration compartment where they present a serious risk of fire. (In certain conditions even ostensibly nonflammable polyaramid fibres have been found to ignite.) Consequently, if adequate particle screening is not provided, the fabric may require a special flame-retardant treatment.

The above notwithstanding, arguably the most difficult conditions in dust collection arise from the presence of moisture in the gas stream or if the dust were of a sticky nature from previous processing. This situation will be aggravated if the fabric were subsequently allowed to dry out, resulting in the formation of nodes or agglomerations of dust particles and leading to an increased weight of dust cake and eventually a critical blinding situation. In such cases, it may be advisable for the fabric to be subjected to special hydrophobic or oleaphobic treatments as part of the finishing process.

13.2.5.3 Equipment considerations

Equipment considerations again focus on the cleaning mechanisms and in particular, the forces applied by them. In the case of shake collectors, the filter sleeves will be subjected to quite vigorous flexing, which could lead to the formation of creases and ultimately holes in the fabric through flex fatigue, a situation that, as stated previously, will be aggravated by the presence of abrasive particles in the gas stream. As a consequence, in addition to resisting stretch from the weight of the dust load, a filter fabric with superior flexibility – at least at the strategic flex points – will provide a longer life.

By comparison, in pulse jet collectors the fabric sleeve is mounted on a wire cage into which, at frequent intervals, a pulse of compressed air is injected. This causes the fabric to expand briefly in a lateral direction after which the force of the exhaust fan, coupled with the fabric's elastic recovery property, returns the element back to a snug fit on the cage. This action has been studied in some depth by Sievert and Loffler.[7] Critical factors here are the actual pulse force and frequency of cleaning, the design and condition of the cages and the 'fit' of the filter sleeve on the cage itself. Too tight results in inefficient cleaning and too slack may result in damage against the cage wires or possibly interference with adjacent elements. This aspect will be aggravated if the cleaning frequency is increased, as may occur with higher dust loading.

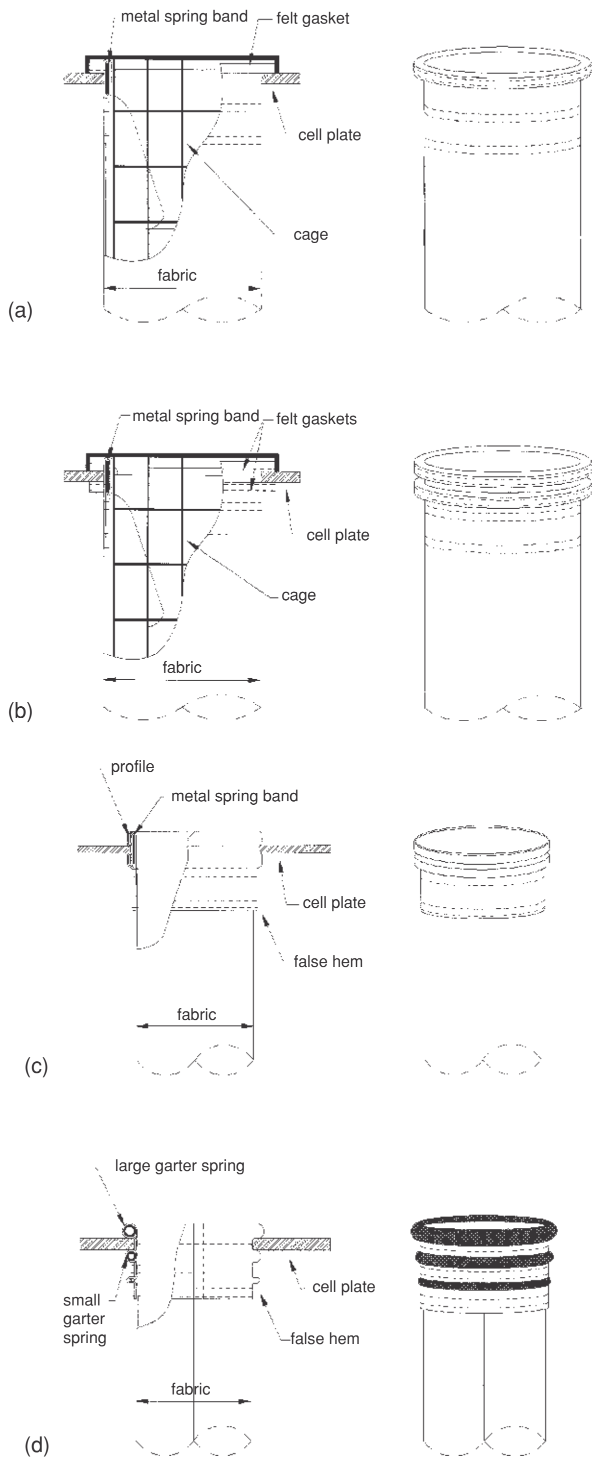
The style of filter will also determine the complexity of the sleeve design. Apart from knitted fabrics, which for this purpose are produced in tubular form, the chosen filter media will first have to be slit to an appropriate width, then formed into a tube. This may be achieved by sewing or, if the polymer is of a thermoplastic nature, by hot air welding, the latter having the advantages of both a higher production speed and obviating the need for sewing threads. In the case of high cost materials such as PPS, this could constitute a substantial saving.

In practice it is normal to manufacture the 'tubes' in quite long lengths, for example 100 m, after which the individual sleeves can be cut to ordered size in preparation for the next stage of fabrication. In the case of reverse air and shake collectors this may involve the fitting of anticollapse rings and possibly metal caps – attachments by which the filter sleeve can be suspended in the filter. Other reinforcements may also be included to enable the sleeve to withstand the effect of frequent flexing.

By comparison, filter sleeves in pulse jet collectors are located in an opening in a cell plate. In this respect they may be mounted in either a vertical or horizontal manner. Since dust is collected on the outside of these sleeves, the fixture at the location point is critical if by-pass of the filter and subsequent emission of dust into the atmosphere is to be avoided. Some possible gasketing arrangements are shown in Fig. 13.6.

13.2.5.4 Cost

In spite of all the design considerations and performance guarantees that are frequently required of the media manufacturer, this is still a highly competitive industry. As a consequence every effort is made to reduce media manufacturing costs, either by judicious sourcing of raw materials, or more efficient manufacturing (including fabrication) techniques.



13.6 Filter sleeve location arrangements. (a) Single felt gasket, (b) double felt gasket, (c) spring band profile, (d) garter springs.

13.3 Fabric construction

Three basic types of construction are found in fabric dust collectors, viz., woven fabrics, needlefelts and knitted structures. The first two are produced in flat form and will require (i) slitting to appropriate width and (ii) converting into tubular sleeves, whereas knitted fabrics may be produced directly in tubular form.

13.3.1 Woven fabrics

Used predominantly in shake collectors, this class of filter fabric may comprise twisted continuous filament yarns, short staple-fibre yarns (cotton or woollen spinning system) or perhaps a combination of both. Weave patterns may be in the form of elementary twills, for example 2/1, 2/2 or 3/1, or perhaps simple satin designs, the latter providing greater flexibility and hence superior resistance to flex fatigue and a smoother surface for superior cake release. Woven fabric area densities are typically in the range 200–500 $g\,m^{-2}$.

Design requirements include resistance to stretch from the mass of the dust cake, resistance to flex fatigue from the shake cleaning mechanism, a surface that will facilitate efficient dust release and a construction that will effect maximum particle capture whilst at the same time providing minimum resistance to gas flow.

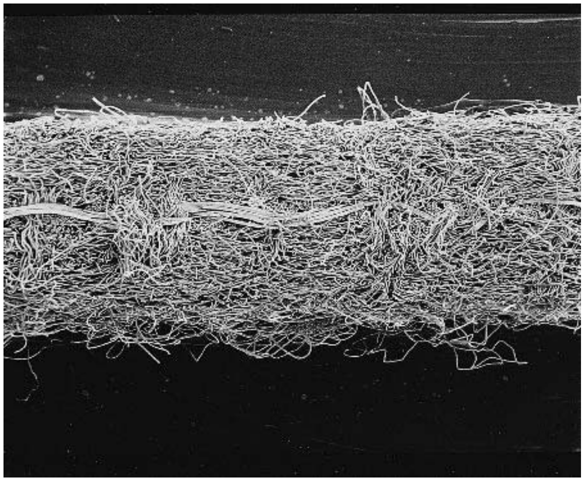
Depending on the choice of yarns, woven fabrics may present either a smooth continuous filament yarn surface to the gas stream, or a more bulky fibrous surface as provided by staple-fibre yarns. Whilst the former will provide superior cake release characteristics, the latter, by virtue of its greater number of pores, will permit higher filtration velocities, greater laminar flow and therefore a lower pressure drop across the fabric. By using a combination of continuous filament warp and staple-fibre weft yarns, preferably in a satin weave for a smoother surface and greater flexibility, an ideal compromise is possible. In this case, the filtration efficiency can be further enhanced by subjecting the weft side to a mechanical raising treatment.

13.3.2 Needlefelts

This type of construction, a cross-section view of which is shown in Fig. 13.7, is by far the most widespread in dust collection processes, providing an infinitely larger number of pores and facilitating considerably higher filtration velocities than woven fabrics.

In the majority of cases they are produced by needle punching a batt of fibre – a number of layers of carded fibre web formed by means of a cross-laying mechanism – on to both sides of a woven basecloth or scrim. This may be carried out in a continuous process or by attachment of a preformed and preneedled batt produced in a separate operation. After 'tacking' the fibre to the scrim, the assembly is consolidated in a secondary, more intensive needle-punching operation, usually with the aid of finer needles. This operation frequently addresses both sides of the felt simultaneously in a single 'double-punch' process.

The use of a woven scrim, whilst not employed in every case, provides the needlefelt with stability and the necessary tensile characteristics to withstand the stresses imposed by the predominantly pulse cleaning mechanism, whereas the batt provides the necessary filtration efficiency and also a measure of protection for the basecloth



13.7 Scanning electron micrograph showing cross-section of needlefelt.

from abrasion caused by constant flexing against the cage wires. Depending on the tensile specification of the finished needlefelt, the area density of scrims is usually in the range 50–150 $g\,m^{-2}$.

Inevitably some damage to the scrim will occur in the needle punching operation, especially if it comprises continuous filament yarns. The design of the scrim is therefore frequently 'overengineered' to compensate for this and the damage may also be alleviated by judicious selection of (i) needle design, (ii) needle fineness, (iii) needle orientation, (iv) needle board pattern, and (v) needling programme, that is, punch rate and penetration.

The needles themselves, typically 75–90 mm in length, are mounted in a board, the arrangement or pattern of which is so designed as to provide a surface which is as uniform as possible and devoid of 'needle tracking lines'. Normally triangular in cross-section, the needles contain a series of barbs which are set into the corners. Typically nine barbs per needle, these are designed to engage the fibres on the downward stroke of the punching action yet emerge completely clean on the up-stroke. Hence the fibres become mechanically locked both to other fibres in the assembly and also to the woven scrim. The barbs may be regularly spaced over the length of the needle blade, or more closely spaced for more intensive needling and the production of a more dense structure. In another design, the barbs are located on only two of the three corners, this style being used where maximum protection to one of the scrim components is required.

The density of the needles in the needleboard, the frequency of needle punching, the style of needle and depth of penetration through the structure will all be influential in controlling the thickness and density of the final assembly, and also the strength retained by the scrim.[8]

The fibres, which form the batt, are normally in the range 1.66–3.33 decitex though trends to considerably finer 'microfibres' (e.g. less than 1 decitex) have gained some prominence. Whilst the latter will provide an even greater number of pores per unit area, and hence more efficient filtration, they will also require a much higher degree of carding, resulting in considerably reduced productivity. In another development, a similar construction can be achieved by means of so-called split-table fibres. Such fibres comprise a number of elements which are bonded together at the extrusion stage. However, as a result of the subsequent mechanical action of carding (or aqueous treatment in the case of water-soluble binders), the individual elements split from the parent structure to produce the appearance of a microfibre needlefelt.

Although most fibres utilised in dust collection are of circular cross-section, irregular, multilobal-shape fibres, as in the case of Lenzing's P84 and peanut shape fibres, as in DuPont's Nomex, are also possible. The latter are of particular value as they possess a higher surface area and hence facilitate the production of needlefelts with potentially superior particle collection capability. Some manufacturers have taken this a stage further by producing structures with a 'veneer' of high particle collection efficiency fibres on the surface whilst retaining coarser, less expensive fibres on the back.

Needlefelt area densities are typically in the range 300–640 $g\,m^{-2}$, lighter qualities being used in reverse air and shake collectors and heavier qualities in pulse jet collectors. The majority of needlefelts actually fall in the range 400–510 $g\,m^{-2}$, these facilitating generally higher filtration velocities. However, in the event that the dust is particularly abrasive, a longer life may be expected from felts in the 540–640 $g\,m^{-2}$ range.

13.3.3 Knitted fabrics

Because they are capable of being produced in seamless tubular form, weft-knitted fabrics provide, in theory, an attractive and economic alternative to both woven and needled constructions. By inlaying appropriate yarns into the knitted structure, the elasticity which is normally associated with such fabrics can also be controlled and the same may be used to enhance the particle collection capability.[9] On the down side, in critical applications, the filtration efficiency will be inferior to a needlefelt construction and further problems are likely to be found in respect of the large number of sleeve diameters which the industry requires. Limitations are also inevitable in respect of the number of physical and chemical finishes which are frequently administered to both woven and needlefelt constructions.

13.4 Finishing treatments

These are designed essentially to improve (i) fabric stability, (ii) filtration collection efficiency, (iii) dust release, and (iv) resistance to damage from moisture and chemical agents. A number of finishing processes are employed to achieve these goals, for example heat setting, singeing, raising, calendering, 'special surface treatments' and chemical treatments.

13.4.1 Heat setting

Improved stability is essential in order to prevent shrinkage during use. Such shrinkage may be caused by the relaxation of tensions imposed on fibres and/or yarns during manufacture, or be due to the inherent shrinkage properties of the raw materials themselves.

The thermal conditions that are often found in a dust collector, will be conducive to fabric relaxation and, if not effectively addressed during manufacture, could lead to serious shrinkage problems during use. For example, in a pulse collector, lateral shrinkage could result in the fabric becoming too 'tight' on the supporting cage, leading to inefficient cleaning and ultimately an unacceptable pressure drop.

As heat is the primary cause of shrinkage, it is logical that fabric stability should be achieved by thermal means. Such an operation is normally referred to as heat setting, and may be carried out by surface contact techniques, 'through air' equipment, or by stentering, the latter two being preferred because they enable greater penetration of heat into the body of the structure. This is particularly relevant in the case of needlefelts because the scrim is to some extent insulated by the batt fibres. Whichever technique is employed, in order to ensure stability during use, the temperature in the heat setting operation will invariably be significantly higher than the maximum continuous operating temperature of the material in question. Furthermore, since complete fibre relaxation is a temperature–time related phenomenon, manufacturers will also process at speeds that are appropriate to achieve the desired effect.

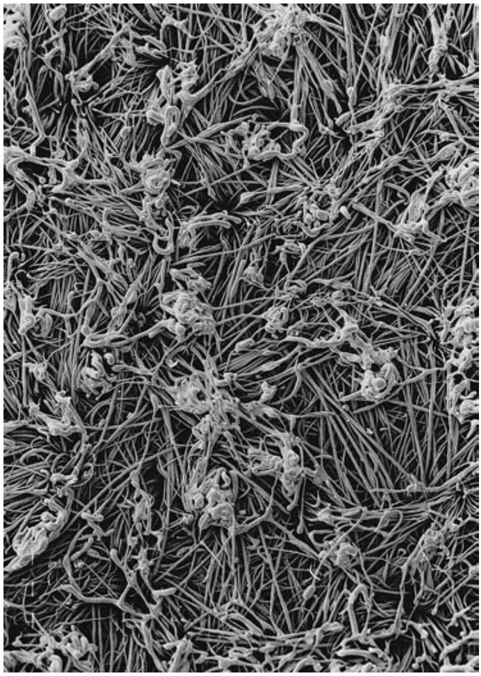
In addition to stabilising the fabric, the heat setting process will also effect an increase in the density of the structure through increased fibre consolidation. This in turn will further assist in achieving a higher level of filtration efficiency.

13.4.2 Singeing

Filter fabrics, especially needlefelts, which are produced from short staple fibres, invariably possess surfaces with protruding fibre ends. Since such protrusions may inhibit cake release by clinging to the dust, it is common practice to remove them. This is achieved by singeing, a process in which the fabric is passed, at relatively high speed, over a naked gas flame or, in another technique, over a heated copper plate. The heat of the flame causes the fibres to contract to the surface of the fabric where, in the case of thermoplastic fibres, they form small hard polymer beads (Fig. 13.8). Singeing conditions (i.e. speed and gas pressure) will normally be adjusted according to polymer type and the intensity required by either the end-use application or the individual manufacturer's preference.

13.4.3 Raising

Whilst the singeing process is designed to denude the fabric of its protruding fibres, the raising process is designed actually to create a fibrous surface, normally on the outlet side of the filter sleeve, to enhance the fabric's dust collection capability. It follows therefore that this process is designed essentially for woven fabrics comprising staple-fibre yarns – at least in the weft direction. In operation the fabric is pulled over a series of rotating rollers termed 'pile' and 'counter pile', each of which is clothed with card wire and mounted concentrically on a large cylinder of approximately 1.5 m diameter. As the cylinder rotates, the pile rollers raise the fibres proud of the surface whereas the counter pile rollers stroke them into a more orderly fashion. Raised fabrics may comprise 100% staple-fibre yarns or a combination of multifilament and staple-fibre yarns, the latter being woven in satin style in which the face side is predominantly multifilament and the reverse side predominantly staple.



13.8 Scanning electron micrograph showing surface of (singed) needlefelt.

The smooth surface provided by the multifilaments will aid cake release whilst the raised staple yarns on the reverse side will enhance particle collection efficiency. A significant measure of width contraction invariably takes place during this operation and proper attention will have to be given to this when designing the fabric.

13.4.4 Calendering

The calendering operation fulfils two objectives, viz. to improve the fabric's surface smoothness and hence aid dust release, and to increase the fabric's filtration efficiency by regulation of its density and permeability. As a result of the latter, the yarns and fibres become more tightly packed, making it more difficult for particles to pass through or even into the body of the fabric.

Most calenders in the industry consist of at least two bowls, one manufactured from chrome-plated steel and the other from a more resilient material such as nylon or highly compressed cotton or wool fibres. The steel bowl is equipped with a heat source, for example gas, electric elements, superheated steam, or circulating hot oil. Thus, by varying the process temperature (usually according to polymer type), pressure and speed, the desired density and degree of surface polish can be achieved. In reality, rather than density, a more common control parameter is measurement of the fabric's air permeability, this normally being expressed in units of cfm (cubic feet per square foot per minute at ½ inch water gauge) or litres per square decimetre per minute at 20 mm water gauge.[10]

The cotton or synthetic bowl may also posses a cambered profile in order to offset the deflection (bending) that occurs as the pressure is applied and that may otherwise lead to non-uniform calendering. Alternatively, since this camber only applies to the operating pressure for which it is designed, the generally preferred approach would be to employ a calender adopting a system such as developed by equipment manufacturers Kusters and Ramisch-Kleinwefer in which uniform pressure can be maintained across the full width of the fabric regardless of the applied force.

Although the calender is useful, not least in regulating permeability, it should not be regarded as a more economical substitute for reduced needling density or, in the case of woven fabrics, more economical thread spacing. Aggressive conditions in the filter may well negate the effect of the calendering operation before the fabric has become fully 'acclimatised' to the conditions. This is especially relevant where the fibres in the filter medium are of a particularly resilient nature, such as those in the acrylic family.

13.4.5 Chemical treatments

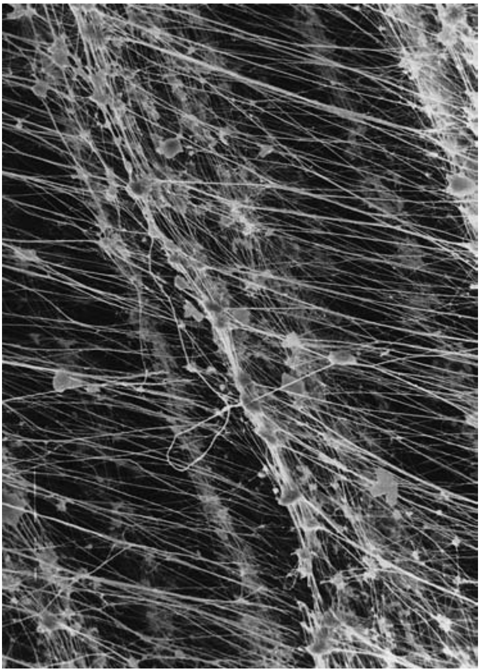
Chemical treatments are normally applied for one of two reasons, namely (i) to assist in dust release, especially where moist sticky dusts, possibly containing oil or water vapour are encountered, or (ii) to provide protection from chemically aggressive gases such as SO_2 and SO_3 referred to earlier. However, in the case of SO_3 it is possible that such chemical treatments, in the presence of moisture, will be less than 100% effective and, in such circumstances, a more chemically resistant fibre must be sought.

Other chemical treatments may also be employed for more specific purposes. For example, proprietary treatments, usually involving silicone or PTFE, enhance yarn-to-yarn or fibre-to-fibre 'lubricity' during pulse or flex cleaning and similarly, where flammability is a potential hazard, padding through commercially available flame-retardant compounds may be necessary.

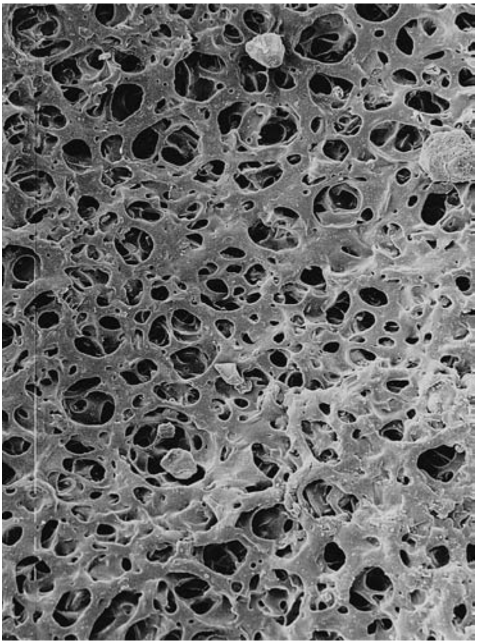
13.4.6 Special surface treatments

This category of treatments is devoted to improving still further the fabric's filtration efficiency and cake release characteristics. In this respect there are basically two types of treatment, namely (i) attachment of a more efficient membrane, for example biaxially stretched PTFE (Fig. 13.9) in a lamination operation, and (ii) the application of a low-density microporous foam (Fig. 13.10). Both these treatments are designed to restrict the dust particles, as far as possible, to the surface of the fabric, thereby reducing the tendency for blinding. The PTFE membrane, comprising an extremely fine structure, is particularly effective in this respect. It may be laminated to the surface of the fabric either by special adhesives or, where appropriate, by flame bonding. Although highly efficient, the gossamer-like surface is rather delicate and care must be exercised when handling filter sleeves produced from such materials. In addition, as PTFE laminated fabrics are relatively expensive, their use is normally restricted to difficult applications, for example where the dust particles are extremely fine or of a particularly hazardous nature or where the interaction with a surface of this type shows unique advantages in respect of cake release.

By comparison, the foam treatment is achieved by (i) mechanically generating a low density latex foam, (ii) applying this foam to the fabric by the knife over roller



13.9 Scanning electron micrograph showing biaxially stretched PTFE membrane.



13.10 Scanning electron micrograph showing microporous coating on needlefelt substrate.

(or knife over air) technique, (iii) drying the foam at a modest temperature, (iv) crushing the foam to produce an open cell structure, and (v) curing the foam at a higher temperature to crosslink the chemical structure. Although the principal ingredient of the treatment is usually an aqueous-based acrylic latex, the precise formulation may comprise a variety of chemical agents to ensure the production of a fine, regular and stable pore structure and perhaps also to provide specific characteristics such as antistatic or hydrophobic properties. The actual density of the foam as applied to the material is also critical to a successful application, too high density leading to excessive wetting of the substrate and resulting in an unacceptable air permeability and too low density leading to inadequate penetration, poor mechanical bonding and hence the risk of delamination.

Acrylic foam-coated needlefelts produced in this manner are capable of continuous operation at temperatures up to approximately 120 °C. However, they are not normally resistant to hydrolytic conditions, these leading to collapse of the structure and hence, premature pressurisation. The latter notwithstanding, in view of the success of foam-coated structures operating in relatively 'safe conditions', the future will undoubtedly see more advanced products of this type, leading to structures that are both more efficient in particle capture and also capable of operation in more chemically and thermally challenging environments.

13.5 Solid–liquid separation

13.5.1 Introduction

Although there are several ways in which solid/liquid separation may be achieved (e.g. settling, floatation, hydrocyclones, evaporation, magnetic, electrostatic, gravity, centrifuge, vacuum, and pressure), the mechanisms that consume the largest volume of textile filter media and on which this section will concentrate, are those of pressure and vacuum.

In focusing on these mechanisms it will be appreciated that, apart from textile fabrics there are also many other forms of filter media. Some of the more common types and their relative collection efficiencies are listed in Table 13.2.

Table 13.2 Comparative particle collection efficiency for various media types

Media type	Approximate minimum particle size retained (μm)
Flat wedge screens	100
Woven wire	100
Sintered metal sheets	3
Ceramic elements	1
Porous plastic sheets	0.1
Yarn (cheese wound) cartridges	2
Compressed, fibre sheets	0.5
Filter aids (powders/fibres)	1
Membranes	0.1
Woven monofilaments	<10
Other woven fabrics	<5
Needlefelts	5
'Link' fabrics	200

13.5.2 Fabric design/selection considerations

There are many factors which confront the technologist when choosing or designing a fabric for a particular application. These may conveniently be grouped under the following general headings:

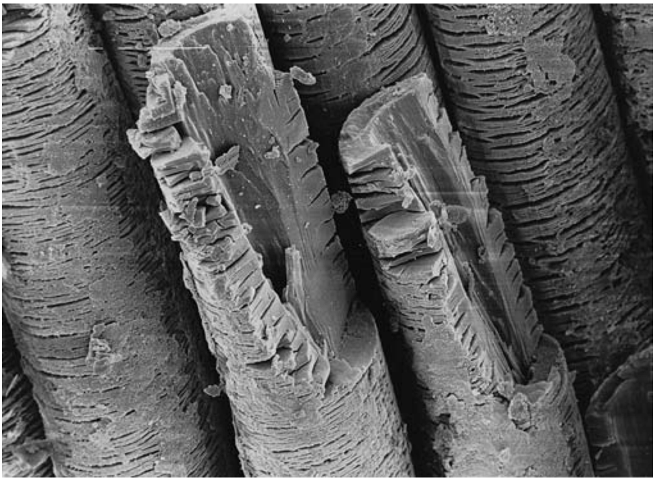
1 thermal and chemical conditions
2 filtration requirements
3 filtration equipment considerations and
4 cost.

13.5.2.1 Thermal and chemical conditions

Before the advent of synthetic materials, the only fibres available for industrial purposes were those of natural origin such as flax, wool and cotton. The last mentioned is still used in one or two applications even today; the tendency of this fibre to swell when wet facilitates the production of potentially highly efficient filter fabrics. On the other hand, the wide range of chemical conditions which prevail in industrial processes and, more significantly, the introduction of more chemically stable synthetic fibres, have effectively led to the demise of cotton in all but a few applications. But even synthetic fibres have their limitations. Polyamide – nylon 6.6 – arguably the first and most widely used true synthetic material is notoriously sensitive to strong acidic conditions and, conversely, polyester is similarly degraded by strong alkaline conditions.

By comparison, polypropylene is generally inert to both strong acids and alkalis and, primarily for these reasons, is the most widely used polymer in liquid filtration. On the down side, this material is limited by its relatively poor resistance to oxidising agents (Fig. 13.11) – nitric acid and heavy metal salts[11] fall into this category – and at temperatures above 90–95 °C stability problems may be encountered, especially if the filter fabric is also subjected to considerable stress. Resistance to organic solvents and mineral oils is also limited.

Some of the more common fibres (and their general properties) which are used in industrial filtration are listed in Table 13.3. Note that the maximum operating tem-



13.11 Scanning electron micrograph showing oxidation damaged polypropylene fibres.

Table 13.3 Fibres and their properties

Fibre type	Density ($g\,cm^{-3}$)	Maximum operating temperature (°C)	Resistance to:		
			Acids	Alkalis	Oxidising agents
Polypropylene	0.91	95	E	E	P
Polyethylene	0.95	80	E	E	P
Polyester (PBT)	1.28	100	G	F	F
Polyester (PET)	1.38	100	G	P	F
Polyamide 6.6	1.14	110	P	VG	P
Polyamide 11	1.04	100	P	VG	P
Polyamide 12	1.02	100	P	VG	P
PVDC	1.70	75	E	VG	VG
PVDF	1.78	100	E	E	G
PTFE	2.10	120+	E	E	VG
PPS	1.37	120+	VG	E	F
PVC	1.37	75	E	E	F
PEEK	1.30	120+	G	G	F
Cotton	1.5	90	P	G	F

PBT = poly(butylene) terephthalate, PET = polyethylene terephthalate, PVDC = polyvinylidene chloride, PVDF = polyvinylidene fluoride, PVC = polyvinyl chloride.
E = excellent, VG = very good, G = good, F = fair, P = poor.

peratures shown in Table 13.3 are somewhat lower than in a previous table and reflect the influence of continuous exposure to aqueous conditions. However, in the absence of official published data these should only be used as a general comparative guide.

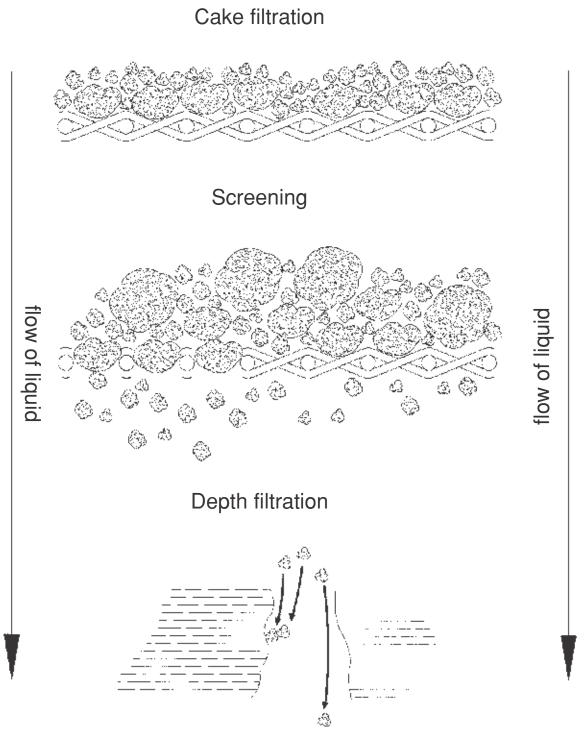
13.5.2.2 Filtration requirements

13.5.2.2.1 Filtrate clarity

The mechanisms by which particles are removed by fabric media may be identified as

1. Screening or straining: this is a simple mechanism in which particles are retained by the medium only as and when they are confronted with an aperture which is smaller than the particles themselves.
2. Depth filtration: in this mechanism the particles are captured through attachment to the fibres within the body of the filter medium, e.g. because of Van der Waal or electrostatic forces, even though they may be smaller than the apertures that are formed. This is particularly relevant to nonwoven media.
3. Cake filtration: this is undoubtedly the most widely encountered mechanism in industrial filtration and involves the accumulation of particles that 'bridge' together in a porous structure on the surface of the fabric. It follows from this that, once formed, the cake effectively becomes the filter medium with the fabric thereafter acting simply as a support. In cases where it is difficult for the particles to form a naturally porous cake, the use of a special precoat or body feed may be employed to assist in this task.

The various mechanisms outlined above are illustrated in Fig. 13.12. These have been the subject of many papers, the more significant of which have been eloquently summarised by Purchas.[12]



13.12 Solid/liquid filtration mechanisms.

Notwithstanding the fact that the filter fabric is used to effect the maximum separation of particles from liquids, absolute clarity is not always necessary. In certain gravity- or vacuum-assisted screening operations the filter fabric is simply designed to capture particles greater than a specific size and in other filtration systems a measure of solids in filtrate can be tolerated before cake filtration takes over and the necessary clarity is achieved. Recirculation of the slurry may also be possible in some applications until the same condition prevails. From this it will be appreciated that in some cases the solids are the more valuable component in the slurry whereas in others the process is concerned with clarification of the liquid, the solids thereafter being of little or no value.

13.5.2.2.2 Filtrate throughput

Although largely dictated by the equipment, restrictions to flow imposed by the unused filter fabric could pose serious pressure losses for a plant engineer and, in some applications, additional problems in forming a satisfactory filter cake.[13] In practice therefore, were it possible to tolerate the presence of a measure of solids in filtrate, some compromise is normally accommodated between throughput and clarity.

13.5.2.2.3 Low cake moisture content

As it is often necessary for filter cakes to be dried before moving to the next process and because drying by thermal means is energy intensive, it is important that as much liquid as possible is removed by mechanical means prior to the actual drying operation. A similar situation applies in effluent treatment operations. If the processed effluent is transported to landfill sites, it is important to reduce the moisture content, first in order to meet local statutory regulations and second, because it is simply uneconomic to transport water. This also applies to mining ore concentrates that incur shipping costs as they too are transported, sometimes across oceans, for further processing.

As with filtrate throughput, whilst the choice of raw materials and the construction of the filter fabric will play a part in controlling cake moisture content, this aspect will again be governed largely by forces within the filter itself, for example membrane squeezing and cake drying by means of compressed air.

13.5.2.2.4 Resistance to blinding

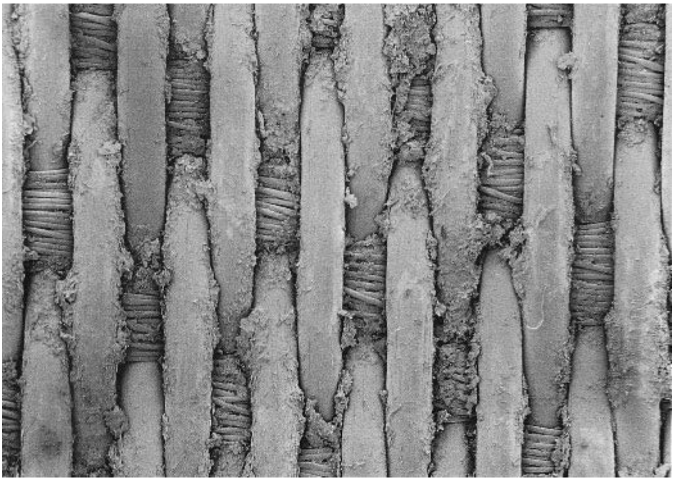
Blinding is a term which is commonly applied to filter fabrics which, after normal cleaning operations, are so contaminated with embedded solids that the resistance to filtrate flow is unacceptably high. The blinding may be temporary or permanent; temporary in the sense that the cloth may be partly or completely rejuvenated by special laundering or in situ cleaning, for example with chemicals and/or high pressure hosing (Fig. 13.13 and Fig. 13.14), and permanent in the sense that the solids are irretrievably trapped within the body of the fabric, perhaps between fibres and filaments.

The compressible nature of the slurry, the shape and size of the particles and the possibility of crystal growth from the process itself are factors which will be addressed, particularly when selecting the fabric components. This will be discussed further in Section 6.

13.5.2.2.5 Good cake release

At the end of the filtration cycle the dewatered filter cake must be removed from the fabric in preparation for the next cycle. It is important that the cake is effectively discharged at this point since any delays will lead to extended filtration cycle times and therefore reduced process efficiency. This is particularly apt in filter press

13.13 Scanning electron micrograph showing used fabric before cleaning.



13.14 Scanning electron micrograph showing used fabric after cleaning.

operations where manual intervention may be necessary to remove sticky cakes. As a consequence, in addition to longer cycle times, the cost of the operator must also be considered. To some extent this topic may be linked to cake moisture content because, broadly speaking, wetter cakes will adhere more tenaciously to the cloth. This problem has been partly addressed by equipment manufacturers with the incorporation of high pressure wash jets and brush cleaning devices, and filter media producers also continue to pursue the development of fabrics that will facilitate the ultimate goal of perfect, unassisted cake release and hence the achievement of a fully automated operation.

13.5.2.2.6 Resistance to abrasive forces

The abrasive forces in this context arise from the shape and nature of the particles in the slurry. Materials with hard sharp quartz-like edges may lead to internal abrasion, the breakage of fibres and filaments and ultimately a weak point and possibly a pinhole in the fabric. Being the point of lowest resistance to flow, enlargement of such a hole then follows (Fig. 13.15) and eventually excessive solids in the filtrate ensues. The filter fabric should therefore be designed, as far as possible, to withstand the impact of such forces. This may be achieved by appropriate yarn and fabric construction, ideally manufactured from the toughest polymer consistent with the chemical conditions in the application.

13.5.2.2.7 Filter aids and body feed

In identifying filtration requirements, it is recognised that, in some cases, the filter fabric may require additional assistance, for example, by way of filter aids, body feeds or even filter papers. The use of filter aids, of which there are many types, is designed to precoat the fabric with a layer of powder, such as diatomaceous earth. This is carried out in order (i) to protect it from blinding, (ii) to assist in the collection of particularly fine particles, or (iii) to enable more efficient cake release. In special circumstances filter papers may also be used for similar reasons, especially where absolute clarity is essential. Body feeds, on the other hand, are added to the

13.15 Scanning electron micrograph showing mechanical damage from abrasive particles.

slurry to be filtered to enable the formation of a more porous cake than would otherwise be the case, thereby enhancing the rate of filtration flow.

13.5.2.3 Filtration equipment considerations

Having determined the preferred type of polymer and identified the various filtration requirements, of equal importance is the need to ensure that the fabric is capable of providing trouble-free performance on the equipment itself. In this respect it should provide (i) resistance to stretch, (ii) resistance to flex fatigue, and (iii) resistance to the abrasive forces that may be present on the filter itself.

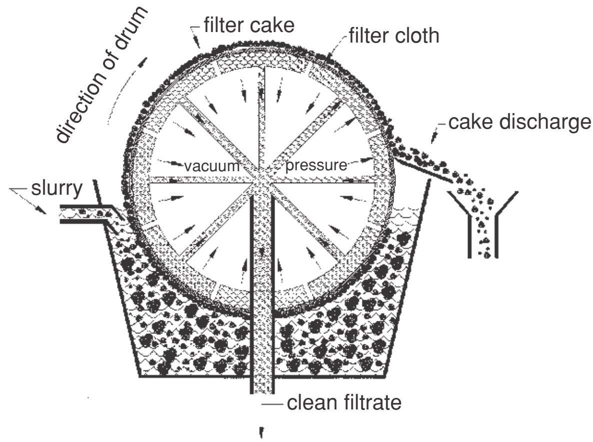
13.5.2.3.1 Resistance to stretch

The propensity for stretch is evident on most types of filter and may arise as a result of cloth tensioning mechanisms, internal pressures or other forces such as the mass of the filter cake and the gravitational pull that it exerts on the fabric. In the case of filter belts, excessive force from the filter's tensioning mechanism may, in extreme cases, cause the belt to extend to the maximum length that the machine can handle. This in turn could lead to drive problems and hence the need to shorten the belt or even replace it. This will be discussed further in Section 13.9.1.

In similar manner, excessive stretch caused by the mass of filter cakes in filter press operations could result in the port holes in the fabric moving out of alignment with corresponding holes in the filter plate, thereby restricting flow of filtrate out of the press. Likewise, in other filtration systems such as pressure leaf filters, the same stretch could result in the formation of creases and ultimately mechanical damage to the fabric.

13.5.2.3.2 Resistance to flex fatigue

In addition to the overall dimensional changes to filter fabrics caused by sustained high tension, which will be aggravated at higher temperatures, corresponding changes to thread spacing may also be encountered, possibly leading to a more open structure and less efficient filtration. A similar type of thread disturbance has also



13.16 Rotary vacuum drum filter.

been observed on rotary vacuum drum and rotary vacuum disc filters, this time caused by flex fatigue.

In such systems, the filter fabric, which may be fabricated to envelop the filter element or simply caulked into its drainage surface, will operate in both vacuum and pressure modes (Fig. 13.16). During the initial phase, dewatering commences as the slurry is drawn by vacuum on to the surface of the immersed fabric and, as the equipment rotates, this continues until completion of approximately two-thirds of a revolution. At this point the vacuum is replaced with compressed air, which causes the fabric to expand. This in turn causes the dewatered filter cake to crack and fall from the fabric under force of gravity.

As previously mentioned, the constant flexing that the fabric receives in moving from vacuum to pressure can lead to a measure of fatigue and possible loss in filtration efficiency, a condition that is further aggravated by the presence of abrasive particles in the slurry.

13.5.2.3.3 Resistance to abrasive forces

Abrasive forces arising from the design and/or construction of the filter itself are found in many forms. In the case of filter belts, a potential reason for abrasion damage is due to the sustained, possibly excessive, pressure of the scraper blade which is engaged to ensure maximum cake removal at the discharge point. In addition to the general pattern of wear which is caused by this blade, local damage resulting from irregularities such as trapped particles, yarn knots or fabric creases will also be inflicted to the detriment of filtrate clarity. Once again the wear pattern will be intensified by the presence of abrasive slurries.

In addition to the scraper blade, abrasive damage and general cloth distortion can also be expected on belt filters from edge tracking or guiding mechanisms, especially if these are poorly maintained. In such cases, the damage can be alleviated by reinforcing the edge of the fabric for example by impregnation with resin treatments or perhaps with hot-melt polymers.

The surfaces against which the fabric will be expected to operate in filter press operations will also be influential in the choice of fabric construction. Whilst the introduction of advanced plastics has considerably reduced the damage that was

Table 13.4 Influence of yarn type on filtration properties

Order of merit	Maximum clarity	Maximum throughput	Low cake moisture content	Resistance to blinding	Ease of cake release	Abrasion resistance
1	Staple	Monofil	Monofil	Monofil	Monofil	Staple
2	Multifil	Multifil	Multifil	Multifil	Multifil	Multifil
3	Monofil	Staple	Staple	Staple	Staple	Monofil

previously inflicted on fabrics by rough, cast iron surfaces, there remain a large number of applications where the use of cast iron is still necessary.

In such circumstances, if the ideal fabric in purely filtration terms is incapable of withstanding abrasive forces of this nature, special fabrication techniques or the use of a backing cloth may be necessary. The latter, being of a more robust construction, will also be designed to facilitate the free flow of filtrate which passes through the primary filter cloth.

From the foregoing it will be evident that, from a technical point of view, the final choice of fabric may not be ideal in all respects. Therefore, as a general guide, Table 13.4 provides some direction about the types of yarn that are most suitable for a particular application.

13.5.2.4 Cost

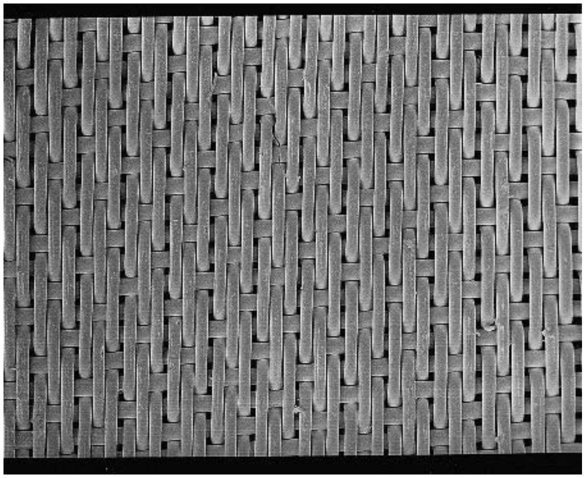
In the majority of applications it can be shown that the cost of the filter fabric is a relatively small fraction of the total product cost. This notwithstanding, it is inevitable that in any application the filter fabric will, at some stage, have to be replaced. The onus of responsibility therefore rests with the cloth manufacturer to develop appropriate materials to provide maximum cost effective performance to ensure continuity of the operation for as long a period as possible.

13.6 Yarn types and fabric constructions

The technologist has basically four types of yarn to choose from when designing a filter fabric, namely monofilament, multifilament, fibrillated tape and staple-fibre yarns.

13.6.1 Monofilaments

Being manufactured from thermoplastic polymers, monofilament yarns are produced by extruding molten polymer chip through an orifice in a precision-engineered dye. On emergence from the extrusion point, the molten polymer is cooled, usually in a water bath, and drawn through a series of rollers to orientate the molecules and provide the monofilament with the desired stress–strain properties. The bath through which the monofil passes may also contain additives such as lubricants to assist in weaving, and antistatic agents to avoid shocks during high speed warping and also to alleviate the attraction of dust and 'fly'. The diameters of the monofilaments used range from 0.1 mm up to 1.0 mm, the smaller diameters being used mainly in applications involving filter presses, pressure leaf and candle filters, rotary vacuum disc and rotary vacuum drum filters, whereas the larger



13.17 Scanning electron micrograph showing monofilament fabric, five-end satin weave.

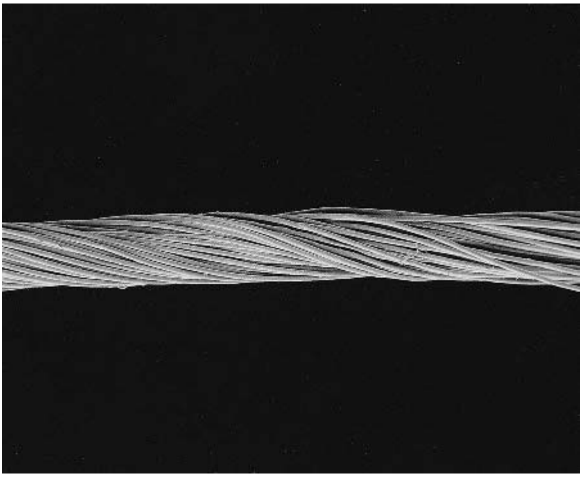
diameters are used mainly in relatively coarse filtration applications involving heavy duty vacuum belt filters or multiroll filter presses. Although normally extruded in round cross-section, for special applications they may also be produced in flat or oval form.

The principal characteristics of monofilament fabrics (Fig. 13.17) may be summarised as (i) resistance to blinding, (ii) high filtrate throughput, and (iii) efficient cake release at the end of the filtration cycle. These characteristics are attributed to the smooth surface of the yarn and, in respect of cake release, weaving in a satin construction can further enhance this. On the down side, the apertures that are formed between adjacent threads and at the interlacing points in the weave (the only points where filtration can take place in monofilament fabrics) may prove to be too large for the separation of very fine particles such as dyestuffs and pigments, even though the warp threads may be quite densely packed. Fabrics containing over 110 threads per centimetre, each of 0.15 mm diameter, are not uncommon. Resistance to abrasive forces is also generally low with monofilament fabrics and some form of reinforcement may be necessary where this is likely to present difficulties.

For most filtration applications involving monofilaments, the majority of diameters used are in the range 0.15–0.35 mm, yielding fabric area densities between 180 and 450 $g\,m^{-2}$. Heavy-duty filter belt applications, on the other hand, usually employ diameters from 0.3–1.0 mm resulting in area densities from 500–1700 $g\,m^{-2}$.

13.6.2 Multifilaments

Although like monofilaments, multifilaments are also extruded through a precision-engineered dye, here the similarity ends; the dye on this occasion contains many more apertures of much smaller size. Moreover, the material to be extruded may again be in the form of a molten polymer or alternatively in the form of a solvent dope, the solvent evaporating on extrusion to be recovered for further use. Drawing of the threads is again carried out to orientate the molecules and develop the appropriate tenacity, this being typically of the order 5.5–6.5 centiN tex^{-1}.



13.18 Scanning electron micrograph showing multifilament yarn.

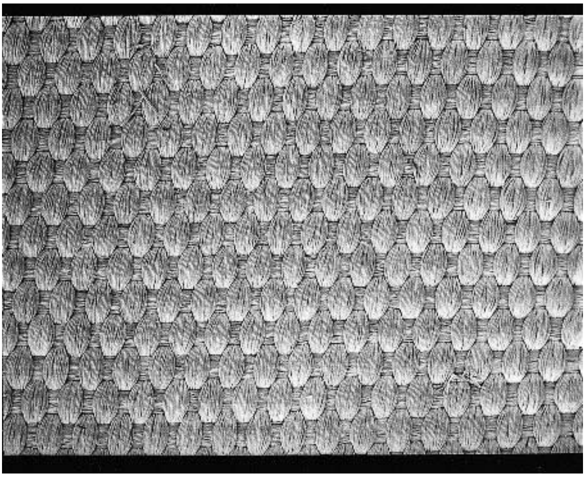
In practice, manufacturers of multifilament yarns produce a number of standard linear densities that, for industrial filtration purposes, may range in fineness from 120 decitex to 2200 decitex, with individual filaments varying from 6–10 decitex. From this it can be shown that the diameter of such filaments will be of the order of 0.03 mm.

The filament assemblies may be held together by air intermingling, texturising or by twist (Fig. 13.18), the latter being preferred for warp purposes owing to the abrasive forces that will impact on the filaments – especially during weaving where the yarn is under considerable tension – and that may otherwise lead to filament breakage. Whilst weaving performance can be improved by suitable choice and addition of lubricant, determination of the optimum level of twist in the yarn will be critical to successful warping and weaving operations; too much twist presents handling difficulties in warping and too little results in yarn damage, inefficient weaving and substandard fabric.

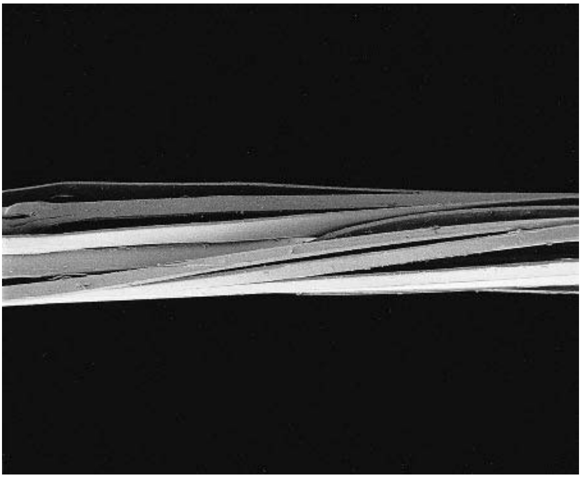
Multifilament fabrics (Fig. 13.19) are characterised by their high strength and resistance to stretch, these properties being enhanced as the tenacity of the yarn increases. Multifilament yarns are also more flexible than monofilaments, a property which facilitates weaving of the tightest and most efficient of all woven fabrics. This is used to particular advantage when filtering fine particles ($<1\,\mu m$) at very high filtration pressures, in some cases in excess of 100 bar.

In view of the tightness of fabric into which they are frequently woven, multifilament fabrics are generally inferior to monofilaments in respect of throughput and their resistance to blinding will be similarly reduced. This is due to the fact that, in addition to the filtration which takes place between adjacent threads, particles are also captured and possibly permanently trapped within the body of the threads themselves; this occurs despite the fact that the filaments may be tightly bound together by twist. The accumulation of such particles leads to swelling of the yarns, a reduction in pore size and a corresponding fall in filtrate throughput.

Fabric area densities in this category vary from as little as $100\,g\,m^{-2}$ to around $1000\,g\,m^{-2}$. The lighter fabrics, depending on the application, may require additional



13.19 Scanning electron micrograph showing multifilament fabric.

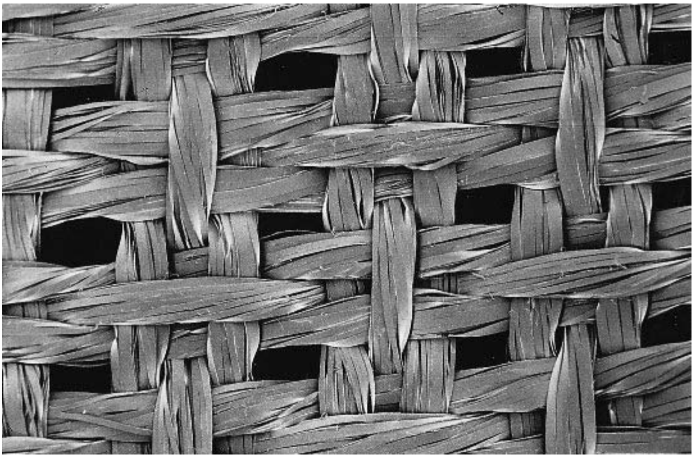


13.20 Scanning electron micrograph showing fibrillated tape yarn.

assistance in the form of a support or backing cloth. This is in order to avoid damage from abrasive filter plates or perhaps to avoid the fabric from being deformed into the indentations of the plate surface itself where it would impede escape of filtrate. Heavier fabrics, on the other hand, will be used, mainly unsupported, in more arduous, higher stress-related applications such as filter belts on vertical automatic filter presses.

13.6.3 Fibrillated tape ('split film') yarns

As the title suggests, these yarns are produced by taking a narrow width polypropylene film then splitting it into a number of components and binding these together by twist (Fig. 13.20). In this sense they may be seen as rather coarse multifilament



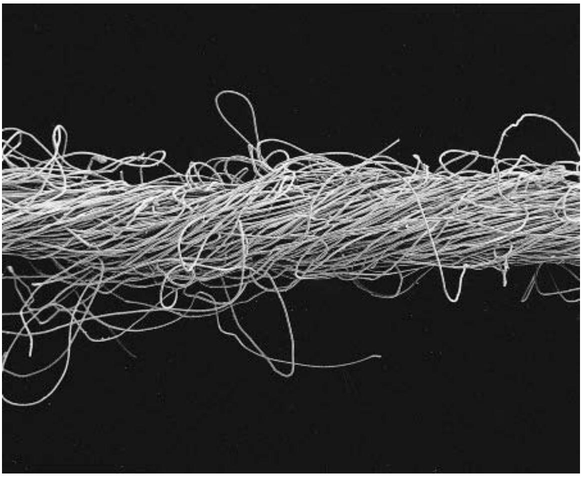
13.21 Scanning electron micrograph showing fibrillated tape fabric.

yarns. However, as they are considerably stiffer than the latter, they are not normally used in filter fabrics as such but rather in more open weave backing cloths. Therefore their function is to provide protection for the more delicate primary filter fabric from damaging surfaces, whilst at the same time permitting the free flow of filtrate from the filtration compartment. The use of a 'mock leno' weave (Fig. 13.21) is ideal in this respect. For the production of such fabrics, which are generally in the 400–600 $g\,m^{-2}$ range, yarn linear densities of around 2200 decitex and higher are employed.

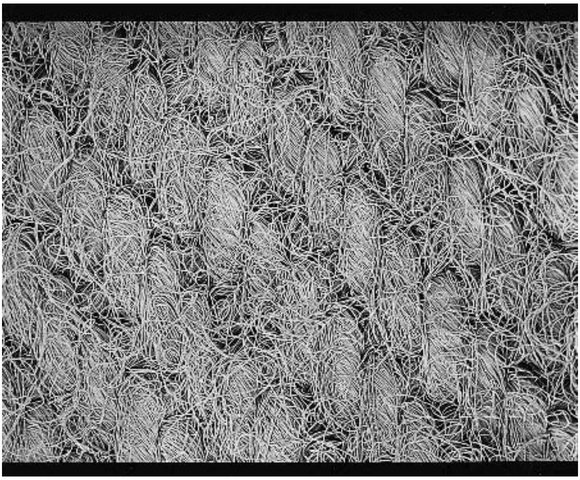
13.6.4 Staple-fibre yarns

The synthetic fibres which are used in these yarns are again produced by a continuous extrusion process, followed by conversion into a short staple length, which will facilitate processing on either rotor or cotton or woollen ring spinning systems. The cotton system tends to produce yarns that are rather lean in character whereas those from the woollen system are more bulky (Fig. 13.22). Similarly, for any given linear density, the cotton yarn tends to be stronger and less extensible than the woollen spun yarn, a feature that may be used to advantage when superior resistance to stretch is required. On the other hand, because of their bulk, higher flow rates may be expected in fabrics woven with woollen spun yarns (Fig. 13.23) and resistance to blinding from solid, non-compressible particles (as distinct from compressible slimes) will also be superior. Although difficult to substantiate, it is believed that this feature is related to the ease by which particles may enter and exit the bulky woollen spun structure.

In addition to particle collection efficiency, fabrics produced from woollen spun staple-fibre yarns are also characterised by their resistance to abrasive forces, such as may be found on rough, possibly chemically corroded cast iron filter plates. For this, and filtration purposes in general, the yarns are usually spun with 3.3 decitex fibres in relatively coarse linear densities, typically from 130–250 tex. Fabrics in this category are normally woven in area densities ranging from 350–800 $g\,m^{-2}$, the lighter and intermediate fabrics generally being used in pressure leaf and rotary vacuum drum filters and the heavier fabrics in filter presses.



13.22 Scanning electron micrograph showing woollen ring-spun yarn.

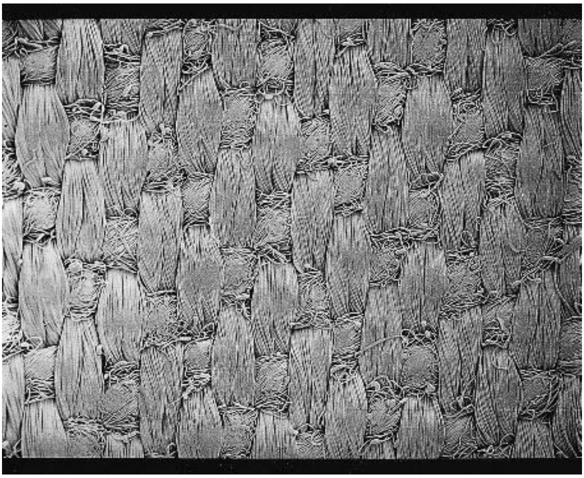


13.23 Scanning electron micrograph showing woollen ring-spun fabric.

When woven in plain weave, maximum efficiency coupled with dimensional stability are usually the key operational requirements, whereas if woven in a twill weave, greater bulk and hence greater resistance to abrasive or compressive forces are usually the dominant factors.

13.6.5 Yarn combinations

By producing fabrics with different components in warp and weft it may be possible to create a structure that utilises the best features of each. The most popular combinations in this respect comprise multifilament warp and staple-fibre weft yarns (Fig. 13.24) and monofilament warp and multifilament weft yarns. In both cases the ratio of warp to weft threads is at least 2:1 and usually considerably higher. This facilitates the production of fabrics with a smooth warp-faced surface for efficient



13.24 Scanning electron micrograph showing fabric woven with multifilament (warp) and woollen ring-spun (weft) yarns.

cake release and also higher warp tensile properties for greater resistance to stretch from the mass of heavy cakes. In the case of the multifilament and staple combination, the inclusion of a staple-fibre weft yarn provides scope for improved resistance to mechanical damage whilst maintaining a high particle collection efficiency and an acceptable throughput. Similarly, the inclusion of a multifilament weft yarn in a monofilament and multifilament fabric will lead to an improvement in filtration efficiency, especially if it is suitably texturised.

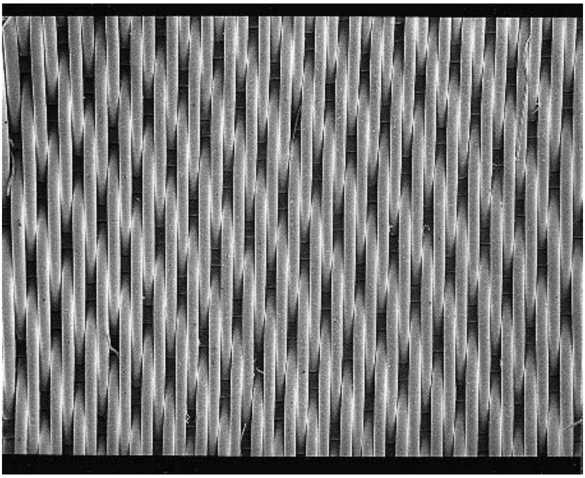
13.7 Fabric constructions and properties

13.7.1 Plain weave

This is the most basic weave of all woven structures that provides the framework for the tightest and most rigid of all single layer filter fabrics, see Fig. 13.19. Because of the sinusoidal path that the yarns follow, this weave is particularly suitable for flexible yarns of the multifilament and short staple-fibre types. The weave is also ideally suited to applications where thread displacement, due for example to high internal pressures, may otherwise be experienced.

13.7.2 Twill weaves

Usually produced in simple 2/2 or 2/1 style, twill weaves enable more weft threads per unit length to be crammed into the fabric than the preceding design (plain weave), as shown in Fig. 13.23. As a consequence, this facilitates the production of fabrics of higher area density and hence greater bulk, features which are particularly suited to woollen spun yarns. Twill weave fabrics are also marginally more flexible than plain weave fabrics, which may be advantageous when fabricating cloths of complex make up or indeed when fitting the cloths on the filter itself, for example, caulking into grooves.



13.25 Scanning electron micrograph showing satin fabric (eight-end design).

13.7.3 Satin weaves

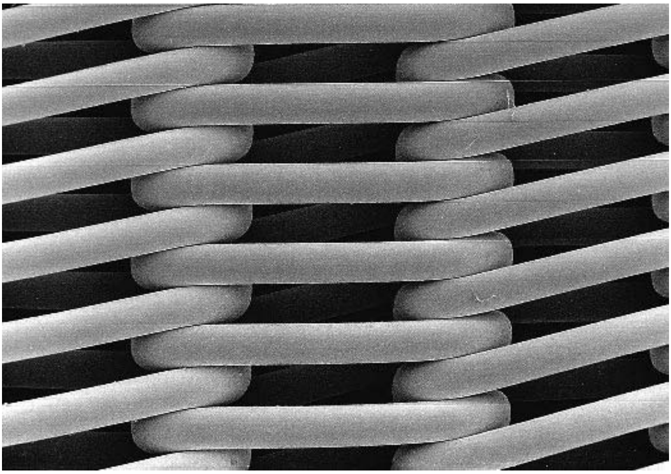
Both regular and irregular satin weaves are employed. The irregular weaves, such as the four-shaft construction, are frequently found in more densely sett high efficiency fabrics, often with two warp threads being woven as one (Fig. 13.24). Although maximum separation may be the principal requirement here, the combination of weave pattern and a double multifilament thread arrangement also creates a smooth surface for superior cake release. By comparison, the regular satin weaves such as the eight-shaft (Fig. 13.25) and 16-shaft constructions are usually employed where efficient cake release and throughput are of greater importance. From this it will be appreciated that the weaves with the longer floats are normally used in conjunction with monofilament yarns.

13.7.4 Duplex and semiduplex weaves

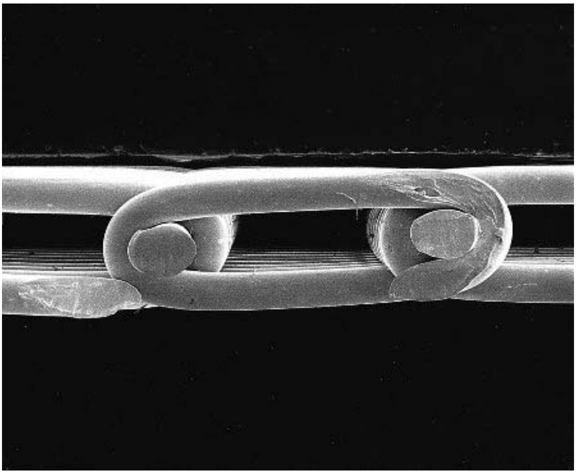
These weaves are frequently, though not exclusively, found in belt filters, either of the vacuum, continuous multiroll press, or of the vertical automatic pressure type. Owing to the interlacing pattern of the threads, it is possible to create fabrics with a measure of a solidity and stability that are ideally suited to filters of the types identified. On the debit side, the cost of weaving such high density fabrics tends to preclude their use in all but a limited number of niche applications.

13.7.5 Link fabrics

As shown in Fig. 13.26, link fabrics are produced by a novel technique in which polyester monofilaments are wound into spiral form then meshed with similar monofilaments, which are spiral wound in the opposite direction. The spirals are subsequently held together by a straight monofilament. By virtue of this form of construction it is possible to produce endless filter belts without the need for special joining techniques such as 'clipper' seams, which are often the weakest point in a filter belt.

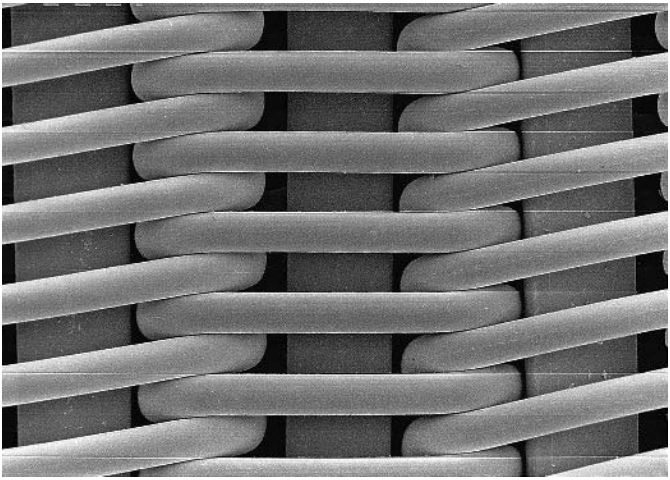


13.26 Scanning electron micrograph showing link construction from the surface (top view).

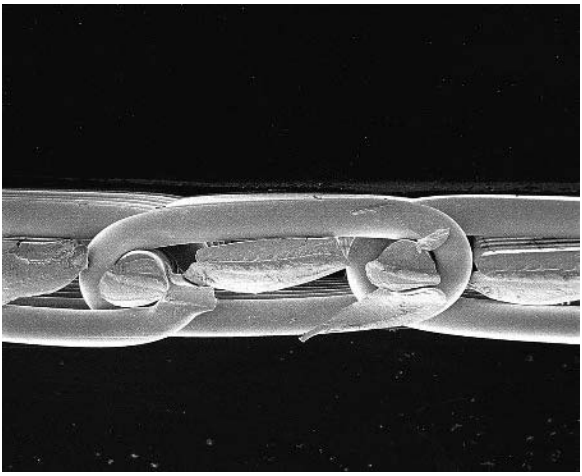


13.27 Scanning electron micrograph showing cross-section of link construction.

Because they are made from relatively coarse monofilaments of around 0.7 mm diameter, link constructions are generally of an open nature and are designed for the filtration of chemically flocculated sludges, these being relatively easy to separate but requiring efficient drainage. From the cross-sectional view (Fig. 13.27) it will also be seen that the monofilaments assume a 'race track' configuration relative to the direction of belt movement. This ensures that the wear pattern on the monofilaments is evenly distributed, that is, as distinct from certain woven fabrics where the warp threads can suffer local abrasion damage at the crown of the interlacing points between warp and weft. In the event that a more efficient link construction is required, additional monofilaments (or other threads) may be inserted as shown in Fig. 13.28 and Fig. 13.29.



13.28 Scanning electron micrograph showing link construction with filler threads from the surface (top view).



13.29 Scanning electron micrograph showing cross-section of link construction with filler threads.

These constructions, which are produced mainly with polyester monofilaments, are ideally suited to multiroll continuous pressure filters which combine both gravity and pressure filtration mechanisms. Such filters are used extensively in coal reclamation and effluent treatment operations.

13.7.6 Needlefelts

The construction of needlefelts has been described in general terms in the previous Section 13.2 on dust collection. For further reading on this subject the monograph by Purdy[14] provides an ideal introduction.

Although widely used in dust collection, needlefelts have found only limited use in liquid filtration because their thickness and density render them prone to blinding in many applications. One area where they have found some success, however, has been in the filtration of metal ore concentrates such as copper on horizontal vacuum belt filters. These applications tend to be very aggressive on the filter fabric, and hence a suitably designed and finished needlefelt is often more cost effective than a considerably more expensive woven fabric, especially if required in lengths of around 80 m and widths up to 6 m. The solids which are captured in such applications quickly form a cake on the surface and, should some penetration occur, as with woollen spun yarns, the bulky nature of the material provides scope for the particles to escape. For such arduous applications, needlefelts are generally in the area density range 800–1000 $g\,m^{-2}$.

13.8 Production equipment

13.8.1 Warping equipment

From the preceding information, it will be appreciated that in the production of woven filter fabrics, which are predominant in solid–liquid separation processes, there is a demand for a wide range of qualities. Because of this, coupled with the knowledge that the fabrics will be required in a variety of lengths and widths, the flexibility provided by section warping makes this the preferred warp preparation technique.

13.8.2 Weaving equipment

In the majority of cases, filter fabrics are woven on either flexible or rigid rapier looms, which require a smaller shed for weft insertion than more traditional shuttle looms. In this respect they generally inflict less damage on the warp sheet. Even so, because filter fabrics are frequently quite densely sett, looms with beat-up forces of the order of 15 $kN\,m^{-1}$ in reed widths up to and in excess of 4 m may be necessary to achieve the required pick spacing. High weft thread densities also demand high warp tensions and these in turn impose substantial stresses on let-off, shedding and take-up mechanisms. As a consequence, only weaving machines that are adequately reinforced in these areas will be suitable for long term performance.

By comparison, heavy duty belt filters may require fabrics up to 8 m in width. For these purposes the warps usually consist of a series of precision wound 'minibeams' or spools which, after preparation, are mounted on a common let-off shaft on the weaving machine. The latter are, of necessity, extremely robust in construction, being similar in style to equipment normally employed in paper-machine fabric manufacture.

Although weft insertion on these heavy duty machines may also be by rapier, for the wider looms insertion by conventional shuttle or projectile shuttle is more common. Furthermore, with weft insertion rates approximately 66% lower than the narrower, more conventional weaving machines, productivity is not particularly high.

13.9 Finishing treatments

Finishing treatments for fabrics employed in liquid filtration applications are designed for three basic reasons, namely (i) to ensure dimensional stability during use, (ii) to modify the surface for more efficient cake release, and (iii) to regulate the permeability of the fabric for more efficient particle collection.

13.9.1 Dimensional stability treatments

As discussed in a previous section, in the production of woven filter fabrics, both fibres and yarns are subjected to considerable stress. Although in the majority of cases the applied forces, being within the material's elastic limit, are unlikely to result in permanent deformation, they will produce a degree of stretch which, with time, will recover. The application of heat will accelerate this recovery process and, similarly, the application of heat may also induce a measure of shrinkage, which is inherent in the fibre, or filament as received. This shrinkage, be it inherent in the fibre or due to a stress recovery phenomenon, may cause several problems during use. Examples include difficulties in actually fitting the cloth on to the filter, misalignment of holes in cloth and filter and, in extreme cases, partial by-pass of the filter cloth by unfiltered slurry. These difficulties will be further aggravated if the fabric is also subjected to a hot tumble-washing programme, which may be necessary in order to rejuvenate the material following temporary blinding.

As in the production of fabrics for dust collection applications, heat is again instrumental in inducing the necessary fabric stability, which, on this occasion, may be achieved through hot aqueous treatment, heat setting or a combination of both. In the case of aqueous treatments these may also include surfactants to remove unwanted fibre and yarn processing aids. Once again media manufacturers will be aware of the machine speeds and temperatures that will be necessary in these processes to achieve the maximum effect.

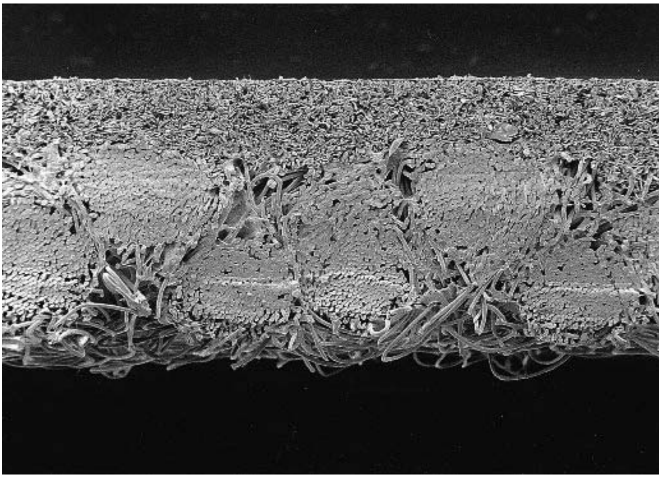
In overcoming the instability that may arise from fibre or yarn shrinkage, it is also important in liquid filtration to ensure that the material is equally stable to forces that may be applied either by the equipment itself, or indeed by the mass of the filter cake. In most cases this is achieved by selection of yarns of appropriate tenacity but, in the case of filter fabrics designed for use on belt filters, additional assistance is necessary. For such applications the fabrics are subjected to a thermal stretching operation that, in addition to increasing the fabric's initial modulus, also eradicates any tension variations that will have been introduced during yarn preparation or weaving and that may otherwise cause lateral tracking problems on the filter.

13.9.2 Surface modifications

Surface modifications include singeing, which has already been discussed in Section 13.4.2.

13.9.2.1 Special surface treatments

Although the surface of a fabric can be significantly enhanced by physical/thermal means such as singeing and calendering, the development of chemical coatings such as Madison Filter (formerly Scapa Filtration)'s Primapor (Fig. 13.30) has led to the



13.30 Scanning electron micrograph showing cross-section of Madison Filter's 'Primapor' microporous fabric.

production of still more efficient filter media. The use of stretched PTFE membranes in liquid filtration has also been reported although, it is suspected, the rather delicate nature of this material will restrict its use to niche applications.

As in dust collection, where surface coatings have been available for many years, the treatments are designed to present a microporous structure to the slurry which effectively restricts the penetration of particles to all but a few micrometres in depth. Consequently, a filter cake quickly forms on the surface of the coating and, by restricting the particles to the surface, the same cake can be easily discharged at the end of the filtration cycle. Unlike the coatings in dust collection however, the microporous structure in liquid applications has to withstand much higher pressures. Failure to do so will result in structural collapse and premature pressurisation of the filter.

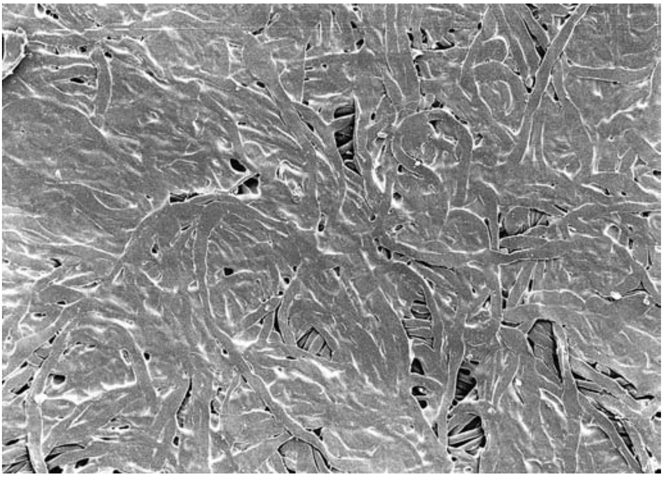
It is predicted that the future will see much more development work in this area, targeted specifically at more efficient and more durable coatings both in terms of structural stability and also resistance to chemical and abrasive agents.

13.9.3 Permeability regulation

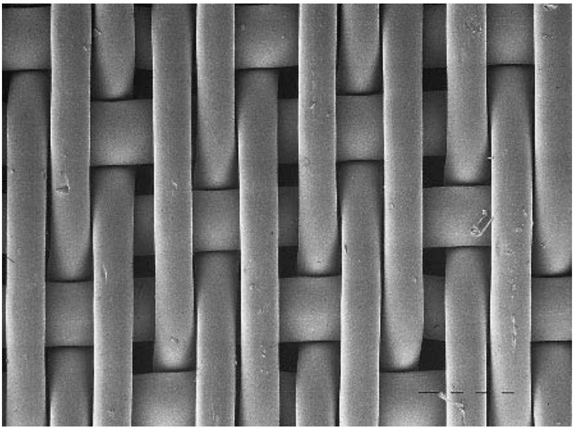
13.9.3.1 Calendering (see also Section 13.4.4)

The calendering operation is able both to modify the surface and also to regulate the fabric's permeability by means of heat and pressure. A third variable, namely the speed at which the fabric is processed, will also have a controlling influence on the effectiveness of the operation.

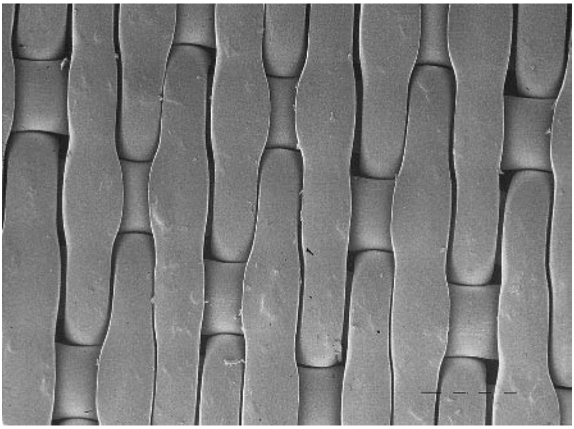
In the case of needlefelts, a reduction in pore size is achieved by compressing the fibres into a more dense structure (loads up to 300 decaN m^{-1} may be necessary) and, by selection of the appropriate conditions, a more durable (Fig. 13.31) surface can also be obtained through partial fusion of the surface fibres. With woven fabrics, on the other hand, some deformation of the yarns may be necessary to achieve the optimum filtration properties. This is particularly graphic in the case of fabrics woven from monofilament yarns as shown in Fig. 13.32 and Fig. 13.33.



13.31 Scanning electron micrograph showing needlefelt with fused fibre surface.



13.32 Scanning electron micrograph showing monofilament fabric before calendering.



13.33 Scanning electron micrograph showing monofilament fabric after calendering.

13.9.3.2 Other techniques

Using the inherent shrinkage characteristics of fibres and yarns, it is possible to effect a reduction in permeability simply by application of heat alone. This has the effect of pulling the threads closer together, thus reducing the fabric's aperture/pore size and resulting in a tighter, more efficient fabric.

Detailed information from yarn and fibre suppliers on the reaction of their products to thermal conditions will be essential, (i) in order to obtain the desired effect, and (ii) in order to ensure the necessary finishing controls.

13.10 Fabric test procedures

13.10.1 General quality control tests

These are carried out in normal textile laboratories in order (i) to ensure that the materials under test have been manufactured in accordance with design specification, and (ii) to monitor any short, medium or long term trends. Such tests are concerned primarily with area density, fabric sett, yarn types and linear densities, fabric structure, air permeability, thickness and density (principally needlefelts), tensile properties and fabric stability.

The resistance to stretch is of particular interest with respect to tensile properties. From previous sections it will be appreciated that although filter fabrics are rarely subjected to forces that will result in tensile failure, they may suffer a degree of stretch that could have serious consequences. Resistance to stretch at relatively low loads (e.g. less than 100 N per 5 cm) is therefore of particular importance from a control point of view. Furthermore, since this phenomenon is temperature related, the ability to carry out such measurements at elevated temperatures is also a useful asset.

Shrinkage tests take one of several forms depending on whether the application is wet or dry. For dust collection applications, measurement of the fabric's free shrinkage in an air circulating oven is the standard practice, the time of exposure and temperature varying according to the specific test procedure.

By comparison, because it is not uncommon in liquid filtration applications for cloths to be removed from the filter and subjected to a laundering operation, a laboratory test programme has to be devised that will reproduce the mechanically induced shrinkage generated by an industrial tumble washing machine. Such action, by virtue of the mass of cloths involved, is inevitably more severe than a domestic machine.

Although test procedures exist for measuring the liquid permeability of fabrics (e.g. by measurement of the time for a specified volume of water to pass through the fabric), either under gravity (falling column) or at a specified vacuum, it is normally more convenient to quantify the permeability of fabrics by air techniques. A typical procedure is described in DIN 53887.[10]

Whichever technique is used, it is important to remember that, although permeability results are a useful pointer in characterising the efficiency of a fabric, they must not be viewed in isolation but rather in conjunction with other fabric parameters such as thickness (needlefelts), area density and threads per unit area (fabric sett).

13.10.2 Performance-related tests

Whilst the above procedures are ideal for routine quality control purposes, they provide very little guidance about the aperture size and hence the actual efficiency of the filter fabric in dealing with particles of known size. In the case of large mesh monofilament screening fabrics, it is possible to calculate the aperture size simply by means of thread diameters and thread spacing. With much tighter constructions on the other hand an alternative approach has to be taken.

Measurement of 'equivalent pore size' by a bubble point procedure[15] is perhaps the most well known and involves immersing the fabric in a suitable wetting fluid and then measuring the air pressure that is necessary to create a bubble on the surface. The pore size can be calculated from the relationship $r = 2T \times 10^5/\sigma Pg$, where r is the pore radius (μm), T is the surface tension of the fluid ($mN\,m^{-1}$), σ is the density of water at the temperature of test ($g\,cm^{-3}$), P is the bubble pressure (mm H_2O) and $g = 981\,cm\,s^{-2}$.

An arguably more relevant approach to assessment of filtration efficiency is proposed by Barlow[16] in which a dilute suspension of flyash in glycerol is pumped through the fabric. By measuring the particle size distribution with the aid of a Coulter counter before and after passage through the fabric – and before the formation of a filter cake – a measure of its filtration efficiency can be obtained.

Information obtained from the above procedures, in combination with previous experience, will be of considerable value when selecting the appropriate fabric for a particular application.

With a small sample of slurry and a laboratory pressure vacuum leaf or piston press,[17] still further refinements can be made. (This of course presumes that the nature of the slurry will be a representative sample whose character will not change irreversibly on leaving the manufacturing plant.) From such tests speedy comparisons can be made on parameters such as throughput, filtrate clarity, cake moisture content and a subjective assessment of cake release. Note that medium/long term blinding will not normally be apparent from such procedures.

In dust collection, the number of laboratory test procedures are legion, most of these being designed to support a particular theory. A more practical procedure on the other hand is described by Barlow[16] and involves the construction of a pilot dust collector. The equipment houses four filter sleeves and is capable of operation in both reverse air and pulse cleaning modes with sufficient flexibility to change the rate of dust feed, velocity, cleaning frequency and pulse pressure. By virtue of its design construction the equipment is also capable of continuous operation for several days, if not weeks, which facilitates a better 'feel' for whether the media under test can cope with a particular situation.

A more convenient means of media comparison, whilst still retaining some of the above practical elements, is described by Anand, Lawton, Barlow and Hardman.[18] In this procedure a single sleeve of smaller size is mounted on a 'plastic cage' and located in a clear perspex cylindrical enclosure. A quantity of dust is added and this is then transformed into a cloud by means of compressed air injected at the base of the unit. The dust-laden air is drawn onto the surface of the sleeve and the subsequent pressure differential monitored by computer. Any particle emissions through the fabric are captured by an ultrafilter and measured gravimetrically. Once again the gas velocity, cleaning frequency, pulse pressure, and pulse duration can be adjusted and, by virtue of the clear Perspex cylinder, the effects of these can be visually observed.

Although both the above procedures provide useful comparative data, such information should only be used as a guide for media selection and not as a means of specifying filtration parameters or indeed actual filtration performance. Thermal and chemical conditions and the condition of the cages inside the filter, none of which can be simply reproduced in the laboratory, may well eclipse laboratory predictions.

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14

Textiles in civil engineering. Part 1 – geotextiles

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14.1 Introduction to geotextiles

Although skins, brushwood and straw–mud composites have been used to improve soft ground for many thousands of years, it is not realistic to refer to these as 'geotextiles'. The important factor that separates them from modern geotextiles is that they cannot be made with specific and consistent properties. When modern polymers were developed in the mid 20th century, it became possible to create textiles with designed forecastable performance and to produce them in large quantities with statistically consistent and repeatable properties. Once this was achieved, the science of geotextiles became possible. In essence, the difference between geotextiles and skins is their numerical or engineering capability.

In the early 1960s and 1970s, some pioneering engineers wondered if textiles could be used to control soils under difficult conditions. For example, very wet soils need draining and textiles were used to line drains, to prevent mud and silt from clogging up the drains. Similarly, engineers tried to use textiles beneath small access roads constructed over very soft wet soils. It was found that these textiles helped to increase the life and performance of roads. Also, early work was being undertaken in the laying of textiles on the coast to prevent erosion by wave action. A number of limited but historical publications were published.[1–2]

However, in those early days, it was not known exactly how these textiles performed their functions. How did they actually filter? How did a relatively weak textile apparently support heavy vehicles and improve road performance? This was a dangerous period for engineers, because it was quite possible that the experience-based employment of geotextiles could lead to their use in unsuitable constructions. It was likely that before long, an engineer would use textiles in a structure that was too large, too demanding or too stressful for the product; a significant failure could result. It was therefore vital that study and research should be undertaken to provide theories and preliminary design equations against which to test site results.

In 1977 Rankilor produced what was probably the first 'design' manual for a commercial product[3] and this was followed by a textbook written in 1980[4] which built on the extensive experience that had been amassed by this time. As is so typical of scientific development, many engineers were soon working worldwide on the development of geotextiles. Another significant textbook by Koerner and Welsh was published in 1980,[5] showing that work in the USA was at an advanced stage. The French, Japanese, Germans, Dutch and workers in other countries were equally active in the utilisation of textiles in civil engineering earthworks at that time.

During the last 20 years of the 20th century, the use of geotextiles spread geographically worldwide and in area terms their use increased almost exponentially. It is expected that their use will continue to increase into the 21st century unabated.

Once textiles were recognised as being numerically capable materials, engineers developed new types of textile and new composites to solve more difficult problems. Woven and nonwoven textiles were joined into composite products; nonwoven products were combined with plastic cores to form fin drains, and woven products were developed from stronger polymers such as polyester to extend the mechanical range of textiles and their uses in soil reinforcement. It is probable that the Dutch were the first to weave heavy steel wires into polypropylene textiles for incorporation into their major coastal land reclamation schemes. During the period 1984–85, Raz and Rankilor explored and developed the design and use of warp knitted fabrics for civil engineering ground uses.[6,7] Rankilor coined the term 'DSF' geotextiles – directionally structured fabric geotextiles; Raz specified the 'DOS' group within the main DSF range – directionally orientated structures.

Within a few years, more than six major manufacturers were producing warp knitted textiles for civil engineering earthworks. Currently, many are commercially available.

It can be considered that the 'first generation' of geotextiles were textiles that were being manufactured for other purposes (such as carpet or industrial sackings) but which were diverted and used for geotechnical purposes. The second generation of geotextiles became generated by manufacturers choosing specific textiles suitable for geotechnical purposes, but using conventional manufacturing techniques. The third generation textiles were actually designed and developed anew specifically for the purpose of geotechnical application – in particular DSF, DOS and composite products.

The development of geotextiles has always been an 'industry-led' science. Academic institutions have almost universally lagged well behind industry, with industrial designers acquiring experience at an ever-increasing rate. Currently, for example, in the USA, there are only a small number of universities teaching geotextile design as part of their main core programmes. In the UK, there are even fewer. Nonetheless, research publications from British academic institutions are of a high quality, showing specialised interests such as weathering,[8,9] filtration,[10] soil reinforcement[11,12] and computer applications.[13]

The establishment of the International Geotextile Society in 1978 led to a coordinated and coherent approach to international development of geotextile design and utilisation. The Society's four-yearly international symposium has been emulated by many other groups and countries, such that the rate of publication of papers is now very high, providing widespread exposure of developments to all interested engineers.

There are some interesting commercial aspects related to geotextiles that are specific to the industry. For example, availability must be considered in the light of the extreme size range of operations into which geotextiles are incorporated. About one-third of all geotextiles are used in small batches of three rolls or less, but a significantly large proportion are used in very large projects incorporating hundreds of thousands of square metres. Supply must therefore be available on call for one or two rolls from local stock and, simultaneously, must be available through agents or directly from the manufacturer in large quantities over a short space of time.

Delivery period is particularly onerous for textile suppliers. The majority of delivery requirements are of a standard industrial nature, but geotextile suppliers have to be able to supply large quantities within a short period for major engineering undertakings. This aspect has deterred many potential geotextile manufacturers from entering the field.

Price is also of interest, in that the cost of the polymer and manufacture can be irrelevant in certain cases. In civil engineering, a textile can be used to 'replace' a more conventional material such as sand in a granular filter. In this case, the cost of the product would be relevant and would be compared to the cost of the sand. Taken into account would be other marginal factors such as time saved in the laying of the textile as opposed to that of laying the sand. If the balance was in favour of the textile, then it might be adopted. However, in different circumstances the same textile might be worth considerably more as a sand replacement, for example, if sand were required to be placed under rapidly moving water or waves. In this case, if the textile could be placed where sand could not, then the comparison is not simply a matter of cost, but of the textile actually allowing construction to take place when the sand could not. Considerably more could be charged for a textile in these circumstances than in the former. Therefore, the cost of textiles is enhanced where they are sold and used as part of a 'system'.

Quality has to be controlled in much the same way as with other textiles – quality variation within the fabric and quality variations over time – but the implications of failure can be so much greater than with normal industrial products. If a major dam were to fail because the textile filter clogged, it would not just be a matter of apologising and replacing the filter with new product! The manufacturer does not take responsibility for the use of fabrics in the ground, but the design consultant does. He will not therefore be willing to certify the use of a textile if he is not satisfied that quality can be maintained at all levels of the process.

It is certainly necessary for modern-day geotextiles to be produced by manufacturers having ISO 9000 certification and it is ideal for this to include 9001, 9002 and 9003. The full range of these certifications covers the manufacturer's operation from raw material supplier through manufacture to storage and delivery.

14.2 Geosynthetics

In the field of civil engineering, membranes used in contact with, or within the soil, are known generically as 'geosynthetics'. This term encompasses permeable textiles, plastic grids, continuous fibres, staple fibres and impermeable membranes. Textiles were the first products in the field, extending gradually to include additional products, but have remained by far the most important of the range. Grids are formed from sheets of plastic that are punched and stretched; meshes are formed from

melted extruded polymer; neither can be categorised as textiles. Geomembranes are continuous sheets of impermeable plastic and are not textiles. The more difficult areas of the geosynthetic range to categorise are those where discrete staple fibres or continuous filament fibres are mixed directly with soil. These are polymer textile fibres and therefore, as such, are included within the definition of geotextiles.

14.2.1 Geotextile types

Geotextiles basically fall into five categories – woven, heat-bonded nonwoven, needlepunched nonwoven, knitted and by fibre/soil mixing.

Woven fabrics are made on looms which impart a regular rectilinear construction to them, but which can vary in terms of the component fibres and the weave construction. They have a surprisingly wide range of applications and they are used in lighter weight form as soil separators, filters and erosion control textiles. In heavy weights, they are used for soil reinforcement in steep embankments and vertical soil walls; the heavier weight products also tend to be used for the support of embankments built over soft soils. The beneficial property of the woven structure in terms of reinforcement, is that stress can be absorbed by the warp and weft yarns and hence by fibres, without much mechanical elongation. This gives them a relatively high modulus or stiffness.

Heat-bonded nonwoven textiles are generally made from continuous filament fine fibres that have been laid randomly onto a moving belt and passed between heated roller systems. These fabrics acquire their coherence and strength from the partial melting of fibres between the hot rollers, resulting in the formation of a relatively thin sheet of textile.

Needlepunched nonwoven fabrics are made from blended webs of continuous or staple filaments that are passed through banks of multiple reciprocating barbed needles. The fabrics derive mechanical coherence from the entangling of fibres caused by the barbs on the reciprocating needles; these fabrics thus resemble wool felts.

In the case of needlepunched textiles, considerable thicknesses (up to more than 10 mm) and weights greater than 2000 $g\,m^{-2}$ can be achieved, whereas the heat-bonding process is limited in its efficacy as thickness increases. If sufficient heat is applied to melt the internal fibres of a thick fabric adequately, then the outer fibres will tend to be overheated and overmelted. Conversely, if appropriate heat is applied to the external fibres, then insufficient heat may be applied to the centre of the sheet, resulting in inadequate bonding and potential delamination in use.

Knitted fabrics, as used in the field of geotextiles, are restricted to warp-knitted textiles, generally specially produced for the purpose. Warp-knitting machines can produce fine filter fabrics, medium meshes and large diameter soil reinforcing grids. However, it is generally found that only the high strength end of the product range is cost effective, usually for soil reinforcement and embankment support functions.

14.2.2 The main geotextile fibre-forming polymers

The two most common fibre polymers used for the manufacture of geotextiles are polypropylene and polyethylene, but polyester is almost inevitably used when high strengths are required. There are other higher strength polymers available on the market, but geotextiles have to be produced in large quantities (some polymers are not available in large volumes) and economically (specialist polymers tend to be

very expensive). On the overall balance of cost against performance, polyester is the present day optimum, while polypropylene and polyethylene vie for being the most chemically resistant.

Care must be taken when considering the properties of geotextile polymers that consideration is restricted to polymers as they are actually produced and used for geotextile manufacturing purposes; they are not in their chemically pure form. For example, raw polyethylene in its colourless translucent form is quite susceptible to light degradation. However, it is not used in this form in geotextiles, but usually contains carbon black as an ultraviolet (UV) light stabiliser. In this black form, it is arguably the most light-resistant polymer.

Also, it must be recognised that real in situ field testing of geotextile polymers is limited. Publications and authorities may quote accelerated laboratory results for xenon UV exposure, high temperature degradation testing, and similar, but these cannot take account of additional degradation factors such as biological attack, or synergistic reactions that may take place. The difficulty, therefore, arises that accelerated laboratory testing may well be pessimistic in one regard and optimistic in the other when used for ranking purposes.

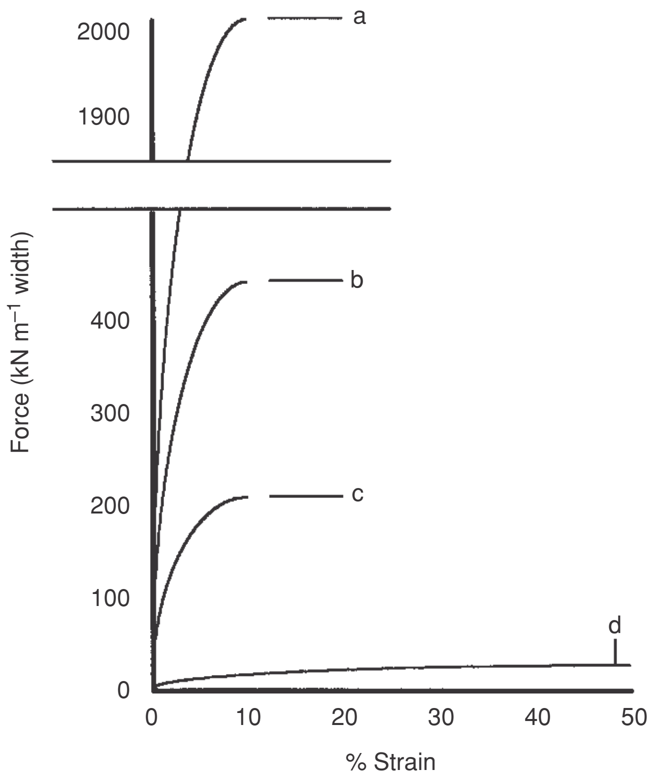
Although polyamide is a common fibre-forming and textile material, nonetheless, it is rarely used in geotextiles, where its cost and overall performance render it inferior to polyester. Some woven materials, for example, have used polyamide in the weft direction, more as a 'fill', where its properties are not critical. Its main asset is its resistance to abrasion, but it displays softening when exposed to water, which appears to have made it unpopular for geosynthetic use. Polyvinylidene chloride fibre is used in Japan and in one or two products in the United States, but not in Europe.

14.3 Essential properties of geotextiles

The three main properties which are required and specified for a geotextile are its mechanical responses, filtration ability and chemical resistance. These are the properties that produce the required working effect. They are all developed from the combination of the physical form of the polymer fibres, their textile construction and the polymer chemical characteristics. For example, the mechanical response of a geotextile will depend upon the orientation and regularity of the fibres as well as the type of polymer from which it is made. Also, the chemical resistance of a geotextile will depend upon the size of the individual component fibres in the fabric, as well as their chemical composition – fine fibres with a large specific surface area are subject to more rapid chemical attack than coarse fibres of the same polymer.

Mechanical responses include the ability of a textile to perform work in a stressed environment and its ability to resist damage in an arduous environment. Usually the stressed environment is known in advance and the textile is selected on the basis of numerical criteria to cope with the expected imposed stresses and its ability to absorb those stresses over the proposed lifetime of the structure without straining more than a predetermined amount. Figure 14.1 compares the tensile behaviours of a range of geotextiles.

On the other hand, damage can be caused on site during the construction period (e.g. accidental tracking from vehicles) or in situ during use (e.g. punching through geotextiles by overlying angular stone). Clearly, in both cases, damage is caused by



14.1 Typical ultimate stress–strain failure levels (a) of high strength and (b) of medium strength polyester woven geotextiles used for embankment support and soil reinforcement, (c) of geogrids and lower strength polyester woven geotextiles used for soil reinforcement and (d) of low strength, highly extensible nonwoven geotextiles used for separation and filtration. (c) represents the current maximum strength capacity of polyethylene geogrids.

an undesirable circumstance which is particularly difficult to remove by design. However, in the latter case, it is possible to perform advanced field testing and to allow appropriate safety factors in calculations.

The ability to perform work is fundamentally governed by the stiffness of the textile in tension and its ability to resist creep failure under any given load condition. The ability to resist damage is complex, clearly being a function of the fibre's ability to resist rupture and the construction of the fabric, which determines how stresses may be concentrated and relieved. In practical terms, geotextiles can be manufactured in a composite form, utilising the protective nature of one type of construction to reduce damage on a working element. For example, a thick nonwoven fabric may be joined to a woven fabric; the woven textile performs the tensile work whilst the nonwoven acts as a damage protective cushion.

The filtration performance of a geotextile is governed by several factors. To understand this, it is essential to be aware that the function of the textile is not truly as a filter in the literal sense. In general, filters remove particles suspended in a fluid, for example, dust filters in air-conditioning units, or water filters, which are intended to remove impurities from suspension. Quite the opposite state of affairs exists with geotextile filters. The geotextile's function is to hold intact a freshly prepared soil

Table 14.1 Recommended time periods for maximum daylight exposure of geosynthetics. Beyond the limits shown damage may occur, depending upon sunlight intensity

	Temperate	Arctic	Desert	Tropical
April to Sept	8 Weeks	4 Weeks	2 Weeks	1 Week
Oct to March	12 Weeks	6 Weeks	2 Weeks	1 Week

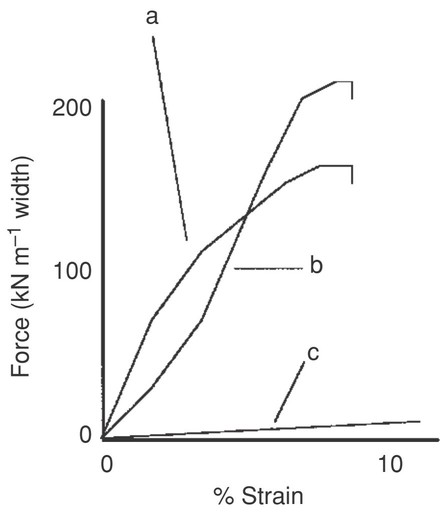
surface, so that water may exude from the soil surface and through the textile without breaking down that surface. If water is allowed to flow between the textile and the soil interface, with particles in suspension, it will tend to clog up the textile which will fail in its function. In practice, it has been found that, in conjunction with a textile, the soil will tend to filter itself, provided that the integrity of its external surface is maintained. The actual process taking place is the passage of a liquid from a solid medium that is held intact by a permeable textile. The process is not one of restraining the passage of solids that are suspended within a liquid medium.

Geotextiles are rarely called upon to resist extremely aggressive chemical environments. Particular examples of where they are, however, include their use in the basal layers of chemical effluent containers or waste disposal sites. This can happen if and when leaks occur, permitting effluent to pass through the impermeable liner, or if the textiles have been incorporated directly in the leachate disposal system above the impermeable liner. Another example might be the use of textiles in contact with highly acidic peat soils, where in tropical countries, pH values down to 2 have been encountered. In industrialised countries where infrastructure developments are being constructed through highly polluted and contaminated areas, geotextiles can also come into contact with adverse environments.

Ultraviolet light will tend to cause damage to most polymers, but the inclusion of additives, in the form of antioxidant chemicals and carbon black powder, can considerably reduce this effect. The only time when a geotextile is going to be exposed to sunlight is during the construction period. It is generally considered that contracts should specify the minimum realistic period of exposure during site installation works. However, this will vary with time of year and latitude. In brief, it can be considered that exposure in UK and northern European type climates can be eight weeks in the summer and twelve in the winter. In tropical countries, however, exposure should be limited to seven days at any time of year before noticeable damage occurs. Table 14.1 lists typical maximum exposure periods.

14.3.1 Mechanical properties

The weight or area density of the fabric is an indicator of mechanical performance only within specific groups of textiles, but not between one type of construction and another. For example, within the overall range of needlepunched continuous filament polyester fabrics, weight will correlate with tensile stiffness. However, a woven fabric with a given area density will almost certainly be much stiffer than an equivalent weight needlepunched structure. Clearly the construction controls the performance. Therefore, it is impossible to use weight alone as a criterion in specifying textiles for civil engineering use. However, in combination with other



14.2 Different stress–strain curve shapes exhibited by the three main types of geosynthetic construction. (a) Geogrids absorb the imposed stresses immediately, giving a high initial modulus. Later, the curve flattens. (b) Woven fabrics exhibit initial straightening of warp fibres which produces a low initial modulus. Later the modulus increases as the straightened polymer fibres take the stress directly. (c) Nonwovens give a curvilinear curve, because extension is primarily resisted by straightening and realignment of the random fibre directions.

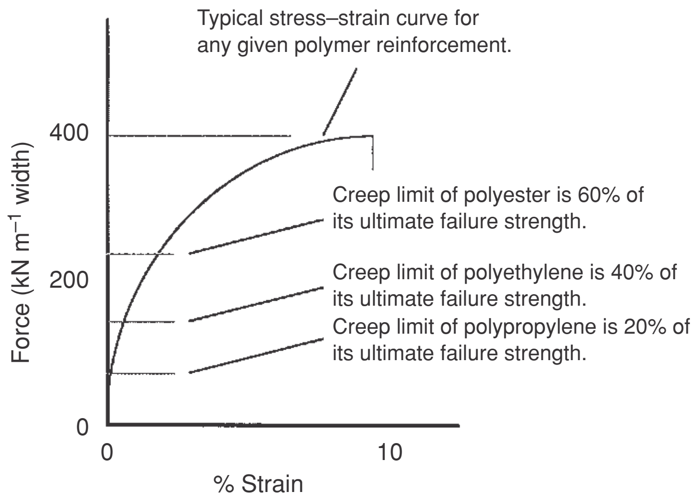
specified factors, weight is a useful indication of the kind of product required for a particular purpose.

The breaking strength of a standard width of fabric or 'ultimate strip tensile failure strength' is universally quoted in the manufacturers' literature to describe the 'strength' of their textiles. Again, this is of very limited use in terms of design. No designer actually uses the failure strength to develop a design. Rather, a strength at a given small strain level will be the design requirement. Therefore, the tensile resistance or modulus of the textile at say, 2%, 4%, and 6% strain is much more valuable. Ideally, continuous stress–strain curves should be provided for engineers, to enable them to design stress resisting structures properly.

Stress–strain curves, as shown in Fig. 14.1 and in Fig. 14.2 above, may well comprise a high strain sector, contributed by the textile structure straightening out, and a low strain sector, contributed by the straightened polymer taking the stress. Of course, the mechanical performance of the common geotextiles will be less as the ambient temperature rises. Because engineering sites are exposed to temperatures varying from –20 °C to 50 °C, this can have important consequences during installation and use.

Creep can cause the physical failure of a geotextile if it is held under too high a mechanical stress. It has been found that in practical terms, both polyester and polyethylene will stabilise against creep if stress levels can be maintained at a sufficiently low level. Although polypropylene does not seem to stabilise at any stress level, its creep rate is so low at small stresses that a 'no creep' condition may be considered to exist in practice.

The 'no creep' condition, measured as elongation, for any particular polymer



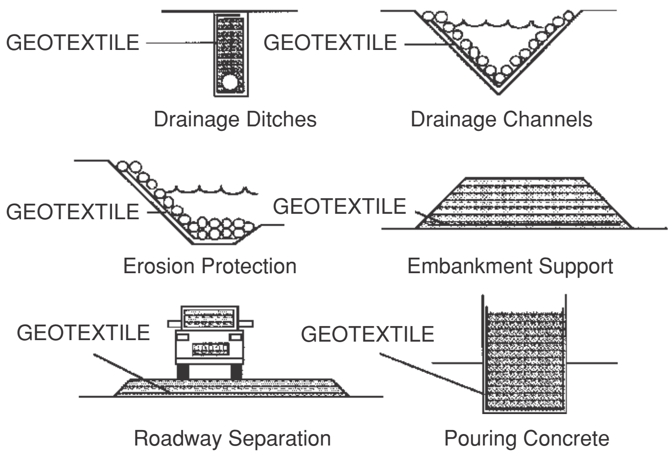
14.3 Approximate limits of creep resistance for different geosynthetic polymer constructions.

textile is defined (usually as a percentage) with respect to the textile's ultimate load-carrying capability. For polyester, it is approximately 60%, for polyethylene about 40% and for polypropylene around 20%. Therefore, for example, a polyester fabric with an ultimate tensile strength of $100\,kN\,m^{-1}$ width cannot be loaded under a long term stress of more than $60\,kN\,m^{-1}$. The higher the level of imposed stress above this point, the more rapid will be the onset of creep failure. Figure 14.3 shows the safe loading limits for most commonly used geotextiles.

Wing tear, grab tear and puncture resistance tests may be valuable because they simulate on-site damage scenarios such as boulder dropping and direct over-running by machines. These tests are developed in standard form in a number of countries, with the standard geosynthetic test specification in the UK being BS 6906 which contains tests for:

1 tensile testing by means of a wide strip test
2 pore size testing by dry sieving
3 water flow testing normal to the plane of the textile
4 puncture resistance testing
5 creep testing
6 perforation susceptibility (cone) testing
7 water flow testing in the plane of the textile
8 testing of sand/geotextile frictional behaviour.

While not normally part of the mechanical requirements of a textile, the strength of joints between sheet edges is an important aspect of geotextile performance. When laying textiles on soft ground for supporting embankments, parallel sheets of textile have to be sewn together so that they do not separate under load. The strength of such sewn joints depends critically on the tensile strength of the sewing thread. Rarely will the sewn joint exceed 30% of the weft ultimate tensile strength. Research and field practice have shown that the strength of a sewn joint depends more upon the tenacity and tension of the sewing thread, the kind of sewing stitch



14.4 Some different drainage and filtration applications for geotextiles in civil engineering.

and the kind of textile lap than the strength of the textile. An erroneous but common concept of joint 'efficiency' has developed which expresses the strength of a sewn seam as a percentage of the textile strength. In fact, relatively weak textiles can be sewn such that the joint is as strong as the textile, thus giving a 100% efficiency. The stronger the textile, the less is the relative strength of the sewn joint, leading to falling efficiencies with stronger fabrics. Thus it is reasonable to request a 75% efficient sewn joint if the textiles being joined are relatively weak, say 20 kN ultimate strength, but it would be impossible to achieve with a textile of say 600 kN ultimate strength. Unfortunately, it is the stronger textiles that tend to need to be joined, in order to support embankments and the like.

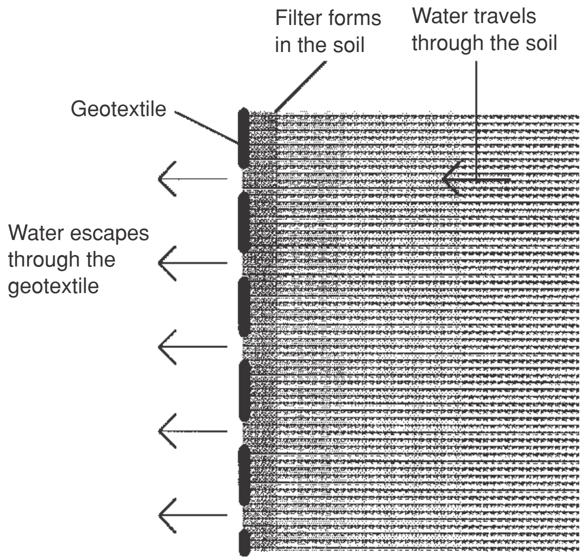
Adhesive joints, on the other hand, can be made using single-component adhesives whose setting is triggered by atmospheric moisture. These can be used to make joints which are as strong as the textile, even for high strength fabrics. Research is still needed on methods of application, but their use should become more widespread in the future.

Apart from tensile testing of joints, there is an urgent need to develop tests that give a meaningful description of the ways that textiles behave when stressed within a confining soil mass and additionally when stressed by a confining soil mass. The standard textile tests used in the past are not able to do this. Research work has been started along these lines but is so far insufficient to provide a basis for theoretical analysis.

14.3.2 Filtration properties

Filtration is one of the most important functions of textiles used in civil engineering earthworks. It is without doubt the largest application of textiles and includes their use in the lining of ditches, beneath roads, in waste disposal facilities, for building basement drainage and in many other ways (Fig. 14.4).

Of all the varied uses for geotextiles, only in a reinforced soil mass is there no beneficial filtration effect. In just about all other applications including drains, access



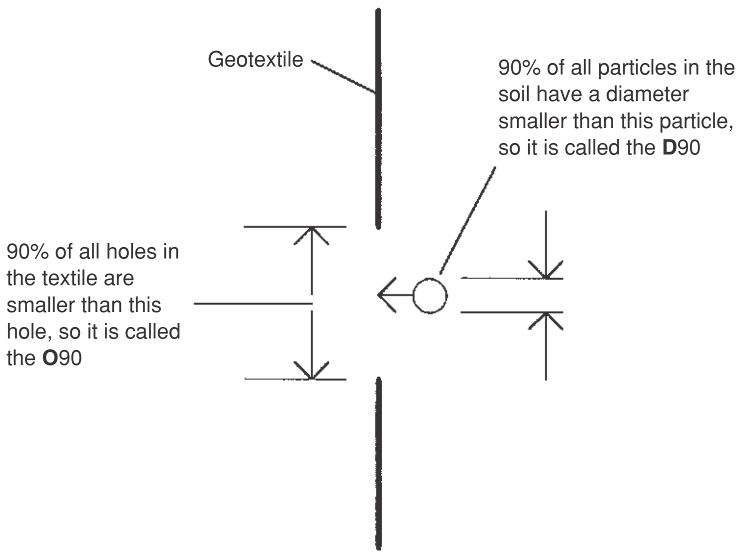
14.5 Internal soil filter zone generated by a geotextile.

roads, river defences, marine defences, embankment support and concrete pouring, the geotextile will play a primary or secondary filtering function.

The permeability of geotextiles can vary immensely, depending upon the construction of the fabric. Various national and international standards have been set up for the measurement of permeability that is required, most often at right angles to the plane of the textile (crossflow), but also along the plane of the textile (in-plane flow, called transmissivity). It is important in civil engineering earthworks that water should flow freely through the geotextile, thus preventing the build-up of unnecessary water pressure. The permeability coefficient is a number whose value describes the permeability of the material concerned, taking into account its dimension in the direction of flow; the units are rationalised in metres per second. Effectively the coefficient is a velocity, indicating the flow velocity of the water through the textile. Usually, this will be of the order of $0.001\,\mathrm{m\,s^{-1}}$. A commonly specified test measures a directly observed throughflow rate, which many feel is more practical than the permeability coefficient; this is the volume throughflow in litres per square metre per second at 100 mm head of pressure. Engineers also use a coefficient called the permittivity, which defines the theoretical permeability irrespective of the thickness of the fabric.

The filtration effect is achieved by placing the textile against the soil, in close contact, thus maintaining the physical integrity of the bare soil surface from which water is passing. Within the first few millimetres of soil, an internal filter is built up and after a short period of piping, stability should be achieved and filtration established (Fig. 14.5).

As previously discussed, filtration is normally achieved by making the soil filter itself, thus using a solid medium system, through which the liquid is flowing. There are, however, special cases where it is specifically required that the textile works in a slurry environment. Examples include tailing lagoons from mining operations and other industrial lagoons where water has to be cleared from slurries. Single textiles



14.6 Relationship between O90 and D90.

do not work well under these conditions, but experimental work has suggested that double layers of different types of textile acting as a composite unit can improve the ability of the individual components to effect filtration without clogging.

The simplest combination reported is a smooth woven textile over a thick needlepunched nonwoven fabric placed so that the former is between the needlepunched component and the slurry. It appears that the woven fabric acts as a 'shield', protecting the nonwoven from the liquid and emulating a soil surface, thus permitting the nonwoven to function more effectively as a filter. The drainage effect of the underlying nonwoven also possibly acts to induce high hydraulic gradients which, reciprocally, assist the woven to function.

The procedure for matching a textile to the soil, in order to achieve stability under difficult hydraulic conditions, is to use a textile whose largest holes are equal in diameter to the largest particles of the soil (see Fig. 14.6 where O90 = D90). Where hydraulic conditions are less demanding, the diameter of the largest textile holes can be up to five times larger than the largest soil particles (O90 = 5D90). Particularly difficult hydraulic conditions exist in the soil (i) when under wave attack, (ii) where the soil is loosely packed (low bulk density), (iii) where the soil is of uniform particle size, or (iv) where the hydraulic gradients are high. Lack of these features defines undemanding conditions. Between the two extremes lies a continuum of variation which requires the engineer to use experience and judgment in the specification of the appropriate O90 size for any given application.

The largest hole sizes and largest particle sizes are assessed by consideration of the largest elements of the fabric and soil. Measuring the largest particles of a soil is achieved by passing the soil through standard sieves. In order to assess a realistic indication of the larger particle diameters, a notional size is adopted of the sieve size through which 90% of the soil passes. This dimension is known as the D90 by convention. Similarly, an indication of the largest holes in a textile is taken as the 90% of the biggest holes in the fabric, the O90.

Even under ideal conditions, if the O90 pore size is bigger than 5D90, then so-called piping will take place. The textile O90 pore size should be reduced from 5D90 towards D90 as the ground and hydraulic conditions deteriorate.

14.3.3 Chemical resistance

Although the chemical mechanisms involved in fibre degradation are complex,[8] there are four main agents of deterioration: organic, inorganic, light exposure and time change within the textile fibres.

Organic agents include attack by micro- and macrofaunas. This is not considered to be a major source of deterioration per se. Geotextiles may be damaged secondarily by animals, but not primarily. For example, few animals will eat them specifically, but in limited instances, when the textile is buried in the ground, it may be destroyed by animals burrowing through. Microorganisms may damage the textiles by living on or within the fibres and producing detrimental by-products. Possibly the most demanding environment for geotextiles is in the surf zone of the sea where oxygenated water permits the breeding of micro- and macroorganisms and where moving water provides a demanding physical stress.

Inorganic attack is generally restricted to extreme pH environments. Under most practical conditions, geotextile polymers are effectively inert. There are particular instances, such as polyester being attacked by pH levels greater than 11 (e.g. the byproducts of setting cement), but these are rare and identifiable.

Geotextiles can fail in their filtration function by virtue of organisms multiplying and blocking the pores, or by chemical precipitation from saturated mineral waters blocking the pores. In particular, water egressing from old mine workings can be heavily saturated with iron oxide which can rapidly block filters, whether textile or granular.

Ultraviolet light will deteriorate geotextile fibres if exposed for significant periods of time, but laboratory testing has shown that fibres will deteriorate on their own with time, even if stored under dry dark cool conditions in a laboratory. Therefore, time itself is a damaging agent as a consequence of ambient temperature and thermal degradation, which will deteriorate a geotextile by an unknown amount.

14.4 Conclusions

Geotextiles are part of a wider group of civil engineering membranes called geosynthetics. They are extremely diverse in their construction and appearance. However, they are generally made from a limited number of polymers (polypropylene, polyethylene and polyester), and are mostly of five basic types: woven, heat-bonded, needlepunched, knitted and direct soil mixed fibres.

The physical properties of this diverse group of products vary accordingly, with ultimate strengths reaching up to 2000 $kN\,m^{-1}$, but commonly between 10 and 200 $kN\,m^{-1}$. Ultimate strains vary up to more than 100%, but the usable range for engineers is generally between 3 and 10%. Similarly, the filtration potential and permeability of different geotextiles vary enormously.

Geotextiles are used in civil engineering earthworks to reinforce vertical and steep banks of soil, to construct firm bases for temporary and permanent roads and highways, to line ground drains, so that the soil filters itself and prevents soil from

filling up the drainpipes and to prevent erosion behind rock and stone facing on river banks and the coast. They have been developed since the mid 1970s, but the advent of knitted and composite fabrics has led to a revival in attempts to improve textile construction in a designed fashion. Better physical properties can be achieved by using more than one fabric and by utilising the best features of each.

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14

Textiles in civil engineering. Part 2 – natural fibre geotextiles

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14.5 Introduction

Processes for the selection, specification, production and utilisation of synthetic geotextiles are well established in developed countries. In many ground engineering situations, for example temporary haul roads, basal reinforcement, consolidation drains, and so on, geotextiles are only required to function for a limited time period whereas suitable synthetic materials often have a long life. Hence, the user is paying for something which is surplus to requirement. Also, conventional geotextiles are usually prohibitively expensive for developing countries. However, many of these countries have copious supplies of cheap indigenous vegetable fibres (such as jute, sisal and coir) and textile industries capable of replicating common geotextile forms. Although, there are numerous animal and mineral natural fibres available, these lack the required properties essential for geotextiles, particularly when the emphasis of use is on reinforcing geotextiles.

Synthetic geotextiles not only are alien to the ground, but have other adverse problems associated with them, in that some synthetic products are made from petroleum-based solutions. As a result of the finite nature of oil, the oil crisis in 1973, the conflict with Kuwait and Iraq in 1991, and the potentially political volatile state of some of the world's other oil producing countries, both the cost and the public awareness of using oil-based products have considerably increased. Natural fibre products of vegetable origin will be much more environmentally friendly than their synthetic equivalents and the fibres themselves are a renewable resource and biodegradable.

14.6 Development of natural materials as geotextiles

The exploitation of natural fibres in construction can be traced back to the 5th and 4th millennia BC as described in the Bible (Exodus 5, v 6–9) wherein dwellings were

14.7 Woven mat and plaited rope reeds used as reinforcement in the Ziggurat at Dur Kurigatzu.

formed from mud/clay bricks reinforced with reeds or straw. Two of the earliest surviving examples of material strengthening by natural fibres are the ziggurat in the ancient city of Dur-Kurigatzu (now known as Agar-Quf) and the Great Wall of China.[1] The Babylonians 3000 years ago constructed this ziggurat using reeds in the form of woven mats and plaited ropes as reinforcement (Fig. 14.7). The Great Wall of China, completed circa 200 BC, utilised tamarisk branches to reinforce mixtures of clay and gravel.[1,2] These types of construction however, are more comparable to reinforced concrete than today's reinforced earth techniques, because of the rigid way in which stress was transferred to the tensile elements and the 'cemented' nature of the fill.

Preconceived ideas over the low apparent tensile strength of natural materials and the perception that they have a short working life when in contact with soil limited their uses, especially for strengthening soil, in geotechnical engineering at this early stage. Also, the lack of reliable methods of joining individual textile components to form tensile fabrics presented a major limitation to their usage.

The first use of a textile fabric structure for geotechnical engineering was in 1926, when the Highways Department in South Carolina USA[3] undertook a series of tests using woven cotton fabrics as a simple type of geotextile/geomembrane, to help reduce cracking, ravelling and failures in roads construction. The basic system of construction was to place the cotton fabric on the previously primed earth base and to cover it with hot asphalt; this however made the fabric perform more like a geomembrane than a geotextile. Although published results were favourable, especially for a fabric that had been in service for nine years, further widescale development of this fabric as a geotextile did not take place. This was probably due to the high extensibility and degradable nature of this particular natural fibre together with the advent of chemical fibres.

The earliest example of jute woven fabric geotextiles for subgrade support was in the construction of a highway in Aberdeen in the 1930s.[4] The British Army also

used a special machine to lay canvas or fascines over beaches and dunes for the invasion of Normandy in 1944.[5]

For thousands of years the textile industry has been spinning fibres to make yarns which in turn can be woven into fabrics. Up until the mid 1930s, these fibres were all naturally occurring, either vegetable or animal. At the beginning of this century the use of natural polymers based on cellulose was discovered, and this was quickly followed by production of chemical or synthetic products made from petroleum-based solutions.

The use of chemical fibre-based geotextiles in ground engineering started to develop in the late 1950s, the earliest two references being (i) a permeable woven fabric employed underneath concrete block revetments for erosion control in Florida[6] and (ii) in the Netherlands in 1956, where Dutch engineers commenced testing geotextiles formed from hand-woven nylon strips, for the 'Delta Works Scheme'.[7]

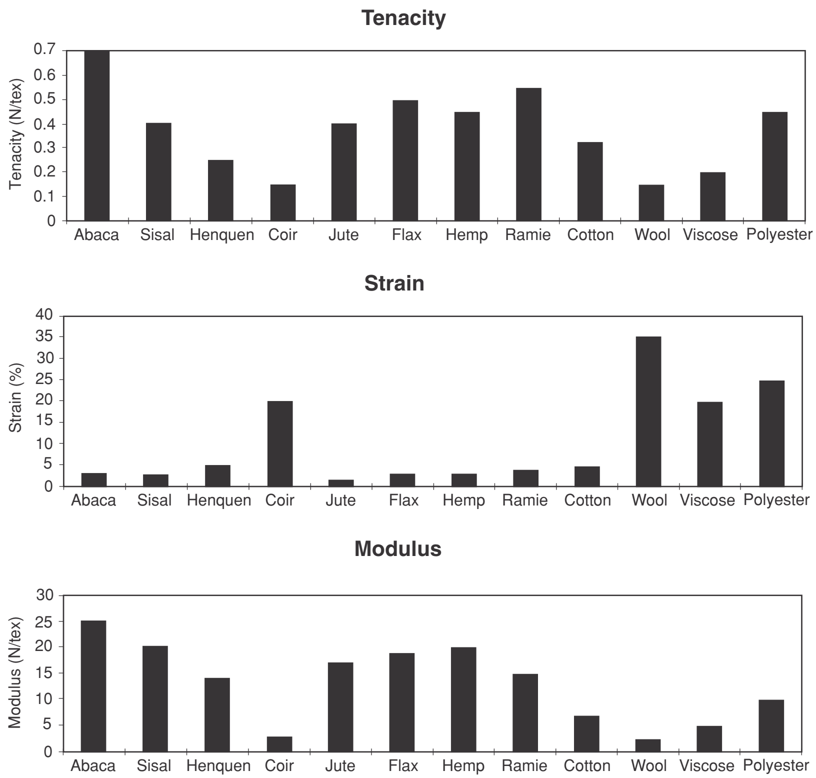
In the early 1960s, the excess capacity of synthetic products caused the manufacturers to develop additional outlets such as synthetic geotextiles for the construction industry. The manufacturers refined their products to suit the requirements of the engineer, rather than the engineer using the available materials to perform the requisite functions, because to a certain extent, fibre fineness and cross-sectional area can be modified to determine satisfactory tensile properties in terms of modulus, work of rupture, creep, relaxation, breaking force and extension. This led to the prolific production of synthetic materials for use in the geotextile industry. These synthetic geotextiles have monopolised the market irrespective of the cost both in economical and ecological terms. This put severe pressure on the manufacturers of ropes and cordage made from natural fibres, almost to the point of their extinction. In 1973, three fundamental applications were identified for the use of geotextiles, namely, reinforcement, separation and filtration,[8] with drainage applications (fluid transmission) also being a significant area. During the 1990s over 800 million m^2 of synthetic geotextiles have been produced worldwide,[9] making it the largest and fastest growing market in the industrial/technical fabrics industry.[10]

Although natural fibres have always been available, no one visualised their potential as a form of geotextile until synthetic fibres enabled diverse use and applications of geotextiles to emerge. Manufacturers are now attempting to produce synthetic fibres which will mimic the properties of natural fibres, but at a greater expense.

14.7 Natural fibres

The general properties of chemical fibres compared to natural fibres still tend to fall into distinct categories. Natural fibres possess high strength, modulus and moisture uptake and low elongation and elasticity. Regenerated cellulose fibres have low strength and modulus, high elongation and moisture uptake and poor elasticity. Synthetic fibres have high strength, modulus and elongation with a reasonable amount of elasticity and relatively low moisture uptake.

Natural fibres can be of vegetable, animal or mineral origin. Vegetable fibres have the greatest potential for use in geotextiles because of their superior engineering properties, for example animal fibres have a lower strength and modulus and higher



14.8 Typical strength, elongation and modulus values of natural fibres relative to those of synthetic fibres.

elongation than vegetable fibres. Mineral fibres are very expensive, brittle and lack strength and flexibility. Figure 14.8 shows typical strength, elongation and modulus values of natural fibres relative to those of synthetic fibres.

The pertinent factor for a geotextile, especially for reinforcement, is that it must possess a high tensile strength. It is known that the best way of obtaining this criterion is in the form of fibres which have a high ratio of molecular orientation. This is achieved naturally by vegetable fibres, but for synthetic polymers the molecules have to be artificially orientated by a process known as stretching or drawing, thus an increase in price is incurred. Hence nature provides ideal fibres to be used in geotextiles. In strength terms vegetable fibres compare very well with chemical fibres, in that the tenacity for cotton is in the region of $0.35\,\mathrm{N\,tex^{-1}}$ and for flax, abaca and sisal it is between $0.4–0.6\,\mathrm{N\,tex^{-1}}$ when dry, increasing when wet to the strength of high tenacity chemical fibres – the tenacity of ordinary chemical fibres is around $0.4\,\mathrm{N\,tex^{-1}}$ (polyester). The Institute Textile de France showed (prior to 1988) that individual flax fibres (separated from their stems within the laboratory, using a process that does not weaken them) have a strength of $2 \times 10^6\,\mathrm{kN\,m^{-1}}$ and modulus of $80 \times 10^6\,\mathrm{kN\,m^{-1}}$, that is, of the same order as Kevlar,[11] a chemically modified polyamide, with exceptionally high strength compared to other synthetic fibres.

Natural fibre plants may be cultivated mainly for their fibre end-use (e.g. jute, sisal and abaca), but vegetable fibres are often a byproduct of food/crop produc-

tion. Flax fibre can be extracted from the linseed plant. Also, hemp fibre is extracted for paper pulp or textile use whilst the soft inner core of the stem is used for livestock bedding. The cultivation of flax and hemp fibre allows farmers to grow the fibre crops on set-aside land (land out of food production as part of a European Union policy to decrease surpluses) which would otherwise be standing idle.

Nature provides plants with bundles of fibres interconnected together by natural gums and resins to form a load-bearing infrastructure. These fibres are pliable, have good resistance to damage by abrasion and can resist both heat and sunlight to a much greater extent than most synthetic fibres. Some fibres can also withstand the hostile nature of the marine environment. However, all natural fibres will biodegrade in the long term as a result of the action of the microorganisms. In certain situations this biodegradation may be advantageous.

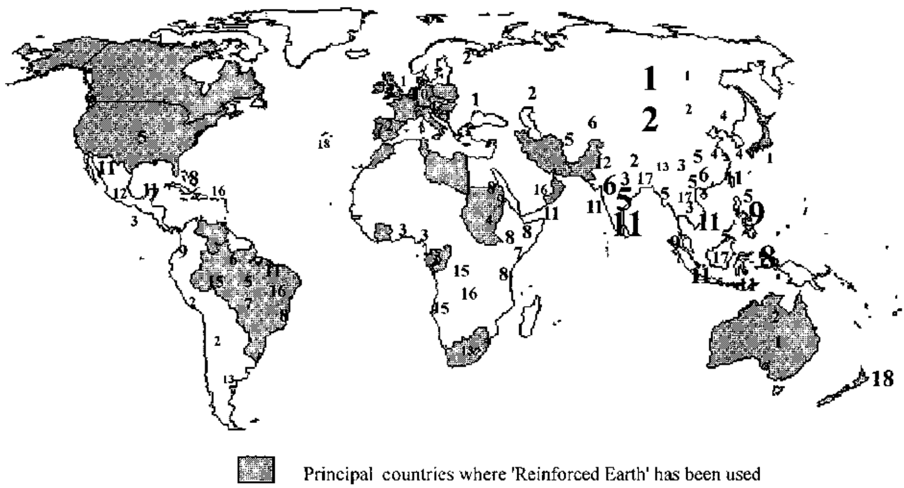
Vegetable fibres contain a basic constituent, cellulose, which has the elements of an empirical formula $(C_6H_{10}O_5)_n$. They can be classed morphologically, that is according to the part of the plant from which they are obtained:

1 *Bast* or *phloem fibres* (often designated as soft fibres) are enclosed in the inner bast tissue or bark of the stem of the dicotyledonous plants, helping to hold the plant erect. Retting is employed to free the fibres from the cellular and woody tissues, i.e. the plant stalks are rotted away from the fibres. Examples of the most common of these are flax, hemp and jute.
2 *Leaf fibres* (often designated as hard fibres) run hawser-like within the leaves of monocotyledonous plants. These fibres are part of the fibrovascular system of the leaves. The fibres are extracted by scraping the pulp from the fibres with a knife either manually or mechanically. Examples of these are abaca and sisal.
3 *Seed and fruit fibres* are produced by the plant, not to give structural support, but to serve as protection for the seed and fruit that are the most vulnerable parts of the plant normally attacked by predators. Examples of these are coir and cotton. With coir fibre, the coconut is dehusked then retted, enabling the fibre to be extracted.

A natural fibre normally has a small cross-sectional area, but has a long length. This length is naturally formed by shorter fibres (often referred to as the cell length) joined together by a natural substance, such as gum or resin (the exception to this is the fibre from the seeds of the plant, vis-à-vis cotton and kapok where the length of the fibre is the ultimate fibre length).

Of the 1000 to 2000 fibre-yielding plants throughout the world,[12] there are some 15–25 plants that satisfy the criteria for commercial fibre exploitation although a number of these are only farmed on a small scale. These main fibres are flax, hemp, jute, kenaf, nettle, ramie, roselle, sunn, urena (bast fibres) abaca, banana, cantala, date palm, henequen, New Zealand flax, pineapple, sisal, (leaf fibre) coir, cotton and kapok (seed/fruit fibres). Figure 14.9 indicates the principal centres of fibre production. The main factors affecting the production/extraction of vegetable fibres are:

1 The quantity of the fibre yield from the plant must be adequate to make fibre extraction a viable proposition.
2 There must be a practical and economical procedure for extracting the fibres, without causing damage to them, if they are to be of any value as a textile material.



14.9 Principal centres of fibre production. 1 Flax, 2 hemp, 3 sunn, 4 ramie, 5 jute, 6 kenaf, 7 roselle, 8 sisal, 9 abaca, 10 nettle, 11 coir, 12 cantala, 13 henequen, 14 kapok, 15 urena, 16 pineapple, 17 banana, 18 New Zealand flax. The size of the numbers indicates the most important countries for the production of fibre.

3 The pertinent properties of the fibre must be equivalent or superior to the existing chemical fibres used for the same given purpose in terms of both end production and machinability.
4 The annual yield of the fibre must be 'repeatable' and sufficiently large, i.e. if a plant has a high yield of fibre, say only every five years, then its marketability declines. Consideration must also be given to the time of harvest, i.e. late harvest yields lower quality fibres.
5 Whether there is a demand for the fibre properties on the market.
6 If there are problems of plant diseases and insect attack – protection from which has seen major improvements in the 20th century.

Advantages of developing such indigenous geotextiles would be:

- robust fibre
- environmental friendliness
- low unit cost
- strength/durability of some natural fibres, which are superior to chemical products
- reinforcing material is on the doorstep of developing countries
- increase in demand for the grower, therefore more money entering the country
- good drapability
- biodegradability
- additional use of byproducts or new use for waste.

14.7.1 Vegetable fibre properties

When selecting the most suitable vegetable fibres for geotextiles, consideration must be given to the general properties of available natural fibres in terms of strength,

elongation, flexibility, durability, availability, variability and their production forms, from the civil engineering and textile aspects. Also, factors affecting the economics of fibre cultivation and extraction on a large commercial scale should be taken into account. Allowing for the above factors, six vegetable fibres have been selected as the most promising to form geotextiles: flax, hemp, jute, abaca, sisal and coir (not in the order of priority). A generalised description of these plants/fibres is given in Tables 14.2 to 14.7, with typical values of their physical, mechanical, chemical and morphological characteristics shown in Tables 14.8 to 14.11.

Hemp and flax can be cultivated in the climatic conditions experienced in temperate countries such as the UK. Hemp does not require any pesticide treatment whilst growing. Both hemp and flax are very similar types of plant and are grown/cultivated in virtually identical conditions, producing almost similar properties in terms of fibre. However, hemp requires a licence from the Home Office for its cultivation, which imposes disadvantages compared to flax. Jute has emerged from its infancy in geotechnical engineering and has found a potential market in the erosion control industry, but may lack durability for other end-uses.

Strength properties of abaca may be superior to those of sisal, but the overall properties/economics of sisal may just outweigh those of abaca, that is, abaca is only cultivated in two countries throughout the world, with a production of less than one-fifth of sisal fibre. However, with leaf fibres retting has to be conducted within 48 hours of harvesting because otherwise the plant juices become gummy, and therefore fibre extraction is more difficult and unclean fibre is produced.

In certain categories, coir does not perform to the same standards as other fibres (i.e. low strength and high elongation), but general factors related to coir overshadow most of the other fibres for specific applications. The energy required to break the coir fibres is by far the highest of all the vegetable fibres, indicating its ability to withstand sudden shocks/pulls. Also, it is one of the best fibres in terms of retention of strength properties and biodegradation rates (in both water and sea water).

Further prioritisation of these six vegetable fibres will ultimately depend on the utilisation/end application of the geotextile.

14.8 Applications for natural geotextiles

The use of geotextiles for short-term/temporary applications to strengthen soil has a particular niche in geotechnical engineering. Geotextiles are used extensively in developed countries to combat numerous geotechnical engineering problems safely, efficiently and economically. They have several functions which can be performed individually or simultaneously, but this versatility relies upon the structure, physical, mechanical and hydraulic properties of the geotextile. Details of the general properties required to perform the functions of the geotextiles for various applications are given in Table 14.12.

14.8.1 Soil reinforcement

Soil is comparatively strong in compression, but very weak in tension. Therefore, if a tensile inclusion (geotextile) is added to the soil and forms intimate contact with it, a composite material can be formed which has superior engineering

Table 14.2 General description of flax plant/fibre

Fibre names and family	Flax	(Liniaceae)
Genus and species	*Linum usitatissimum*	(Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 16–32 mm, stem length 0.9–1.2 m. Harvested after 90 days of growth when stems are green-yellow. 30 bundles of fibre in stem, each bundle contains 10–14 individual (ultimate) fibres. Low input crop fits well on a rotation scheme (6–7 years)[13]	
Countries of cultivation	Russia (80%), China, Egypt, Turkey, Philippines, Malaysia, Sri Lanka, Japan, New Zealand, UK, Poland, France, Belgium, Netherlands, USA, Canada, Argentina, West Indies, Japan and Taiwan	
Environmental – climate requirements	90% of the world's production is grown between 49° to 53°N, but can be cultivated between 22° to 65°N and 30° to 45°S	
Soil type	Rich deep loams, slightly acidic[13]	
Components of yield	One quarter of stem consists of fibre. Stem is pulled out of ground not cut, therefore longer fibres are obtained. 5–7 tonnes of flax per hectare, of which 15–20% can be extracted as long fibre, 8–10% as short fibre or tow, 5–10% seed, 45–50% woody core or shives.[13] There has been little flax produced in the UK because until recently there was no processing industry, however there is now an EC subsidy for seed flax to produce linseed oil[13]	
Uses	Linen, twines, ropes fishing nets, bags, canvas & tents. Tow fibre; high grade paper, i.e. cigarette paper and banknotes. Linseed oil and linseed flax fibre	
World annual production (tonnes)	830 000[14] 3rd most important fibre in terms of cash and acreage. Ranks 4th for the total fibre production (1st cotton, 2nd jute, 3rd kenaf)	
£ per tonne	Long line 800–2000, tow 300–700[15]	
Fibre extraction – retting	Retting affects the colour, 85% by dew retting (3–7 wks) fibre grey in colour, producing cheaper better fibre by less labour intensive way than dam, tank and chemical retting. After retting, fibre is broken away from the stems and combed	
Effects from water, sea water, pests, etc.	Fibre strength increases when wet. Pests; flea, beetles and thrips, however in general flax is not very vulnerable[13]	
Cross-section bundles	Roundish elongated irregular[16]	
Ultimate fibre	Nodes at many points, cell wall thick and polygonal in cross-section. Cell long and transparent	
Longitudinal view	Cross-marking nodes and fissures[16]	
Fibre cell ends	Ends taper to a point or round[17]	
Properties compared to other fibres	Physical and chemical properties are superior to cotton	
General fibre detail, colour, etc.	Yellowish-white, soft and lustrous in appearance. High degree of rigidity and resists bending. Russian flax weak but very fine	
General	Inextensible fibre, more elongation obtained when dry. One of the highest tensile strength and modulus of elasticity of the natural vegetable fibres. Density same as polymers, thus used as alternative reinforcement to glass, aramid and carbon in composites. Good conductor of heat and can be cottonised	

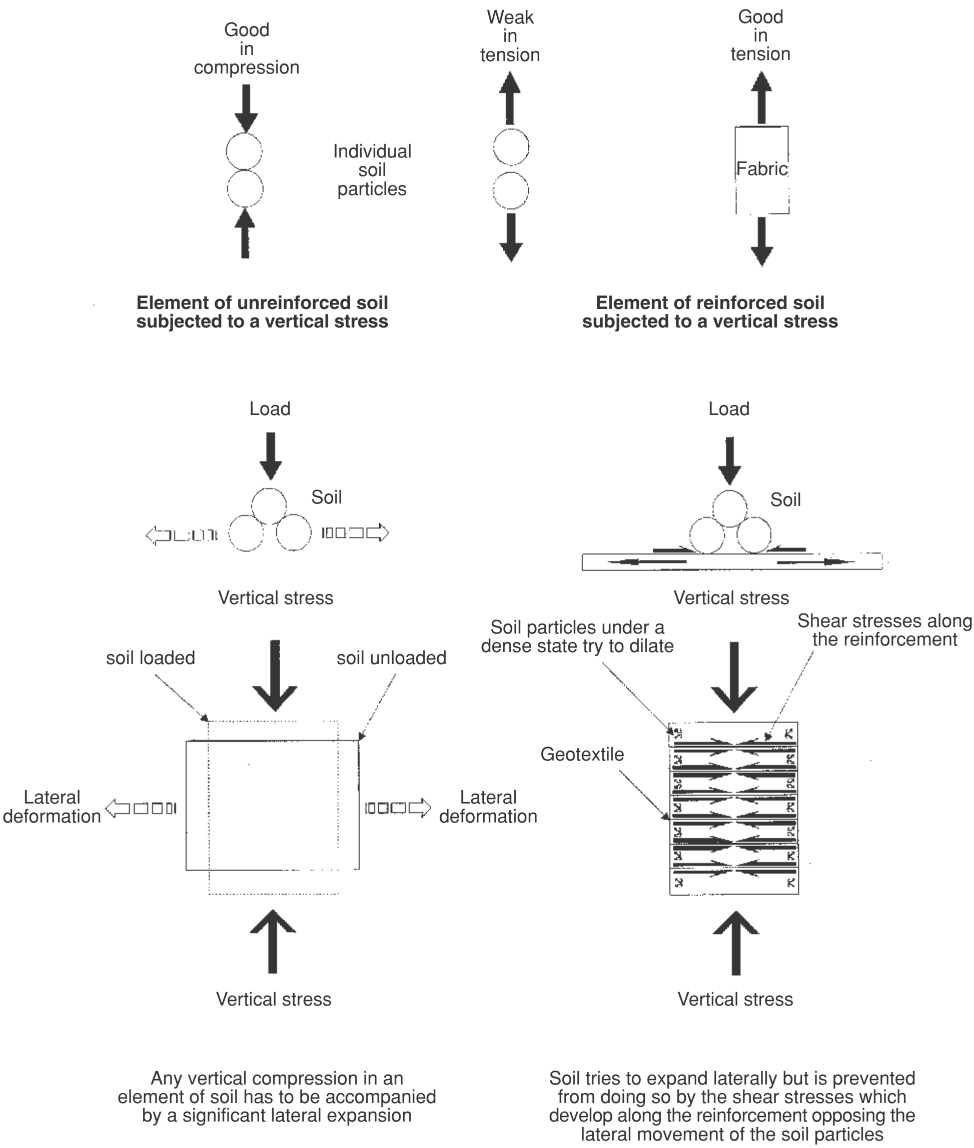
Table 14.3 Generalised description of hemp plant/fibre

Fibre names and family	Hemp	(Moraceae)
Genus and species	*Cannabis sativa*	(Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 4–20 mm, stem length 4.5–5 m. Harvested after 90 days	
Countries of cultivation	Russia, Italy, China, Yugoslavia, Romania, Hungry, Poland, France, Netherlands, UK and Australia	
Environmental – climate requirements	Annual rainfall >700 mm mild climate with high humidity	
Soil type	Best results from deep, medium heavy loams well-drained and high in organic matter. Poor results from mucky or peat soils and should not be grown on the same soil yearly	
Components of yield	Not hard to grow. Hemcore Ltd in 1994 grew 2000 acreage in East Anglia	
Uses	Ropes, marine cordage, ships sails, carpets, rugs, paper, livestock bedding and drugs	
World annual production (tonnes)	214 000[14] Ranks 6th in importance of vegetable fibre	
£ per tonne	300–500[15]	
Fibre extraction – retting	Same process as flax, at 15–20°C retting takes 10 to 15 days. Separation of the fibre from the straw can be carried out mechanically; this is commercially known as green hemp	
Effects from water, sea water, pests, etc.	Not weakened or quickly rotted by water or salt water. No pesticide protection required for growth	
Cross-section bundles	Similar to flax[16]	
Ultimate fibre	Similar to flax, polygonal in cross-section	
Longitudinal view	Similar to flax[16]	
Fibre cell ends	Rounded tips, ends of cell are blunt	
Properties compared to other fibres	Stronger, more durable, stiffer and more rigid and coarser than most vegetable fibres	
General fibre detail, colour, etc.	Harsh, stiff and strong fine white lustrous and brittle. Suitable for weaving of coarse fabric	
General	30 varieties, narcotic drug terrahydrocannabinol (THC), in some countries cultivation illegal (cultivated now <0.3% THC thus no narcotic value). Lacks flexibility and elasticity, i.e. brittle fibre. One hectare of hemp produces as much pulp as 4 acres of forest. Can be cottonised, i.e. up to 50% hemp, does not spin easily but produces useful yarns	

characteristics to soil alone. Load on the soil produces expansion. Thus, under load at the interface between the soil and reinforcement (assuming no slippage occurs, i.e. there is sufficient shear strength at the soil/fabric interface) these two materials must experience the same extension, producing a tensile load in each of the reinforcing elements that in turn is redistributed in the soil as an internal confining stress. Thus the reinforcement acts to prevent lateral movement because of the lateral shear stress developed (Fig. 14.10). Hence, there is an inbuilt additional lateral confining stress that prevents displacement. This method of reinforcing the soil can be extended to slopes and embankment stabilisation. The following exam-

Table 14.4 Generalised description of jute plant/fibre

Fibre names and family	Jute (Tiliaceae)
Genus and species	*Corchorus capsularus* and *Corchorus olitorius* (Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 20 mm, stem length 2.5–3.5 m. Harvested after 90 days, small pod stage best fibre yield
Countries of cultivation	India, Bangladesh, China, Thailand, Nepal, Indonesia, Burma, Brazil, Vietnam, Taiwan, Africa, Asia and Central and South America
Environmental – climate requirements	Annual rainfall >1800 mm required >500 mm during the growing season, high humidity between 70–90%, temperature between 70–100 °F, i.e. hot damp climates
Soil type	Rich loam soils produce best results, well-drained soils obtain reasonable results, with rocky – sandy soils producing poor results
Components of yield	Easily cultivated and harvested. Line sowing increases yield by 25–50% and reduces cost of cultivation by 25%
Uses	Ropes, bags, sacks, cloths. Erosion control applications; geojute, soil-saver, anti-wash, etc.
World annual production (tonnes)	2 300 000[14] 2nd most important fibre in terms of cash and acreage
£ per tonne	300–500[15]
Fibre extraction – retting	Same process as flax. Late harvest requires prolonged retting. 1–5% oil & water emulsion is added to soften the fibre for spinning into yarns
Effects from water, sea water, pests, etc.	Fibre deteriorates rapidly when exposed to moisture. Plant; damage by excessive: heat, drought, rainfall and floods. Pests; semilooper, mite, hairy, caterpillar and apion
Cross-section bundles	Varying size roundish or elongated[16]
Ultimate fibre	Sharply polygonal, rounded (5–6 sides) corners; wall thickness varies
Longitudinal view	Fissures and cross marking are unlikely. Lumen varies in size along each fibre
Fibre cell ends	Round tips partly pointed and tapered
Properties compared to other fibres	Not as strong as hemp and flax nor as durable
General fibre detail, colour, etc.	White, yellow, red or grey; silt like and easy to spin. Difficult to bleach and can never be made pure white owing to its lack of strength. If kept dry will last indefinitely, if not will deteriorate in time
General	Holds 5 times its weight of water. Cheap and used in great quantities, high initial modulus, but very little recoverable/ elasticity (woody fibre); exhibiting brittle fracture, having small extension at break. Poor tensile strength, good luster (silky), high lignin content. Individual fibres vary greatly in strength owing to irregularities in the thickness of the cell wall



14.10 Principle of reinforced earth.

ples illustrate typical applications where geotextiles are employed to strengthen soil for a limited amount of time.

14.8.1.1 Long-term embankments

Many developing countries have engineering situations where geotextiles could be employed to great benefit, for example hillside stabilisation, embankment and flood bank strengthening and construction over soft ground. Such countries often have copious, renewable supplies of natural fibres. Labour is also abundant in these developing countries, therefore it is more desirable to construct inexpensive short-term projects, monitor and assess their stability periodically and rebuild them

Table 14.5 Generalised description of abaca plant/fibre

Fibre names and family	Abaca or Manila hemp	(Musaceace)
Genus and species	*Musa textilis*	(leaf fibre)
Plant type – harvesting	Perennial plant, 12–30 stems per plant, leaves 2–4 m, stem diameter 130–300 mm, stems length 7.5 m. Stem contains 90% water/sap with 2–5% fibre the rest soft cellular tissue. Plant life 10–20 years without replanting, fertilisation or rotation, thus impoverishes the soil. Productivity life 7–8 years, harvest 3 stalks every 4–5 months	
Countries of cultivation	Philippines (85%) & Ecuador (15%)	
Environmental – climate requirements	Warm climate, shade, abundant moisture and good drainage. Altitude <900 m heavy rainfall (2500–3000 mm per year) uniformly distributed throughout the year and high humidity are most advantageous. Too much heat causes excessive evaporation from the leaves, thus damages them and the fibres. Also immersion in water injures the plant	
Soil type	Needs little cultivation, best grown in very fertile and well-drained soils	
Components of yield	Fibre obtained from the stem of the leaves not the expanded portion of the leaf. After efflorescence plant dies. Yield up to 1 tonne of dry fibre per acre. Maximum production between 4–8 years. 100 kg of fresh leaves produce 1–3 kg of fibre	
Uses	Marine cordage (naturally buoyant), fishing nets, mission ropes, well-drilling cables, paper and tea bags	
World annual production (tonnes)	70 000[14]	
£ per tonne	680–1150	
Fibre extraction – retting	Within 48 hours if not the plant juices become gummy thus fibre extraction is more difficult and unclean fibre is produced also waste water is acidic. Fibre extracted by separating the ribbons (tuxies) of the fibre from the layers of pulp by a knife to remove the residual pulp then hung to dry (this process can be carried out by machines)	
Effects from water, sea water, pests, etc.	Good water-resisting properties, hydroscopic, not affected by salt water. Pests; brown aphids, corm weevil, slug caterpillar	
Cross-section bundles	Roundish, slightly indented or round to elliptical[16]	
Ultimate fibre	Cells are uniform, smooth and regular surface, thus poor interlock, i.e. hard to make into a yarn. Polygonal, slightly rounded corners[16]	
Longitudinal view	Smooth cross-markings rare[16]	
Fibre cell ends	Thin smooth walls and sharp or pointed ends tapered. Cell diameter 3–4 times thicker than the cell wall. Cylindrical, long and regular in width	
Properties compared to other fibres	Superior to flax, better than hemp for marine ropes and hawers	
General fibre detail, colour, etc.	Cream and glossy, stiff and tenacious; even texture, very light weight	
General	Strong and sufficiently flexible to provide a degree of give when used in ropes where strength, durability and flexibility are essential. There are 4 groups of fibre yielded from this plant, depending on where the leaves have come from; (i) Outside sheaths (*Primera baba*) dark brown/light purple & green strips (i.e. exposure to sun) Grade 4–5. (ii) Next to outside (*segunda baba*) light green and purple, Grade 3. (iii) Middle (Media), Grade 2. (iv) Innermost (Ubod), Grade 1. The grade also depends on knife type to extract the fibre	

Table 14.6 Generalised description of sisal plant/fibre

Fibre names and family	Sisal
Genus and species	*Agave sisalana* (Leaf fibres)
Plant type – harvesting	Perennial plant, leaves 1–2 m long each containing about 1000 fibres
Countries of cultivation	Central America, Mexico, Brazil, Philippines, India, Florida, Africa, Venezuela, Tanzania, Kenya, Madagascar, Mozambique, Angola and Ethiopia
Environmental – climate requirements	If rainfall is erratic growth is spasmodic, thus low annual yield. Temperature between 27–32 °C (<16 °C), frost damages leaves, optimum rainfall 1200–1800 mm, but can withstand droughts, when other plants would perish, requires substantial amounts of strong sunlight
Soil type	Grows on dry, porous, rocky, not too acidic or low in nutrients free draining soils. Hardy plant can grow in mimimum rainfall 250–375 mm per year. Waterlogging and salinity are fatal to sisal
Components of yield	If the leaves are in the shade poor quality fibre is produced. Also cold, frost and hail can damage the leaves (fibre). There are spines at the tips of leaves. The leaves are harvested after 2–4 years of growth and then at intervals, after efflorescence plant dies, 45 kg of leaves produce approximately 2 kg of long and tow fibre
Uses	Twines, ropes, rugs, sacking, carpets, cordage and agricultural. Tow (waste product) used for upholstery
World annual production (tonnes)	378 000[14]
£ per tonne	450–1100[15]
Fibre extraction – retting	Within 48 hours if not the plant juices become gummy, thus fibre extraction is more difficult and unclean fibre is produced. Machines are used which scrape the pulpy material from the fibre, after washing, the fibre is dried and bleached in the sun, or oven-dried
Effects from water, sea water, pests, etc.	It was once believed that sisal deteriorated rapidly in salt water; experience has shown that this is not the case. Sisal is widely used for marine ropes.
Cross-section bundles	(i) Crescent to horse-shoe often split.[16] (ii) Few or no hemi-concentrical bundles with cavities.[16] (iii) Round ellipt[16]
Ultimate fibre	Polygonal wall, thick to medium.[16] Stiff in texture, wide central cavity (may be wider than the cell wall), marked towards the middle
Longitudinal view	Smooth[16]
Fibre cell ends	Same thickness as abaca, but half as long. Rounded tips, seldom forked – pointed[16]
Properties compared to other fibres	Shorter, coarser and not quite as strong as abaca. Also lower breaking load and tends to break suddenly without warning. Can be spun as fine as jute. Sisal can be grown under a wider range of conditions then henequen
General fibre detail, colour, etc.	Light yellow in colour, smooth, straight, very long and strong fibre. Number of different types of cells inside a sisal plant; normal fibre cell straight, stiff, cylindrical and often striated
General	Blooms once in its lifetime then dies. Cheap, stiff, inflexible, high strength and good lustre. Sisal fibre is equivalent hand or machine stripped. Dark bluish-green leaves, having a waxy surface to reduce water loss

Table 14.7 Generalised description of coir plant/fibre

Fibre names and family	Coir	(Coconut fibre)
Genus and species	*Cocos nucifera*	(Seed/fruit fibre)
Plant type – harvesting	Perennial plant 70–100 nuts per year, fruit picked every alternate month throughout the year. Best crop between May & June, economic life 60 years. Two types of coir; brown and white. Brown coir obtained from slightly ripened nuts. White coir obtained from immature nuts (green coconuts) fibre being finer and lighter in colour	
Countries of cultivation	India (22%), Indonesia (20%), Sri Lanka (9%), Thailand, Malaysia, Brazil, Philippines, Mexico, Kenya, Tanzania, Asia, Africa, Kerala State, Latin America and throughout the Pacific regions	
Environmental – climate requirements	20°N to 20°S latitude, planted below an altitude of 300 m. Temperature 27–32 °C, diurnal variations <7 °C, rainfall between 1000–2500 mm, >2000 hours of sunshine i.e. high humidity and plenty of sunlight	
Soil type	Wide range of soils. Best results are from well-drained, fertile alluvial and volcanic soils	
Components of yield	Husk to nut ratio, size of nuts, fibre quality, huskability, pests and diseases. Harvesting: men climb trees, from ground, or use a knife on the end of a bamboo pole, monkeys (*Macacus nemestrima*) also climb trees to collect the nuts	
Uses	Known as the tree of life, because source of many raw materials; leaves used for roofs and mats, trunks for furniture, coconut meat for food, soap and cooking oil, roots for dyes and traditional medicines, husk for ropes, cordage and sailcloths; in marine environments	
World annual production (tonnes)	100 000[14]	
£ per tonne	200–800[15]	
Fibre extraction – retting	Retting pits (brown fibre up to 9 months, white fibre 2–6 weeks). Dehusked manually or mechanically (brown fibre only)	
Effects from water, sea water, pests, etc.	Coir is resistant to degradation by sea water, endures sudden pulls, that would snap the otherwise much stronger ropes, made from hemp or other hard fibres	
Cross-section bundles	Round mostly, with cavities, hemi-concentrical bundles[16]	
Ultimate fibre	Polygonal to round, also oblong walls, medium thickness. Round and elliptical in cross-section[16]	
Longitudinal view	Smooth[16]	
Fibre cell ends	Blunt or rounded[16]	
Properties compared to other fibres	Mature brown coir fibre contains more lignin and less cellulose than fibres such as flax and cotton	
General fibre detail, colour, etc.	Reddish-brown strong, elastic filaments of different lengths, thicker in middle and tapers gradually towards the ends. Naturally coarse, suitable for use in sea water, high lignin content makes it resistant to weathering	
General	Extremely abrasive and rot resistant (high % of lignin) under wet and dry conditions and retains a high percentage in tensile strength. Surface covered with pores, but relatively waterproof, being the main natural fibre resistant to damage by salt water	

Table 14.8 Typical values of chemical, mechanical, morphological and physical characteristics of vegetable fibres

Chemical composition of plant fibres							
Fibre type	Cellulose (%)	Hemi-cellulose (%)	Pectin (%)	Lignin (%)	Water-soluble (%)	Fat and Wax (%)	Moisture (%)
Flax	64.1	16.7	1.8	2.0	3.9	1.5	10.0
Jute	64.4	12.0	0.2	11.8	1.1	0.5	10.0
Hemp	67.0	16.1	0.8	3.3	2.1	0.7	10.0
Sisal	65.8	12.0	0.8	9.9	1.2	0.3	10.0
Abaca	63.2	19.6	0.5	5.1	1.4	0.2	10.0
Coir	35–45	1.25–2.5		30–46		1.3–1.8	20

Figures in Tables 14.8 to 14.11 are obtained from reference sources Lewin and Pearce,[17] McGovern,[18] van Dam,[19] and Mandal.[20]

Table 14.9 Mechanical parameters from stress–strain for vegetable fibres

Fibre type	Tensile (kN m^{-2} $\times 10^6$)	Tenacity (N tex^{-1})	Initial modulus (N tex^{-1})	Extension at break (%)	Work of rupture (N tex^{-1})
Flax	0.9	0.54–0.57	17.85–18.05	1.6–3	0.0069–0.0095
Jute	0.2–0.5	0.41–0.52	19.75	1.7	0.005
Hemp	0.3–0.4	0.47–0.6	17.95–21.68	2.0–2.6	0.0039–0.0058
Sisal	0.1–0.8	0.36–0.44	25.21	1.9–4.5	0.0043
Abaca	1.0	0.35–0.67	17.17	2.5–3	0.0077
Coir	0.1–0.2	0.18	4.22	16	0.0157

Table 14.10 Morphological plant fibre characteristics

Fibre type	Long length (mm)	Diameter (mm)	Fineness (Denier)	Cell length (mm)	Cell diameter (um)
Flax	200–1400	0.04–0.62	1.7–18	4–77	5–76
Jute	1500–3600	0.03–0.14	13–27	0.8–6	5–25
Hemp	1000–3000	0.16	3–20	5–55	10–51
Sisal	600–1000	0.1–0.46	9–406	0.8–8	7–47
Abaca	1000–2000	0.01–0.28	38–400	3–12	6–46
Coir	150–350	0.1–0.45		0.3–1.0	15–24

Table 14.11 Physical plant fibre characteristics

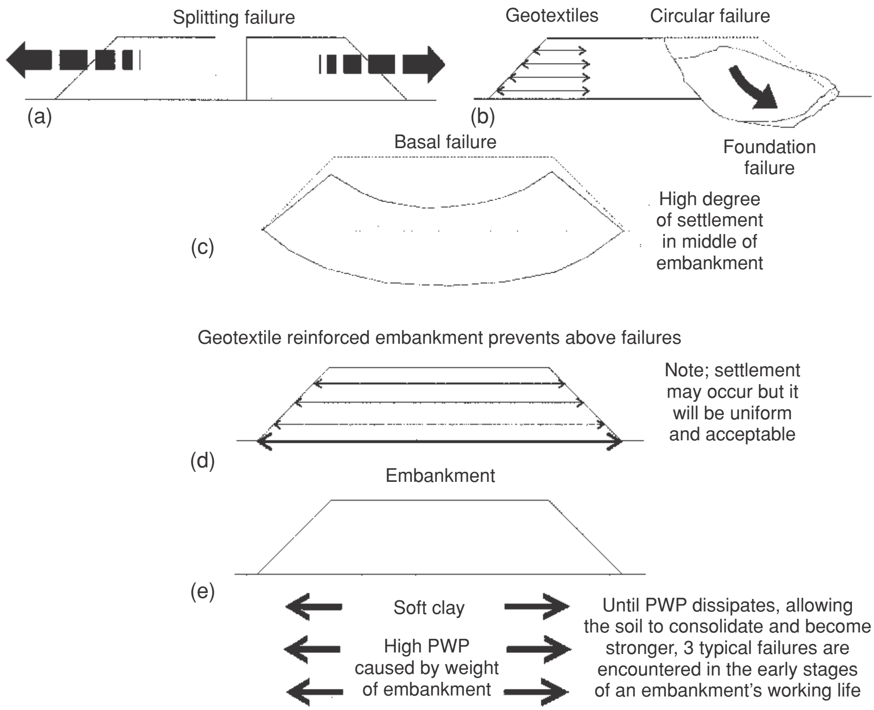
Fibre type	Specific gravity (%)	Specific heat (cal g^{-1} °C^{-1})	Moisture regain (%) 65% RH 20 °C	Absorption (%)	Volume swelling (%)	Specific heat (cal g^{-1} °C^{-1})	Porosity (%)	Apparent density (g cm^{-3})	True density (g cm^{-3})
Flax	1.54		12	7	30		10.7	1.38	1.54
Jute	1.5	0.324	13.8	10–12.5	45	0.324	14–15	1.23	1.44
Hemp	1.48	0.323	12	8		0.323			1.5
Sisal	1.2–1.45	0.317	14	11	40	0.317	17	1.2	1.45
Abaca	1.48		14	9.5			17–21	1.2	1.45
Coir	1.15–1.33			10					1.15

able 14.12 Functional requirements for geotextiles

eotextiles nctions	Tensile strength	Elongation	Chemical resistance	Biodegradability	Flexibility	Friction properties	Interlock	Tear resistance	Penetration	Puncture resistance
einforcement	iii	iii	ii–iii	iii	i	iii	iii	i	i	i
ltration	i–ii	i–ii	iii	iii	i–ii	i–ii	iii	iii	ii	ii
eparation	ii	iii	iii	iii	iii	i	ii	iii	iii	ii
rainage	na	i–ii	iii	iii	i–ii	na	ii	ii–iii	iii	iii
rosion control	ii	ii–iii	i	iii	iii	ii	i	ii	ii	i–ii

eotextiles nctions	Creep	Permeability	Resistance to flow	Properties of soil	Water	Burial	UV light	Climate	Quality assurance & control	Costs
einforcement	iii	na-i	i	iii	iii	iii	ii	na	iii	iii
ltration	na	ii–iii	i	ii	iii	iii	na	iii	iii	iii
eparation	na	ii–iii	i	na	iii	iii	na	i	ii	iii
rainage	na	iii	i	na	iii	iii	na	iii	iii	iii
rosion control	na	ii	iii	na	iii	na	iii	iii	i	iii

= Highly important, ii = important, i = moderately important, na = not applicable.

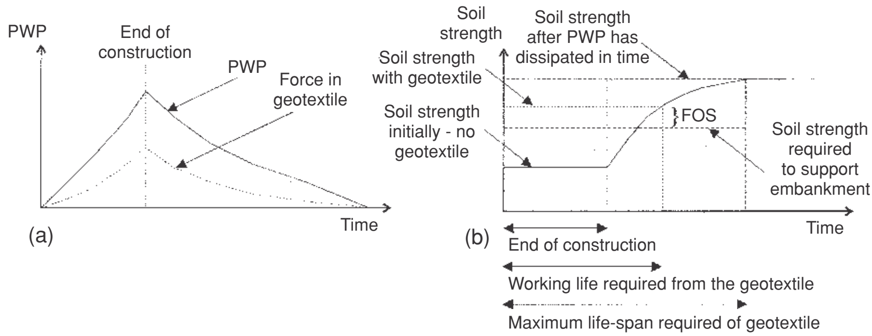


14.11 Short-term applications for geotextiles in embankments.

after a number of years if necessary (i.e. when the natural material has lost sufficient strength owing to the degradation process that it can no longer withstand the applied tensile forces). Furthermore, this procedure enriches the soil thereby improving growing conditions without introducing harmful residues. Although, it is not suggested, these natural geotextiles would be a universal panacea; they would have a significant impact on the economy of developing countries.

14.8.1.2 Short-term embankments

Geotextiles provide an invaluable solution to the problem of constructing embankments over soft compressible ground where water fills the pores between the soil particles under the embankment. The load from the embankment fill increases the tendency for the embankment to fail. Figure 14.11(a) to (c) illustrates three typical modes of failure that may be encountered (splitting, circular and basal) caused because the underlying soft soil does not have sufficient strength to resist the applied shear stresses (water has no shear strength). The use of geotextiles at vertical increments in an embankment and/or at the bottom of it, between the underlying soft soil and embankment fill (Fig. 14.11(d)), would provide extra lateral forces that either prevent the embankment from splitting or introduce a moment to resist rotation. Compression of the soft soil beneath the embankment will occur, but this will be uniform, which is acceptable. The embankment loading increases the water pressure in the pores in the underlying ground, especially at the centre of the embankment, whilst the pore water pressure (PWP) in the soil at and preceding the



14.12 Stabilising force to be provided by the geotextile will diminish with time. FOS = factor of safety.

extremities of the embankment is low in comparison (Fig. 14.11(e)). Thus, there is a pressure gradient set-up and water migrates from beneath the embankment sideways so that the PWP falls. Stability of the embankment will improve in time (1–2 years) as the excess PWP from the underlying soft soil dissipates (Fig. 14.11(e) and Fig. 14.12(a)). Hence its strength will increase and the stabilising force that has to be provided by the geotextile will diminish with time as shown in Fig. 14.12(b). This decrease (in the required stabilising force) can be designed to correspond to the rate of deterioration of the vegetable fibre geotextile. If necessary the rate of dissipation of the excess PWP can be enhanced by the use of consolidation drains.

14.8.1.3 Specialist areas – short-term

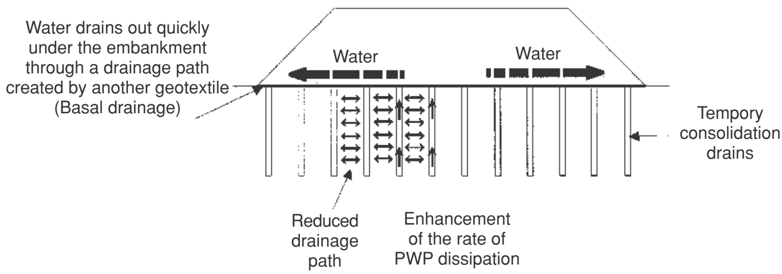
The armed forces often have to construct temporary roads/structures very quickly when they are dealing with confrontations. Also, these structures must be capable of being demolished if the soldiers have to retreat. By employing indigenous vegetable fibre materials as reinforcing geotextiles, the additional costs associated with the long life of synthetic geotextiles are not incurred. Decommissioning the reinforced structure is a low cost procedure – the structure can be destroyed by machinery or explosives and the natural geotextiles left to rot in the soil or set on fire, without leaving any resources for the enemy to exploit.

14.8.2 Drainage (fluid transmission)

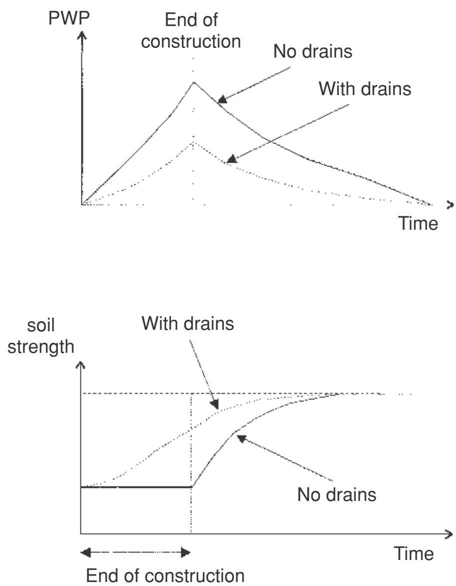
Normally the strength of soil is determined by its water content; as the water content decreases its strength increases and vice versa. A geotextile can convey fluids or gases within the plane of the geotextile to an egress point.

14.8.2.1 Consolidation/basal drains

The drainage system allows dissipation of excess pore water pressure, thus consolidation can take place and the soil strength is increased. The rate of dissipation of excess pore water pressure can be enhanced by using temporary drains in the soil so that the drainage path is reduced (Fig. 14.13). This type of drain is only required to perform for a limited time period, until consolidation has taken place (Fig. 14.14).



14.13 Temporary consolidation drains.



14.14 Comparison of time and strength of soil with and without consolidation drains.

14.8.3 Filtration

A geotextile acts as a filter by permitting the flow of liquid and gases, but preventing the passage of soil particles which can cause settlement due to loss of ground. The pore size within the geotextile is selected to avoid blocking, blinding and clogging.

Ground drains are used to prevent/intercept water flow, normally to reduce the risk of a rise in pore water pressure. Typically these drains are vertically sided trenches, lined with a geotextile and then filled with coarse gravel. Initial loss of soil particles will be high adjacent to the geotextile. This causes a zone (in the remaining soil particles) to bridge over the pores in the geotextile and retain smaller particles, which in turn retain even smaller particles. Thus a natural graded filter is formed which will prevent additional washout of fine particles, after which the geotextile becomes more-or-less redundant. If the geotextile was not used to encapsulate the coarse granular drainage material, too much wash-through of particles

would occur and this would either cause the drain to block or cavities to develop and lead ultimately to subsidence.

14.8.4 Separation

A geotextile acts as a separator by preventing the intermixing of coarse and fine soil materials whilst allowing the free flow of water across the geotextile. For instance, when a geotextile is placed between the subsoil and the granular sub-base of an unpaved road, it prevents the aggregate from being punched down into the soil during initial compaction and subsequently from the dynamic loading of vehicle axles. An example of a short-term use of a geotextile is in a temporary haul road that is formed during the construction of the permanent works, where it is only required to function for a limited amount of time before being removed. The temporary haul road is dug up and disposed of. A geotextile made from natural fibres, such as jute, coir, and so on, would be more suitable for such applications, because it would be biodegradable and hence more environmentally friendly.

14.8.5 Erosion control/absorption

A rapidly developing area for geotextiles is in the erosion control industry where they are employed for short-term effects. This usage differs from the other applications of geotextiles in that they are laid on the surface and not buried in the soil. The main aim is to control erosion whilst helping to establish vegetation which will control erosion naturally. The geotextile is then surplus to requirements and can degrade, enriching the soil. Geotextiles can reduce runoff, retain soil particles and protect soil which has not been vegetated, from the sun, rain and wind. They can also be used to suppress weeds around newly planted trees. Erosion control can be applied to riverbanks and coastlines to prevent undermining by the ebb and flow of the tide or just by wave motion.

14.9 Engineering properties of geotextiles

The physical and mechanical properties of soil are virtually unaffected by the environment over substantial periods. The natural fibre geotextiles could be used where the life of the fabrics is designed to be short. The definition of a short-term timescale varies from site to site and application to application. It depends ultimately on a number of factors, such as the size of the job, the construction period, the time of the year (weather), and so on. However, from the wealth of accumulated knowledge, a conservative design life expectancy of the geotextiles may be made for each given end-use. Applications exist where geotextiles are only required to perform for a few days after laying (drainage/filtration) or have to last up to a hundred years (reinforced earth abutments). The design life of natural fibre fabrics will be dictated by the type of fibre and the conditions to which they will be subjected. However, design lives of a few months to 4–5 years should be achieved for natural fibre geotextiles used in non-extreme situations, particularly since the need for the geotextile declines with the passage of time.

Natural materials such as timber have been used in the construction industry for a long time. However, the use of timber is limited because it is only used as a block,

that is, the individual components are not utilised. With natural fibres the stalks/stems can be stripped away to leave just the fibre which can be adapted to suit many different purposes in numerous forms and shapes with a wide range of properties. The key to developing geotextiles from natural fibres is the concept of designing by function, that is, to identify the functions and characteristics required to overcome a given problem and then manufacture the product accordingly. Provided the function can be satisfied technically and economically, these can compete with synthetic materials and in some situations they will have superior performance to their artificial counterparts.

14.10 Present state and uses of vegetable fibre geotextiles

The major use of vegetable fibre geotextiles is in the erosion control industry. Jute is readily biodegradable and ideally suited for the initial establishment of vegetation that in turn provides a natural erosion prevention facility. By the time natural vegetation has become well established the jute has started to rot/break down and disappear (6–12 months), without polluting the land.

Bangladesh, China, India and Thailand produce and sell jute geotextiles for erosion control. These are coarse mats, with open mesh woven structures made from 100% jute yarn produced on traditional jute machines. The jute geotextiles are laid on the surface of the slopes, where the weight and drapability of the mats encourage close contact with the soil. Between 1960 and 1980 a number of studies conducted by universities and highway departments demonstrated the effectiveness of jute geotextiles for surface erosion control.[21] Typical properties of a jute geotextiles[22] are:

- Pore size: 11 mm by 18 mm
- Open area ratio: 60–65%
- Water permeability: >500 litres $m^{-2} s^{-1}$ (100 mm head)
- Water absorption: 485%
- Breaking strength:
  warp 7.5 kN m^{-1}
  weft 5.2 kN m^{-1}

Some research has been directed towards reducing the degradation rate of jute, which can be made almost rot-proof by treating the fabric with a mixture of oxides and hydroxides of cobalt and manganese with copper pyroborate. Even after 21 days exposure in multiple-biological culture tanks, jute which had been subjected to this treatment had retained 96% of its original tensile strength. In soil incubation tests, the chemically treated jute had a 13-fold increase in lifetime over untreated jute.[23] Tests have been conducted on phenol formaldehyde-treated polypropylene–jute blended fabrics buried in soil to assess their susceptibility to microbial attack compared to untreated samples. It was concluded that the treated jute could withstand microbial attack more effectively than the untreated jute.[24] However, treated jute loses some of its 'environmental friendliness'.

There has been no substantial research on the engineering properties of vegetable fibres for soil strengthening or on the development of new and novel geotextile structures made from vegetable fibres for exploiting the beneficial properties of the fibre, fabric and ground for short-term or temporary applications.

14.11 Performance of natural fibre geotextiles for soil strengthening

An area which may offer the most new and upcoming potential for the use of vegetable fibres as geotextiles is to strengthen soils, as demonstrated by Sarsby *et al.*[25] in 1992. Hence, the remainder of this chapter is devoted to the use of vegetable fibres for this specific application.

Factors affecting the suitability of vegetable fibres for reinforcing geotextiles can be identified as: durability, tensile properties, creep behaviour, manufacturing feasibility and soil/geotextile interaction. To be accepted these materials must satisfy/fulfil all of the above criteria to some degree. The aim of this section is not to 'design' for a specific limited application, but to determine whether acceptable balances of properties may be established. To achieve this, comparisons are made between different vegetable fibre yarns for long-term stability, that is, for biodegradation and creep. Also, nine different vegetable fibre geotextiles are compared with two synthetic products in terms of fabric stress–strain and shearing interactive properties.

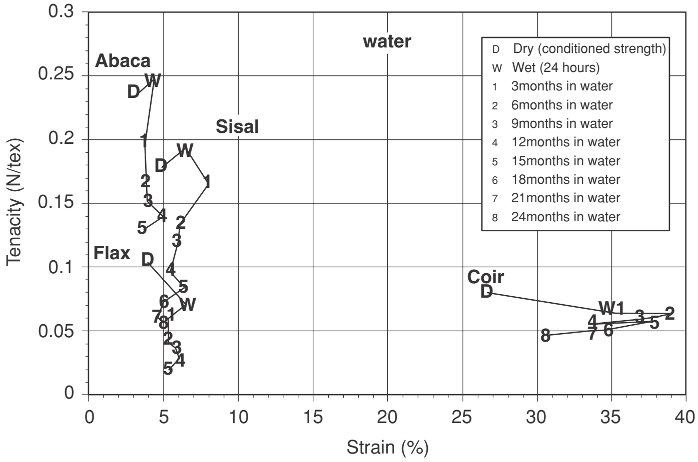
14.11.1 Long-term stability of natural fibre geotextiles

A geotextile should show the ability to maintain the requisite properties over the selected design life. One of the reasons for using vegetable fibre geotextiles is that they biodegrade when they have served their working life, but they must be sufficiently durable in different and aggressive ground conditions to last the prescribed duration. Only purely environmental deterioration will be considered, no damage to the geotextile caused by installation will be taken into account. The effects of biodegradation and creep will be considered for four vegetable fibre yarns which are particularly suitable for soil reinforcement: flax, abaca, sisal and coir.

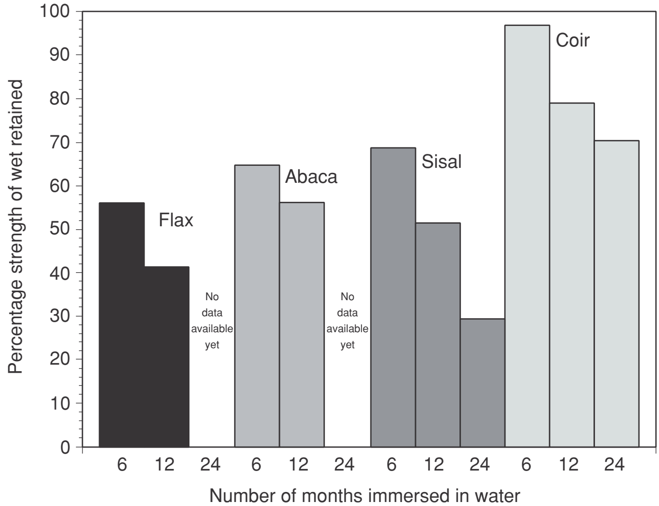
14.11.1.1 Durability/biodegradation rates

There are numerous factors which combine together to influence the rate of deterioration of vegetable fibres. However, to demonstrate simply the differences in the rates of deterioration, the change in strength and elongation of the four vegetable fibre yarns (fully immersed in water) is shown in Fig. 14.15.

The values shown are the average of five samples, tested after every three months. The samples were removed from the water and tested immediately, in other words the wet strength is given. This was chosen as representing the conditions most likely to be found in the ground. The original conditioned tex values were used at each testing stage to determine the yarns' tenacity. The initial strength of abaca and sisal (both leaf fibres) yarns increases by approximately 4% and 9%, respectively, when wet. However, with flax and coir (bast and seed/fruit fibres, respectively) there is a reduction in strength by 31% and 18%, respectively. This is in contrast to the earlier reference to the strength properties of flax increasing when wet. The reduction in strength could be accounted for by the yarn structure, rather than the fibre properties themselves. For the flax, abaca and sisal yarns there is a steady reduction in tenacity with time, with slight variations in strain. In contrast, the variations in the strength of coir yarn are minor, the difference between the groups of readings probably resulting from variations in the natural product itself. Figure 14.16 shows the



14.15 Effect of the deterioration process on the stress–strain properties of vegetable fibre yarns.

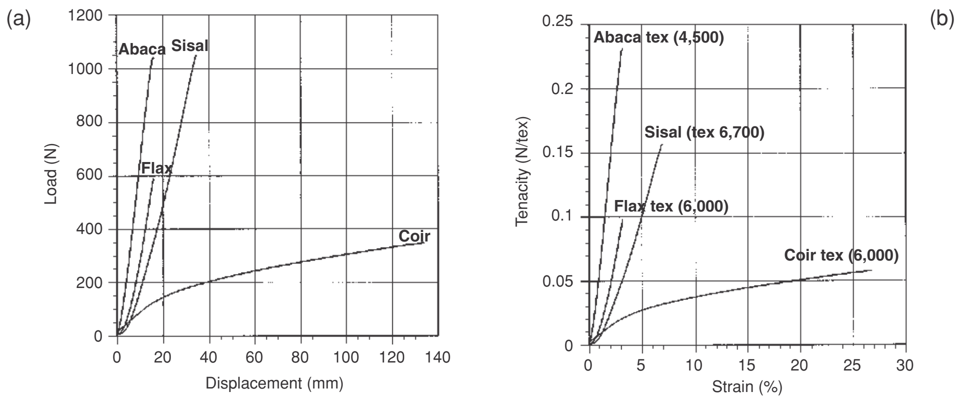


14.16 Percentage strength retained for vegetable fibre yarns in water for 6, 12 and 24 months.

percentage of the 24 hours wet strength retained for 6, 12 and 24 months. It can be seen that coir has retained by far the highest amount of strength. This was also true for coir and jute ropes which were immersed in pulverised fuel ash (PFA) for 10 and 36 months[25] – the reduction in strength for the coir was 38% and 47%, respectively whereas for jute it was 75% and 100%.

14.11.1.2 Creep

Creep and stress relaxation of geotextiles are prime factors in serviceability failure over the fabric's design life. Creep is a time-dependant increase in strain under



14.17 (a) Load–displacement and (b) stress–strain properties of the four vegetable fibre yarns.

constant load (e.g. reinforced walls), whereas stress relaxation is the reduction in tensile stress with time when subjected to constant strain (e.g. basal embankment reinforcement).

The main variables influencing creep for vegetable fibres geotextiles could be related to:

1 The fibre cell structure (e.g. abaca contains spiral molecules which are in a parallel configuration to each other, producing low extension).
2 Yarn type (e.g. between adjacent flax fibres cohesion is present, however with sisal no cohesion is present, the fibres are held together by twist only).
3 Fabric structure forms (e.g. crimp in woven structures).

Laboratory tests have been carried out in which the variables were load and time, with temperature and relative humidity being kept constant at 20°C and 65%, respectively. Uniform loads of 40%, 20% and 10% of the maximum load (representing factors of safety of 2.5, 5 and 10) were applied to the four different vegetable fibre yarns and a gauge length of 500mm was monitored.

Figure 14.17 illustrates typical short term load/extension curves at constant strain for flax, abaca, sisal and coir yarns, with the values of total strain and creep strain given in Table 14.13. Total strain includes the initial strain the sample undergoes when the load is applied plus the creep strain (this latter is the increase in change in length due to the passage of time, after the initial elongation).

14.12 Geotextile structure forms

Table 14.14 indicates the eleven different types of geotextile structure and fibre type together with their standard properties.

The creation of reinforcing geotextiles made from vegetable fibres introduces new manufacturing restraints, compared with the use of synthetic fibres and structures on existing textile machines. Numbers 1 to 5 of these structures have been designed, developed and produced in the Textile Centre at Bolton Institute from novel structure runs with selected natural fibres, namely flax, sisal and coir, to enable

Table 14.13 Total strain and creep strain of vegetable fibre yarns

Type of yarn	Max. load (kN)	Max. strain (%)	40% load (kN)	Strain at 40% load	20% load (kN)	Strain at 20% load	10% load (kN)	Strain at 10% load
Sisal	1.05	6.90	0.42	3.50	0.21	2.30	0.11	1.50
Abaca	1.04	3.19	0.42	1.40	0.21	0.80	0.10	0.50
Coir	0.35	26.71	0.14	3.70	0.07	1.50	0.04	0.70
Flax	0.68	4.02	0.27	2.30	0.14	1.50	0.07	0.90

Total strain for 10 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.6	2.7	1.5
Abaca	1.8	1.3	0.6
Coir	5.1	2.0	1.7
Flax	2.4	1.5	0.9

Creep strain for 10 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.1	0.4	0.0
Abaca	0.4	0.5	0.1
Coir	1.4	0.5	1.0
Flax	0.1	0.0	0.0

Total strain for 100 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.6	2.8	1.6
Abaca	1.9	1.4	0.7
Coir	6.0	2.3	1.8
Flax	2.6	1.5	1.0

Creep strain for 100 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.1	0.5	0.1
Abaca	0.5	0.6	0.2
Coir	2.3	0.8	1.1
Flax	0.3	0.0	0.1

Total strain for 1000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.8	3.0	1.8
Abaca	2.0	1.4	0.7
Coir	6.9	2.7	2.0
Flax	2.8	1.5	1.1

Creep strain for 1000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.3	0.7	0.3
Abaca	0.6	0.6	0.2
Coir	3.2	1.2	1.3
Flax	0.5	0.0	0.2

Total strain for 10 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	5.0	3.2	2.0
Abaca	2.1	1.5	0.8
Coir	7.9	3.1	2.1
Flax	2.9	1.6	1.2

Creep strain for 10 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.5	0.9	0.5
Abaca	0.7	0.7	0.3
Coir	4.2	1.6	1.4
Flax	0.6	0.1	0.3

Total strain for 100 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	5.2	3.3	2.1
Abaca	2.2	1.5	0.8
Coir	8.8	3.4	2.3
Flax	3.1	1.7	1.2

Creep strain for 100 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	–	1.0	0.6
Abaca	–	0.7	0.3
Coir	5.1	1.9	1.6
Flax	–	0.2	0.3

Table 14.14 Standard properties of vegetable fibres and commercially available geotextiles

	Average of 5 fabric samples for all test results shown	Disp. at max. load (mm)	Load at max. (kN)	% Strain at max. load	Stress at max. load (MPa) ($N\,mm^{-2}$)	Load/Width at max. load ($kN\,m^{-1}$)	Modulus ($kN\,m^{-1}$)	Toughness (MPa) ($N\,mm^{-2}$)	Mass ($g\,m^{-2}$)	Thickness (mm) weight 100 g
1	Knitted flax sisal inlay (strength direction)	16.35	10.33	8.18	38.98	206.60	4657.64	3.85	1753.23	5.3
	Knitted flax sisal inlay (*x*-strength direction)	80.04	1.03	40.02	3.74	20.57	93.02	0.50		
2	Knitted grid flax sisal (strength direction)	14.88	7.88	7.44	32.63	143.58	2647.04	3.88	1613.81	4.4
	Knitted grid flax sisal (*x*-strength direction)	97.76	1.09	48.88	4.35	19.15	84.26	0.47		
3	Plain weave sisal warp flax weft (warp direction)	19.28	8.99	9.64	49.94	179.80	2604.24	4.34	1289.95	3.6
	Plain weave sisal warp flax weft (weft direction)	58.07	0.22	29.04	1.22	4.40	50.65	0.06		
4	Plain weave sisal warp coir weft (warp direction)	32.68	5.65	16.34	14.86	113.00	683.24	1.59	1895.48	7.6
	Plain weave sisal warp coir weft (weft direction)	51.70	1.32	25.85	3.48	26.42	256.73	0.73		
5	6 × 1 woven weft rib sisal warp coir weft (warp direction)	16.69	8.53	8.35	14.10	170.60	2947.56	0.96	3051.75	12.1
	6 × 1 woven weft rib sisal warp coir weft (weft direction)	68.16	5.58	34.08	9.23	111.70	710.27	2.87		
6	Plain weave coir geotextile (warp direction)	56.23	0.99	28.12	2.47	19.74	114.56	0.50	1110.99	8.0
	Plain weave coir geotextile (weft direction)	44.01	0.89	22.00	2.23	17.86	142.40	0.41		
7	Knotted coir geotextile (long direction)	105.90	0.92	52.95	5.93	18.38	56.11	1.87	605.37	3.1
	Knotted coir geotextile (width direction)	389.60	0.33	194.80	2.12	6.56	12.80	0.90		
8	Nonwoven hemp (machine direction)	112.70	0.11	56.37	0.48	2.15	2.48	0.16	683.16	4.5
	Nonwoven hemp (*x*-machine direction)	85.47	0.17	42.74	0.76	3.43	4.14	0.22		
9	Nonwoven coir latex (machine direction)	12.26	0.20	6.13	0.74	4.07	107.58	0.07	1018.24	5.5
	Nonwoven coir latex (*x*-machine direction)	11.18	0.15	5.59	0.54	2.95	72.05	0.05		
10	Plain weave synthetic polyester (warp direction)	16.35	2.07	8.17	51.62	41.30	768.72	2.94	432.09	0.8
	Plain weave synthetic polyester (weft direction)	19.62	2.30	9.81	57.50	46.00	669.36	3.52		
11	Synthetic warp knitted polyester (warp direction)	55.78	2.32	27.89	27.31	46.42	446.42	4.18	430.13	1.7
	Synthetic warp knitted polyester (weft direction)	102.87	0.11	51.43	1.31	2.23	70.64	0.26		

the creation of the most suitable compositions of fabrics. They have been created with the fundamental properties required to form geotextiles to reinforce soil, in that they have been designed to provide:

1 The highest possible strength in one direction, combined with ease of handling and laying on site
2 Soil particle interlock with the fabric to such an extent that the soil/fabric interface exhibits greater shearing resistance than the surrounding soil, i.e. the soil/fabric coefficient of interaction (α) is greater than one
3 A degree of protection to the high strength yarns during installation
4 A tensile strength in the range of 100–200 $kN\,m^{-1}$.
5 Ease of manufacture on conventional textile machines.

Numbers 1 and 2 are the most novel structures developed, being of weft knitting origin. The knitted structure is formed from a flax yarn (tex $\approx$ 400) encapsulating high strength sisal yarns (tex $\approx$ 6700). Knitted flax and inlay sisal yarns can be substituted by other natural fibres yarns.

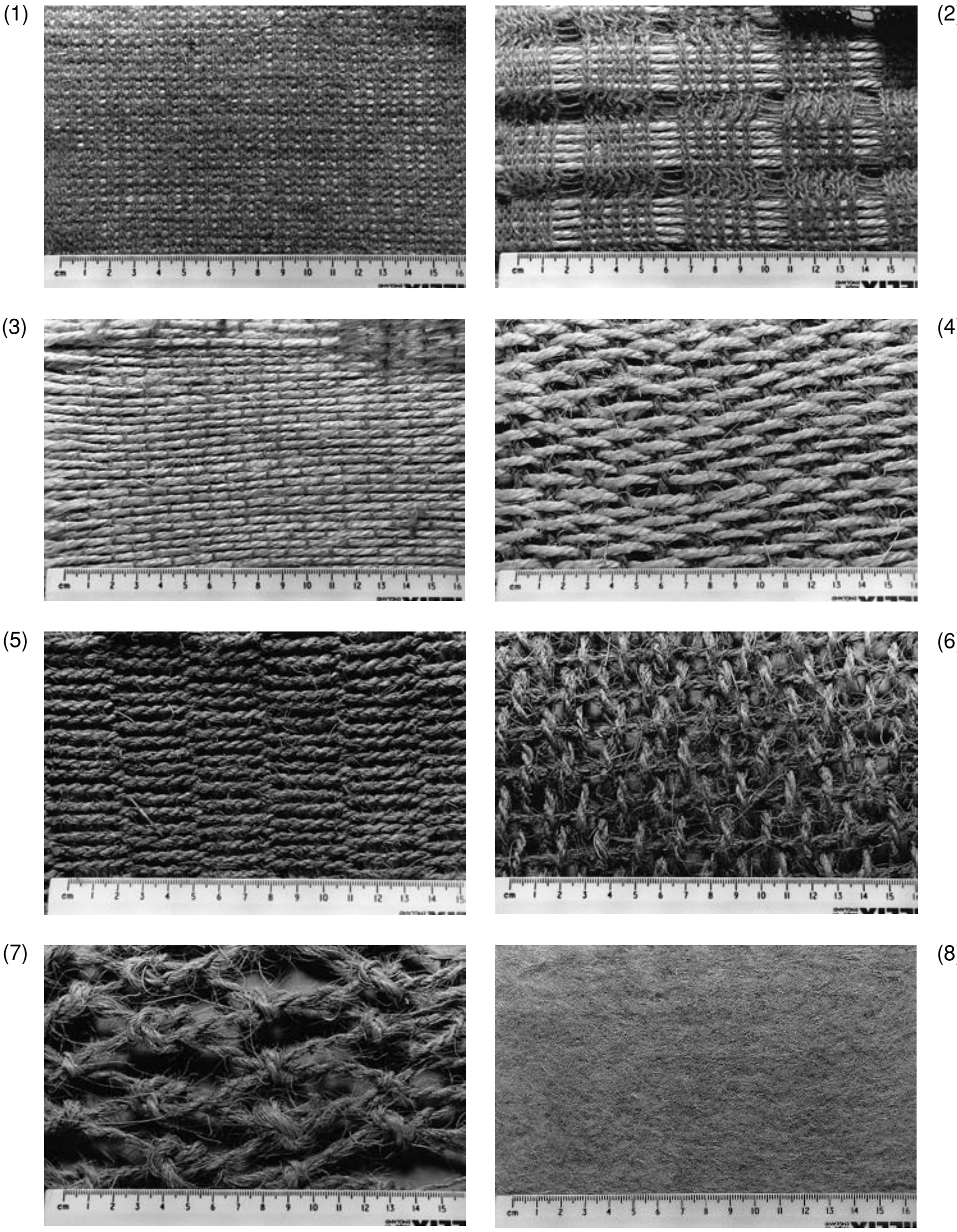
The knitted flax/sisal inlay number 1 (Fig. 14.18) has as many straight inlay yarns as possible in one direction which gives the geotextile its high strength, without introducing crimp into these yarns. Thus a fabric is produced which has low extensibility compared with conventional woven structures. The knitted loops hold the inlay yarn in a parallel configuration during transportation and laying on site; under site conditions it would be impractical to lay numerous individual sisal yarns straight onto the ground. The knitted loops also provide some protection for the sisal inlay yarns during installation/backfilling. The most advantageous use of the knitted loops in this structure is that they form exactly the same surface on both sides of the fabric and the sand is in contact not only with the knitted loops but with the inlay yarns as well. Thus the shear stress from the sand is transmitted directly to both the inlay yarns and the knitted skeleton.

With the grid flax/sisal geotextile number 2 (Fig. 14.18), at predetermined intervals needles were omitted and the sisal inlay yarn left out, to produce large apertures in the geotextile. This is similar in form to the Tensar Geogrid (commercial polymer grids designed for soil reinforcement), which allows large gravel particles to penetrate into the structure thereby 'locking' the gravel in this zone and forcing it to shear against the gravel above and below the geotextile, rather than just relying on the surface characteristics.

Structures 3 to 5 employed traditional woven patterns, but exploited combinations of different types of yarn and thickness to produce advantageous fabric properties for reinforcing geotextiles.

The plain weave sisal warp/flax weft geotextile number 3 (Fig. 14.18) allows the maximum possible number of the high strength sisal yarns to be laid in one direction, whilst the flax weft yarns hold the sisal yarns together during transportation and laying on site. By only using very thin weft yarns compared to the warp yarns no crimp is introduced in these warp yarns. This structure is not as stable as the knitted structures and the flax weft yarns offer no protection for the sisal warp yarns during installation.

The plain weave sisal warp/coir weft geotextile number 4 (Fig. 14.18) provides the sisal strength yarn in one direction whilst using the coir weft yarn to form ridges in the structures caused by its coarseness, thus creating abutments which the soil has to shear around. By using a thick weft yarn, crimp is introduced into the warp

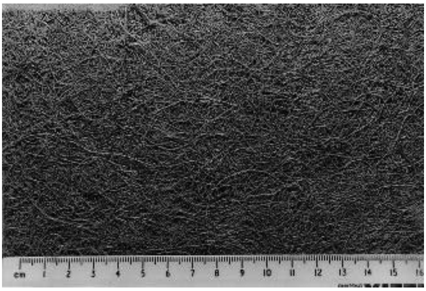


14.18 Photographs of different fabric structures used for tensile and shear interactive tests. (1) Knitted flax/sisal inlay, (2) knitted grid flax/sisal, (3) plain weave sisal warp/flax weft, (4) plain weave sisal warp/coir weft, (5) 6×1 woven weft rib sisal warp/coir weft, (6) plain weave coir warp/coir weft, (7) knotted coir grid, (8) nonwoven hemp, (9) nonwoven coir latex, (10) plain weave synthetic polyester, (11) synthetic warp-knitted polyester.

yarn and this in turn creates a more extensible geotextile, as well as providing no protection for the sisal strength yarns.

The woven 6×1 weft rib geotextile number 5 (Fig. 14.18) was designed to provide the ultimate protection for the high strength sisal yarns but without introducing any

(9)



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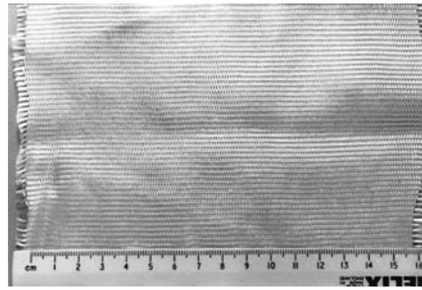

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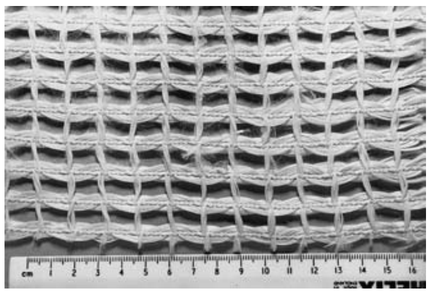


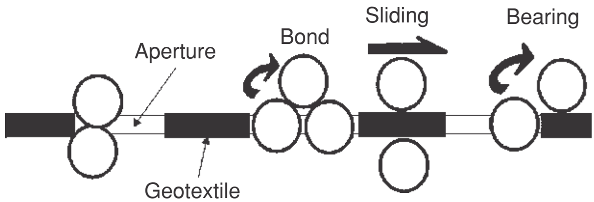
14.18 *Continued.*

crimp. However, this structure has comparatively lower productivity because of the high weft cover factor and thus it is more costly.

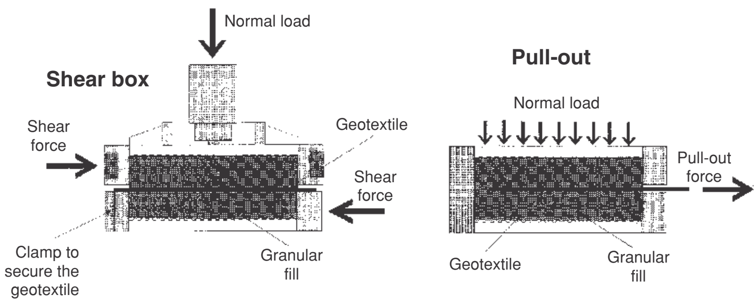
Numbers 6 to 11 are all commercially available geotextile products, with 6 to 9 being of a natural fibre origin. The coir knotted geotextile (Fig. 14.18) was chosen to study the effect of larger particle interlock with the fabric and large abutments formed by the knots. This geotextile was obtained from India (Aspinwall & Co. Ltd.) where the knots are produced by hand. The nonwoven samples 8 and 9 (Fig. 14.18) were obtained from Thulica AB, Sweden, for a comparison with the knitted and woven natural fibre structures. However, geotextiles 10 and 11 are of a synthetic origin from the midrange of synthetic products commercially available. These were used for a direct comparison with the natural fibre geotextiles using exactly the same tests and procedures. Both of these synthetic geotextiles were made of polyester, number 10 was a plain weave structure and number 11 was a warp-knitted grid (Fig. 14.18).

14.13 Frictional resistance of geotextiles

The frictional shearing resistance at the interface between the soil and the geotextile is of paramount importance since it enables the geotextile to resist pull-out failure and allows tensile forces to be carried by the soil/geotextile composite. The resistance offered by the fabric structure can be attributed to the surface roughness characteristics of the geotextile (soil sliding) and the ability of the soil to penetrate the fabric, that is, the aperture size of the geotextile in relation to the particle size of the soil, which affects bond and bearing resistance (Fig. 14.19). Bond resistance is created when soil particles interlock with the geotextile and permit these ‘locked’



14.19 Forms of shearing resistance; sliding, bond and bearing.



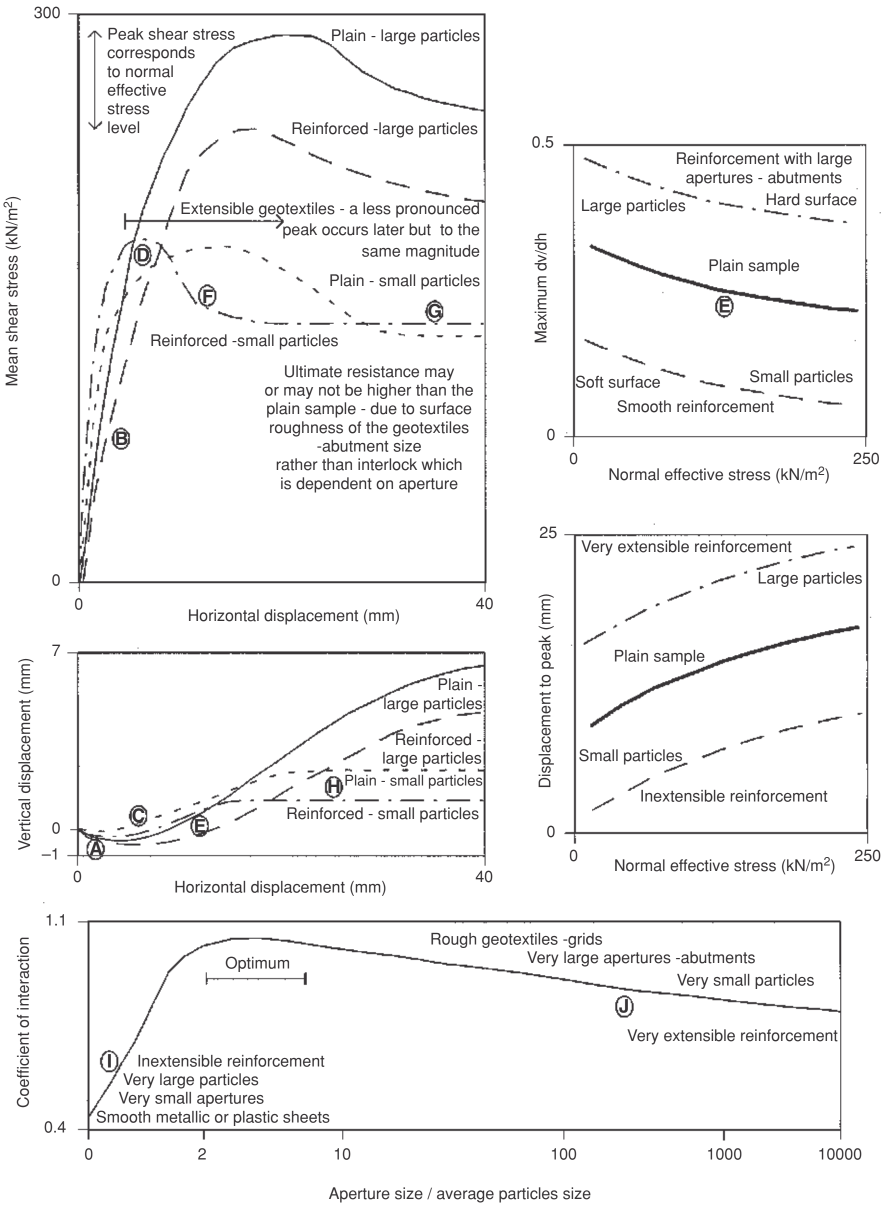
14.20 Laboratory tests to determine the frictional resistance of a geotextile.

particles in the apertures to shear against ambient soil in close vicinity above and below the geotextile surface, whereas bearing resistance, which can only really be assessed by pull-out tests, is the effect of soil having to shear around abutments in the geotextiles, or at the end of the apertures, in the direction of shear. This mode of resistance is very similar to that encountered in reinforced anchors and is determined by relating the pull-out force to the sum of projected area of the transverse members in the geotextile.

The efficiency of geotextiles in developing shearing resistance at the soil–fabric interface is indicated by the coefficient of interaction (α) defined as the ratio of the friction coefficient between soil and fabric ($\tan\delta$) and the friction coefficient for soil sliding on soil ($\tan\phi$). There are two conventional laboratory tests to determine the frictional resistance of a geotextile; the direct shear box and the pull-out test (Fig. 14.20). The main distinction between these tests is that in the direct shear box test, the soil is strained against the fabric, whereas in the pull-out test, strain is applied to the fabric thereby mobilising different degrees of shearing resistance along the fabric corresponding to a relative position of the fabric from the applied load and the extensibility of the fabric.

14.13.1 Performance of vegetable fibre geotextiles during shear

The stress–strain response and volumetric behaviour for all the geotextiles in both sand and gravel are typical of a densely packed granular dilating medium. Figure 14.21 illustrates typical curves that should be expected, relating the physical properties of the geotextiles to that of the fill. Initial volumetric compression (A) would occur to a higher degree than in plain soil as a result of the soil bedding in the geotextile. At relatively small strains, the stress level would increase rapidly more-or-



14.21 Typical shearing interactive curves, relating the physical properties of the geotextiles to that of the fill. Values indicated on these proposed charts are only shown as an estimate of the range of typical values which may lie within, for dense sand and gravel fills.

less linearly with strain (B). The stress increase will be at a higher rate than in plain soil if the geotextile limits the movement between adjacent soil particles caused by soil interlocking with the fabric. Volumetric expansion will develop at the same time, that is the soil will be dilating (C). At maximum shearing resistance the stress–strain response should produce a well-defined peak in the shear stress (D), more pro-

nounced than in plain soil, because of the 'locked' nature of the soil particles. This should correspond to the rate of maximum volume change (E), which is likely to be greater in reinforced samples than in plain soil, particularly if introduction of the geotextile produces 'abutments' around which the soil has to shear. At this stage all the available shearing resistance, under the given vertical pressure, has been mobilised and the shear stress at the soil–fabric interface is equal to the shear strength. This stage is followed by a reduction in shearing resistance, as particle interlocking is 'released', (F) towards the final state (G), where constant volume is maintained (H). Thus a thin rupture zone of the soil at critical density is produced. By increasing the particle size in the direct shear box the behaviour will be modified slightly, because the nature ratio of the soil–fabric contact will be reduced. The opportunity for movement between ambient soil particles will be reduced as will the soil–fabric interlock as the size of the apertures in the geotextile approach the diameter of the particles (I). With very small particles or large apertures the converse will apply (J), in that the ratio of particles to aperture size will be large and thus will permit additional freedom of movement between sand grains in the shearing zone. Furthermore, the use of larger particles will produce a less rapid stress/strain response, i.e. considerably more horizontal shear displacement is needed, more effort is therefore required, to enable a gravel particle to ride over another gravel particle than it would for corresponding sand particles. Therefore no constant volume shearing zones will be expected in a sample with large particles. The extensibility of the fabric is of paramount importance for producing different degrees of soil strain. The geotextile is required to strain sufficiently to permit maximum soil strength to be mobilised, but not to the extent that serviceability failure occurs.

14.13.2 Coefficient of interaction

Values of the shearing angle and coefficient of interaction, α, of the geotextiles sheared in sand and gravel are shown, together with a summary of their stress–strain values, in Table 14.15. The results for the nonwoven samples were not as favourable as the other geotextiles, for tensile strength and shearing interactive properties, indicating that these structures are not as suitable for soil reinforcement. Some of the α values are more than 1 for the sand, indicating that by introducing the geotextile in the sand it actually strengthens the ambient sand. This could possibly be due to the surface texture of some of these geotextiles, because the sand grains can interlock with the fabric and reduce movement. This scenario can be described as if sand were sheared against sandpaper producing a higher frictional resistance than shearing sand against sand. As a result of sand shearing against sand, the sand grains above and below the failure plane are free to move, but with the sandpaper the sand grains grains are unable to move. In a practical situation if α is more than 1, the failure surface would just be pushed up away from the geotextile into the region of sand against sand. The fabric structure can be further assessed by applying a flow rule analysis to the soil/fabric interface data, as demonstrated by Pritchard,[26] to enable an assessment of whether a higher shearing resistance was developed from the surface roughness characteristics of the geotextile (smoothness of the fabric) or as a result of interlock, that is, from a higher dilational component (the effect from the apertures and abutments in the fabric).

able 14.15 Shearing interactive values of vegetable fibre geotextiles compared to two synthetic geotextiles

	Geotextiles	($kN\,m^{-1}$)	% Strain at max.	θ′max Sand	∝ for θ′max	θ′r Sand	∝ for θ′r	θ′max Gravel	∝ for θ′max
	Fill vs Fill			40.5°	1.00	33.1°	1.00	54.7°	1.00
1	Knitted flax sisal inlay	207	8	40.9°	1.01	33.0°	1.00	50.5°	0.86
2	Knitted grid flax sisal	144	7	38.8°	0.94	32.5°	0.98	50.9°	0.87
3	Plain weave sisal warp flax weft	180	10	40.0°	0.98	32.4°	0.97	49.8°	0.84
4	Plain weave sisal warp coir weft	113	16	42.1°	1.06	33.1°	1.00	53.4°	0.95
5	6 × 1 Woven weft rib sisal coir	170	8	42.0°	1.05	33.2°	1.00	50.9°	0.87
6	Plain weave coir geotextile	20	28	41.9°	1.05	33.1°	1.00	51.2°	0.88
7	Knotted coir geotextile	18	53	43.5°	1.11	36.7°	1.21	51.8°	0.90
8	Nonwoven hemp	2	56	39.3°	0.96	34.8°	1.07	44.6°	0.70
9	Nonwoven coir latex	4	6	34.7°	0.81	–	–	36.4°	0.52
0	Plain weave synthetic (polyester)	41	8	40.4°	1.00	31.9°	0.95	46.6°	0.75
1	Warp knitted grid synthetic (polyester)	46	28	38.4°	0.93	31.8°	0.95	51.3°	0.88

ests conditions are: 300 × 300 mm shear box. Fill; Leighton Buzzard sand and limestone gravel (average particle diameter 0.8 mm and 6 mm, respectively). Nominal ormal stress; 200, 150, 100 and 50 $kN\,m^{-2}$. Nominal unit weight of 96% and 94% of the maximum nominal dry unit weight for the sand and gravel, respectively. Accu-cy of ±0.01 $Mg\,m^{-3}$ from the mean dry density in subsequent shear box tests. Leading side of the bottom half of the shear box had the geotextile clamped to it.
max = maximum shear angle.

14.14 Conclusions

Vegetable fibre geotextiles offer environmentally friendly, sustainable, cost effective, geotechnical solutions to many ground engineering problems, in both developed and less developed countries. The main area where they have been employed is in the erosion control industry, but new and novel structures are being produced which exploit advantageous fabric/ground interaction properties. One of the main areas, with the largest potential for development, is to use these natural products temporarily to strengthen the ground, during and just after construction, until the soil consolidates and becomes stronger. These reinforcing geotextiles then biodegrade leaving no alien residue in the ground.

From the extensive research conducted on vegetable fibres, the six most promising fibres for geotextiles are flax, hemp, jute (bast), sisal, abaca (leaf) and coir (seed/fruit). These can be refined down to the four most suitable fibres, flax, abaca, sisal and coir, when taking into account the relevant properties required for soil reinforcement.

It has been shown that coir yarns are far more durable than any of the other vegetable fibre yarns when tested in water. Also, the coir rope exhibited excellent durability qualities compared to that of the jute rope when subjected to a hostile environment of PFA. However, the coir yarn exhibited significantly higher creep rates than flax, abaca and sisal at increased load levels.

Vegetable fibre geotextiles have been found to have superior properties to the mid-range reinforcing synthetic geotextiles for soil reinforcement, when considering tensile strength (between 100–200 $kN\,m^{-1}$) and frictional resistance (α approximately 1). The high degree of frictional resistance of the vegetable fibre geotextiles probably develops from both the coarseness of the natural yarns and the novel structure forms.

Finally it must be pointed out that the success of synthetic geotextiles is due to excess manufacturing capacity and the large amount of research and development that has been carried out in relation to their production, properties and application and not simply because they are superior to fabrics made from natural fibres.

14.15 Relevant British Standards

BS 2576: 1986 Determination of breaking strength and elongation (strip method) of woven fabrics.
BS 6906: Part 1: 1987 Determination of the tensile properties using a wide width strip.
BS 6906: Part 2: 1987 Determination of the apparent pore size distribution by dry sieving.
BS 6906: Part 3: 1987 Determination of the water flow normal to the plane of the geotextile under a constant head.
BS 6906: Part 4: 1987 Determination of the puncture resistance (CBR (California bearing ratio) puncture test).
BS 6906: Part 5: 1987 Determination of creep.
BS 6906: Part 6: 1987 Determination of resistance to perforation (cone drop test).
BS 6906: Part 7: 1987 Determination of in-plane flow.
BS 6906: Part 8: 1987 Determination of geotextile frictional behaviour by direct shear.

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14

Textiles in civil engineering. Part 1 – geotextiles

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14.1 Introduction to geotextiles

Although skins, brushwood and straw–mud composites have been used to improve soft ground for many thousands of years, it is not realistic to refer to these as 'geotextiles'. The important factor that separates them from modern geotextiles is that they cannot be made with specific and consistent properties. When modern polymers were developed in the mid 20th century, it became possible to create textiles with designed forecastable performance and to produce them in large quantities with statistically consistent and repeatable properties. Once this was achieved, the science of geotextiles became possible. In essence, the difference between geotextiles and skins is their numerical or engineering capability.

In the early 1960s and 1970s, some pioneering engineers wondered if textiles could be used to control soils under difficult conditions. For example, very wet soils need draining and textiles were used to line drains, to prevent mud and silt from clogging up the drains. Similarly, engineers tried to use textiles beneath small access roads constructed over very soft wet soils. It was found that these textiles helped to increase the life and performance of roads. Also, early work was being undertaken in the laying of textiles on the coast to prevent erosion by wave action. A number of limited but historical publications were published.[1–2]

However, in those early days, it was not known exactly how these textiles performed their functions. How did they actually filter? How did a relatively weak textile apparently support heavy vehicles and improve road performance? This was a dangerous period for engineers, because it was quite possible that the experience-based employment of geotextiles could lead to their use in unsuitable constructions. It was likely that before long, an engineer would use textiles in a structure that was too large, too demanding or too stressful for the product; a significant failure could result. It was therefore vital that study and research should be undertaken to provide theories and preliminary design equations against which to test site results.

In 1977 Rankilor produced what was probably the first 'design' manual for a commercial product[3] and this was followed by a textbook written in 1980[4] which built on the extensive experience that had been amassed by this time. As is so typical of scientific development, many engineers were soon working worldwide on the development of geotextiles. Another significant textbook by Koerner and Welsh was published in 1980,[5] showing that work in the USA was at an advanced stage. The French, Japanese, Germans, Dutch and workers in other countries were equally active in the utilisation of textiles in civil engineering earthworks at that time.

During the last 20 years of the 20th century, the use of geotextiles spread geographically worldwide and in area terms their use increased almost exponentially. It is expected that their use will continue to increase into the 21st century unabated.

Once textiles were recognised as being numerically capable materials, engineers developed new types of textile and new composites to solve more difficult problems. Woven and nonwoven textiles were joined into composite products; nonwoven products were combined with plastic cores to form fin drains, and woven products were developed from stronger polymers such as polyester to extend the mechanical range of textiles and their uses in soil reinforcement. It is probable that the Dutch were the first to weave heavy steel wires into polypropylene textiles for incorporation into their major coastal land reclamation schemes. During the period 1984–85, Raz and Rankilor explored and developed the design and use of warp knitted fabrics for civil engineering ground uses.[6,7] Rankilor coined the term 'DSF' geotextiles – directionally structured fabric geotextiles; Raz specified the 'DOS' group within the main DSF range – directionally orientated structures.

Within a few years, more than six major manufacturers were producing warp knitted textiles for civil engineering earthworks. Currently, many are commercially available.

It can be considered that the 'first generation' of geotextiles were textiles that were being manufactured for other purposes (such as carpet or industrial sackings) but which were diverted and used for geotechnical purposes. The second generation of geotextiles became generated by manufacturers choosing specific textiles suitable for geotechnical purposes, but using conventional manufacturing techniques. The third generation textiles were actually designed and developed anew specifically for the purpose of geotechnical application – in particular DSF, DOS and composite products.

The development of geotextiles has always been an 'industry-led' science. Academic institutions have almost universally lagged well behind industry, with industrial designers acquiring experience at an ever-increasing rate. Currently, for example, in the USA, there are only a small number of universities teaching geotextile design as part of their main core programmes. In the UK, there are even fewer. Nonetheless, research publications from British academic institutions are of a high quality, showing specialised interests such as weathering,[8,9] filtration,[10] soil reinforcement[11,12] and computer applications.[13]

The establishment of the International Geotextile Society in 1978 led to a coordinated and coherent approach to international development of geotextile design and utilisation. The Society's four-yearly international symposium has been emulated by many other groups and countries, such that the rate of publication of papers is now very high, providing widespread exposure of developments to all interested engineers.

There are some interesting commercial aspects related to geotextiles that are specific to the industry. For example, availability must be considered in the light of the extreme size range of operations into which geotextiles are incorporated. About one-third of all geotextiles are used in small batches of three rolls or less, but a significantly large proportion are used in very large projects incorporating hundreds of thousands of square metres. Supply must therefore be available on call for one or two rolls from local stock and, simultaneously, must be available through agents or directly from the manufacturer in large quantities over a short space of time.

Delivery period is particularly onerous for textile suppliers. The majority of delivery requirements are of a standard industrial nature, but geotextile suppliers have to be able to supply large quantities within a short period for major engineering undertakings. This aspect has deterred many potential geotextile manufacturers from entering the field.

Price is also of interest, in that the cost of the polymer and manufacture can be irrelevant in certain cases. In civil engineering, a textile can be used to 'replace' a more conventional material such as sand in a granular filter. In this case, the cost of the product would be relevant and would be compared to the cost of the sand. Taken into account would be other marginal factors such as time saved in the laying of the textile as opposed to that of laying the sand. If the balance was in favour of the textile, then it might be adopted. However, in different circumstances the same textile might be worth considerably more as a sand replacement, for example, if sand were required to be placed under rapidly moving water or waves. In this case, if the textile could be placed where sand could not, then the comparison is not simply a matter of cost, but of the textile actually allowing construction to take place when the sand could not. Considerably more could be charged for a textile in these circumstances than in the former. Therefore, the cost of textiles is enhanced where they are sold and used as part of a 'system'.

Quality has to be controlled in much the same way as with other textiles – quality variation within the fabric and quality variations over time – but the implications of failure can be so much greater than with normal industrial products. If a major dam were to fail because the textile filter clogged, it would not just be a matter of apologising and replacing the filter with new product! The manufacturer does not take responsibility for the use of fabrics in the ground, but the design consultant does. He will not therefore be willing to certify the use of a textile if he is not satisfied that quality can be maintained at all levels of the process.

It is certainly necessary for modern-day geotextiles to be produced by manufacturers having ISO 9000 certification and it is ideal for this to include 9001, 9002 and 9003. The full range of these certifications covers the manufacturer's operation from raw material supplier through manufacture to storage and delivery.

14.2 Geosynthetics

In the field of civil engineering, membranes used in contact with, or within the soil, are known generically as 'geosynthetics'. This term encompasses permeable textiles, plastic grids, continuous fibres, staple fibres and impermeable membranes. Textiles were the first products in the field, extending gradually to include additional products, but have remained by far the most important of the range. Grids are formed from sheets of plastic that are punched and stretched; meshes are formed from

melted extruded polymer; neither can be categorised as textiles. Geomembranes are continuous sheets of impermeable plastic and are not textiles. The more difficult areas of the geosynthetic range to categorise are those where discrete staple fibres or continuous filament fibres are mixed directly with soil. These are polymer textile fibres and therefore, as such, are included within the definition of geotextiles.

14.2.1 Geotextile types

Geotextiles basically fall into five categories – woven, heat-bonded nonwoven, needlepunched nonwoven, knitted and by fibre/soil mixing.

Woven fabrics are made on looms which impart a regular rectilinear construction to them, but which can vary in terms of the component fibres and the weave construction. They have a surprisingly wide range of applications and they are used in lighter weight form as soil separators, filters and erosion control textiles. In heavy weights, they are used for soil reinforcement in steep embankments and vertical soil walls; the heavier weight products also tend to be used for the support of embankments built over soft soils. The beneficial property of the woven structure in terms of reinforcement, is that stress can be absorbed by the warp and weft yarns and hence by fibres, without much mechanical elongation. This gives them a relatively high modulus or stiffness.

Heat-bonded nonwoven textiles are generally made from continuous filament fine fibres that have been laid randomly onto a moving belt and passed between heated roller systems. These fabrics acquire their coherence and strength from the partial melting of fibres between the hot rollers, resulting in the formation of a relatively thin sheet of textile.

Needlepunched nonwoven fabrics are made from blended webs of continuous or staple filaments that are passed through banks of multiple reciprocating barbed needles. The fabrics derive mechanical coherence from the entangling of fibres caused by the barbs on the reciprocating needles; these fabrics thus resemble wool felts.

In the case of needlepunched textiles, considerable thicknesses (up to more than 10 mm) and weights greater than 2000 $g\,m^{-2}$ can be achieved, whereas the heat-bonding process is limited in its efficacy as thickness increases. If sufficient heat is applied to melt the internal fibres of a thick fabric adequately, then the outer fibres will tend to be overheated and overmelted. Conversely, if appropriate heat is applied to the external fibres, then insufficient heat may be applied to the centre of the sheet, resulting in inadequate bonding and potential delamination in use.

Knitted fabrics, as used in the field of geotextiles, are restricted to warp-knitted textiles, generally specially produced for the purpose. Warp-knitting machines can produce fine filter fabrics, medium meshes and large diameter soil reinforcing grids. However, it is generally found that only the high strength end of the product range is cost effective, usually for soil reinforcement and embankment support functions.

14.2.2 The main geotextile fibre-forming polymers

The two most common fibre polymers used for the manufacture of geotextiles are polypropylene and polyethylene, but polyester is almost inevitably used when high strengths are required. There are other higher strength polymers available on the market, but geotextiles have to be produced in large quantities (some polymers are not available in large volumes) and economically (specialist polymers tend to be

very expensive). On the overall balance of cost against performance, polyester is the present day optimum, while polypropylene and polyethylene vie for being the most chemically resistant.

Care must be taken when considering the properties of geotextile polymers that consideration is restricted to polymers as they are actually produced and used for geotextile manufacturing purposes; they are not in their chemically pure form. For example, raw polyethylene in its colourless translucent form is quite susceptible to light degradation. However, it is not used in this form in geotextiles, but usually contains carbon black as an ultraviolet (UV) light stabiliser. In this black form, it is arguably the most light-resistant polymer.

Also, it must be recognised that real in situ field testing of geotextile polymers is limited. Publications and authorities may quote accelerated laboratory results for xenon UV exposure, high temperature degradation testing, and similar, but these cannot take account of additional degradation factors such as biological attack, or synergistic reactions that may take place. The difficulty, therefore, arises that accelerated laboratory testing may well be pessimistic in one regard and optimistic in the other when used for ranking purposes.

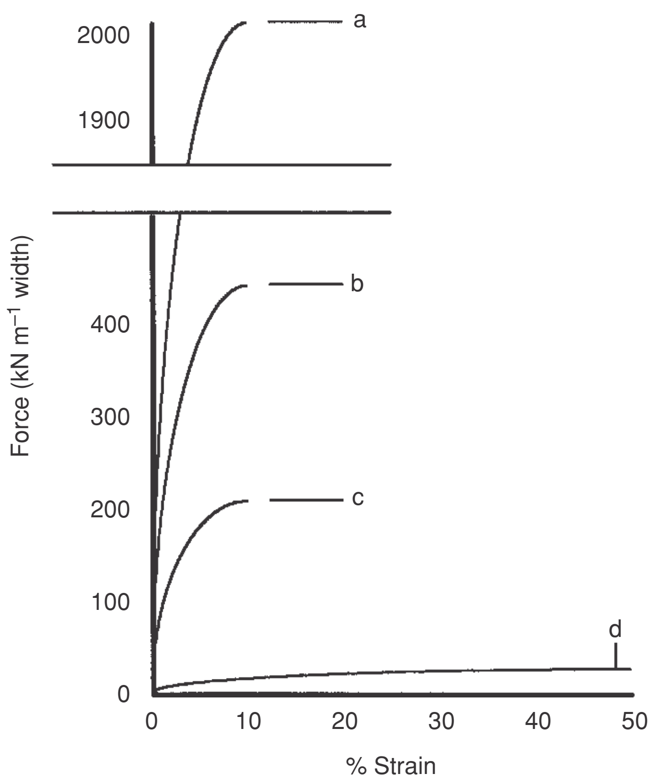
Although polyamide is a common fibre-forming and textile material, nonetheless, it is rarely used in geotextiles, where its cost and overall performance render it inferior to polyester. Some woven materials, for example, have used polyamide in the weft direction, more as a 'fill', where its properties are not critical. Its main asset is its resistance to abrasion, but it displays softening when exposed to water, which appears to have made it unpopular for geosynthetic use. Polyvinylidene chloride fibre is used in Japan and in one or two products in the United States, but not in Europe.

14.3 Essential properties of geotextiles

The three main properties which are required and specified for a geotextile are its mechanical responses, filtration ability and chemical resistance. These are the properties that produce the required working effect. They are all developed from the combination of the physical form of the polymer fibres, their textile construction and the polymer chemical characteristics. For example, the mechanical response of a geotextile will depend upon the orientation and regularity of the fibres as well as the type of polymer from which it is made. Also, the chemical resistance of a geotextile will depend upon the size of the individual component fibres in the fabric, as well as their chemical composition – fine fibres with a large specific surface area are subject to more rapid chemical attack than coarse fibres of the same polymer.

Mechanical responses include the ability of a textile to perform work in a stressed environment and its ability to resist damage in an arduous environment. Usually the stressed environment is known in advance and the textile is selected on the basis of numerical criteria to cope with the expected imposed stresses and its ability to absorb those stresses over the proposed lifetime of the structure without straining more than a predetermined amount. Figure 14.1 compares the tensile behaviours of a range of geotextiles.

On the other hand, damage can be caused on site during the construction period (e.g. accidental tracking from vehicles) or in situ during use (e.g. punching through geotextiles by overlying angular stone). Clearly, in both cases, damage is caused by



14.1 Typical ultimate stress–strain failure levels (a) of high strength and (b) of medium strength polyester woven geotextiles used for embankment support and soil reinforcement, (c) of geogrids and lower strength polyester woven geotextiles used for soil reinforcement and (d) of low strength, highly extensible nonwoven geotextiles used for separation and filtration. (c) represents the current maximum strength capacity of polyethylene geogrids.

an undesirable circumstance which is particularly difficult to remove by design. However, in the latter case, it is possible to perform advanced field testing and to allow appropriate safety factors in calculations.

The ability to perform work is fundamentally governed by the stiffness of the textile in tension and its ability to resist creep failure under any given load condition. The ability to resist damage is complex, clearly being a function of the fibre's ability to resist rupture and the construction of the fabric, which determines how stresses may be concentrated and relieved. In practical terms, geotextiles can be manufactured in a composite form, utilising the protective nature of one type of construction to reduce damage on a working element. For example, a thick nonwoven fabric may be joined to a woven fabric; the woven textile performs the tensile work whilst the nonwoven acts as a damage protective cushion.

The filtration performance of a geotextile is governed by several factors. To understand this, it is essential to be aware that the function of the textile is not truly as a filter in the literal sense. In general, filters remove particles suspended in a fluid, for example, dust filters in air-conditioning units, or water filters, which are intended to remove impurities from suspension. Quite the opposite state of affairs exists with geotextile filters. The geotextile's function is to hold intact a freshly prepared soil

Table 14.1 Recommended time periods for maximum daylight exposure of geosynthetics. Beyond the limits shown damage may occur, depending upon sunlight intensity

	Temperate	Arctic	Desert	Tropical
April to Sept	8 Weeks	4 Weeks	2 Weeks	1 Week
Oct to March	12 Weeks	6 Weeks	2 Weeks	1 Week

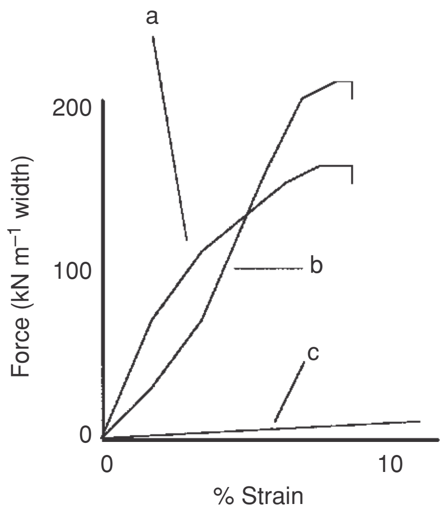
surface, so that water may exude from the soil surface and through the textile without breaking down that surface. If water is allowed to flow between the textile and the soil interface, with particles in suspension, it will tend to clog up the textile which will fail in its function. In practice, it has been found that, in conjunction with a textile, the soil will tend to filter itself, provided that the integrity of its external surface is maintained. The actual process taking place is the passage of a liquid from a solid medium that is held intact by a permeable textile. The process is not one of restraining the passage of solids that are suspended within a liquid medium.

Geotextiles are rarely called upon to resist extremely aggressive chemical environments. Particular examples of where they are, however, include their use in the basal layers of chemical effluent containers or waste disposal sites. This can happen if and when leaks occur, permitting effluent to pass through the impermeable liner, or if the textiles have been incorporated directly in the leachate disposal system above the impermeable liner. Another example might be the use of textiles in contact with highly acidic peat soils, where in tropical countries, pH values down to 2 have been encountered. In industrialised countries where infrastructure developments are being constructed through highly polluted and contaminated areas, geotextiles can also come into contact with adverse environments.

Ultraviolet light will tend to cause damage to most polymers, but the inclusion of additives, in the form of antioxidant chemicals and carbon black powder, can considerably reduce this effect. The only time when a geotextile is going to be exposed to sunlight is during the construction period. It is generally considered that contracts should specify the minimum realistic period of exposure during site installation works. However, this will vary with time of year and latitude. In brief, it can be considered that exposure in UK and northern European type climates can be eight weeks in the summer and twelve in the winter. In tropical countries, however, exposure should be limited to seven days at any time of year before noticeable damage occurs. Table 14.1 lists typical maximum exposure periods.

14.3.1 Mechanical properties

The weight or area density of the fabric is an indicator of mechanical performance only within specific groups of textiles, but not between one type of construction and another. For example, within the overall range of needlepunched continuous filament polyester fabrics, weight will correlate with tensile stiffness. However, a woven fabric with a given area density will almost certainly be much stiffer than an equivalent weight needlepunched structure. Clearly the construction controls the performance. Therefore, it is impossible to use weight alone as a criterion in specifying textiles for civil engineering use. However, in combination with other



14.2 Different stress–strain curve shapes exhibited by the three main types of geosynthetic construction. (a) Geogrids absorb the imposed stresses immediately, giving a high initial modulus. Later, the curve flattens. (b) Woven fabrics exhibit initial straightening of warp fibres which produces a low initial modulus. Later the modulus increases as the straightened polymer fibres take the stress directly. (c) Nonwovens give a curvilinear curve, because extension is primarily resisted by straightening and realignment of the random fibre directions.

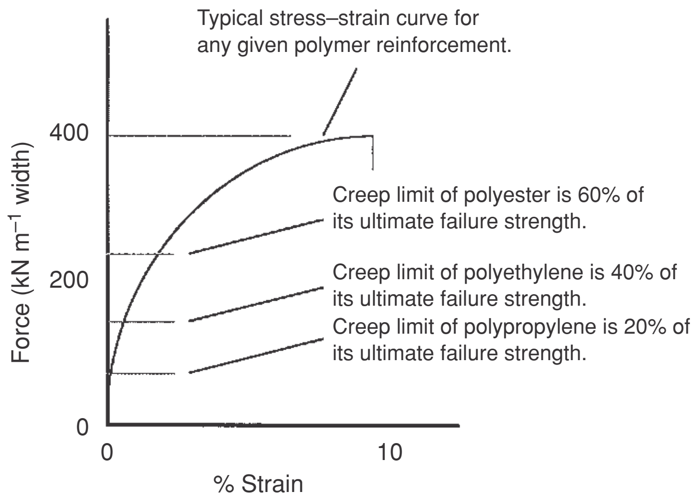
specified factors, weight is a useful indication of the kind of product required for a particular purpose.

The breaking strength of a standard width of fabric or 'ultimate strip tensile failure strength' is universally quoted in the manufacturers' literature to describe the 'strength' of their textiles. Again, this is of very limited use in terms of design. No designer actually uses the failure strength to develop a design. Rather, a strength at a given small strain level will be the design requirement. Therefore, the tensile resistance or modulus of the textile at say, 2%, 4%, and 6% strain is much more valuable. Ideally, continuous stress–strain curves should be provided for engineers, to enable them to design stress resisting structures properly.

Stress–strain curves, as shown in Fig. 14.1 and in Fig. 14.2 above, may well comprise a high strain sector, contributed by the textile structure straightening out, and a low strain sector, contributed by the straightened polymer taking the stress. Of course, the mechanical performance of the common geotextiles will be less as the ambient temperature rises. Because engineering sites are exposed to temperatures varying from –20 °C to 50 °C, this can have important consequences during installation and use.

Creep can cause the physical failure of a geotextile if it is held under too high a mechanical stress. It has been found that in practical terms, both polyester and polyethylene will stabilise against creep if stress levels can be maintained at a sufficiently low level. Although polypropylene does not seem to stabilise at any stress level, its creep rate is so low at small stresses that a 'no creep' condition may be considered to exist in practice.

The 'no creep' condition, measured as elongation, for any particular polymer



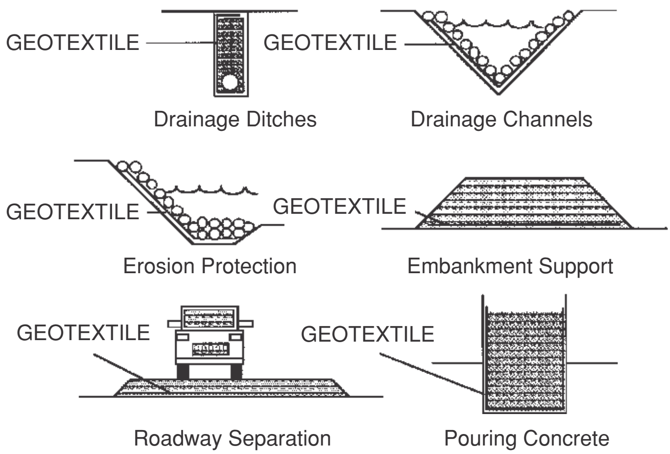
14.3 Approximate limits of creep resistance for different geosynthetic polymer constructions.

textile is defined (usually as a percentage) with respect to the textile's ultimate load-carrying capability. For polyester, it is approximately 60%, for polyethylene about 40% and for polypropylene around 20%. Therefore, for example, a polyester fabric with an ultimate tensile strength of 100 kN m^{-1} width cannot be loaded under a long term stress of more than 60 kN m^{-1}. The higher the level of imposed stress above this point, the more rapid will be the onset of creep failure. Figure 14.3 shows the safe loading limits for most commonly used geotextiles.

Wing tear, grab tear and puncture resistance tests may be valuable because they simulate on-site damage scenarios such as boulder dropping and direct over-running by machines. These tests are developed in standard form in a number of countries, with the standard geosynthetic test specification in the UK being BS 6906 which contains tests for:

1 tensile testing by means of a wide strip test
2 pore size testing by dry sieving
3 water flow testing normal to the plane of the textile
4 puncture resistance testing
5 creep testing
6 perforation susceptibility (cone) testing
7 water flow testing in the plane of the textile
8 testing of sand/geotextile frictional behaviour.

While not normally part of the mechanical requirements of a textile, the strength of joints between sheet edges is an important aspect of geotextile performance. When laying textiles on soft ground for supporting embankments, parallel sheets of textile have to be sewn together so that they do not separate under load. The strength of such sewn joints depends critically on the tensile strength of the sewing thread. Rarely will the sewn joint exceed 30% of the weft ultimate tensile strength. Research and field practice have shown that the strength of a sewn joint depends more upon the tenacity and tension of the sewing thread, the kind of sewing stitch



14.4 Some different drainage and filtration applications for geotextiles in civil engineering.

and the kind of textile lap than the strength of the textile. An erroneous but common concept of joint 'efficiency' has developed which expresses the strength of a sewn seam as a percentage of the textile strength. In fact, relatively weak textiles can be sewn such that the joint is as strong as the textile, thus giving a 100% efficiency. The stronger the textile, the less is the relative strength of the sewn joint, leading to falling efficiencies with stronger fabrics. Thus it is reasonable to request a 75% efficient sewn joint if the textiles being joined are relatively weak, say 20 kN ultimate strength, but it would be impossible to achieve with a textile of say 600 kN ultimate strength. Unfortunately, it is the stronger textiles that tend to need to be joined, in order to support embankments and the like.

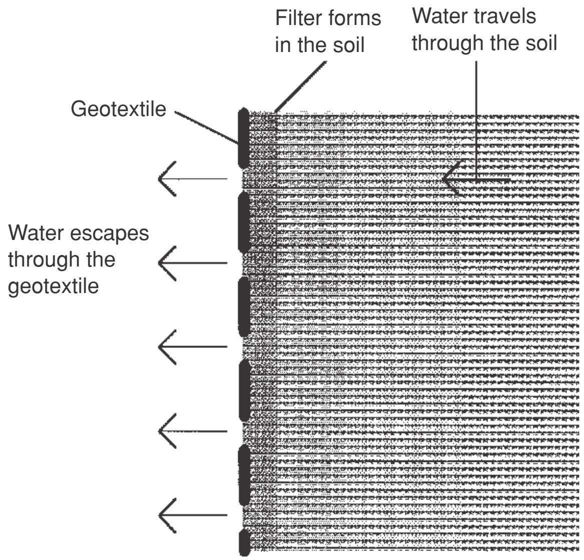
Adhesive joints, on the other hand, can be made using single-component adhesives whose setting is triggered by atmospheric moisture. These can be used to make joints which are as strong as the textile, even for high strength fabrics. Research is still needed on methods of application, but their use should become more widespread in the future.

Apart from tensile testing of joints, there is an urgent need to develop tests that give a meaningful description of the ways that textiles behave when stressed within a confining soil mass and additionally when stressed by a confining soil mass. The standard textile tests used in the past are not able to do this. Research work has been started along these lines but is so far insufficient to provide a basis for theoretical analysis.

14.3.2 Filtration properties

Filtration is one of the most important functions of textiles used in civil engineering earthworks. It is without doubt the largest application of textiles and includes their use in the lining of ditches, beneath roads, in waste disposal facilities, for building basement drainage and in many other ways (Fig. 14.4).

Of all the varied uses for geotextiles, only in a reinforced soil mass is there no beneficial filtration effect. In just about all other applications including drains, access



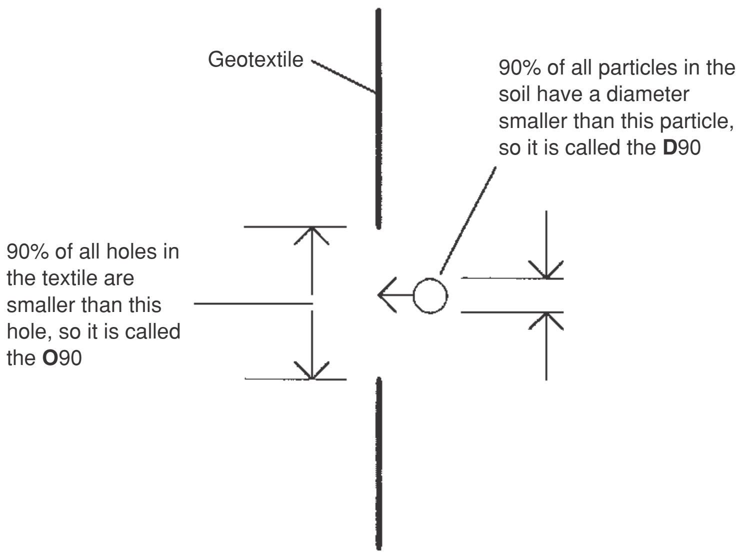
14.5 Internal soil filter zone generated by a geotextile.

roads, river defences, marine defences, embankment support and concrete pouring, the geotextile will play a primary or secondary filtering function.

The permeability of geotextiles can vary immensely, depending upon the construction of the fabric. Various national and international standards have been set up for the measurement of permeability that is required, most often at right angles to the plane of the textile (crossflow), but also along the plane of the textile (in-plane flow, called transmissivity). It is important in civil engineering earthworks that water should flow freely through the geotextile, thus preventing the build-up of unnecessary water pressure. The permeability coefficient is a number whose value describes the permeability of the material concerned, taking into account its dimension in the direction of flow; the units are rationalised in metres per second. Effectively the coefficient is a velocity, indicating the flow velocity of the water through the textile. Usually, this will be of the order of $0.001\,\mathrm{m\,s^{-1}}$. A commonly specified test measures a directly observed throughflow rate, which many feel is more practical than the permeability coefficient; this is the volume throughflow in litres per square metre per second at 100 mm head of pressure. Engineers also use a coefficient called the permittivity, which defines the theoretical permeability irrespective of the thickness of the fabric.

The filtration effect is achieved by placing the textile against the soil, in close contact, thus maintaining the physical integrity of the bare soil surface from which water is passing. Within the first few millimetres of soil, an internal filter is built up and after a short period of piping, stability should be achieved and filtration established (Fig. 14.5).

As previously discussed, filtration is normally achieved by making the soil filter itself, thus using a solid medium system, through which the liquid is flowing. There are, however, special cases where it is specifically required that the textile works in a slurry environment. Examples include tailing lagoons from mining operations and other industrial lagoons where water has to be cleared from slurries. Single textiles



14.6 Relationship between O90 and D90.

do not work well under these conditions, but experimental work has suggested that double layers of different types of textile acting as a composite unit can improve the ability of the individual components to effect filtration without clogging.

The simplest combination reported is a smooth woven textile over a thick needlepunched nonwoven fabric placed so that the former is between the needlepunched component and the slurry. It appears that the woven fabric acts as a 'shield', protecting the nonwoven from the liquid and emulating a soil surface, thus permitting the nonwoven to function more effectively as a filter. The drainage effect of the underlying nonwoven also possibly acts to induce high hydraulic gradients which, reciprocally, assist the woven to function.

The procedure for matching a textile to the soil, in order to achieve stability under difficult hydraulic conditions, is to use a textile whose largest holes are equal in diameter to the largest particles of the soil (see Fig. 14.6 where O90 = D90). Where hydraulic conditions are less demanding, the diameter of the largest textile holes can be up to five times larger than the largest soil particles (O90 = 5D90). Particularly difficult hydraulic conditions exist in the soil (i) when under wave attack, (ii) where the soil is loosely packed (low bulk density), (iii) where the soil is of uniform particle size, or (iv) where the hydraulic gradients are high. Lack of these features defines undemanding conditions. Between the two extremes lies a continuum of variation which requires the engineer to use experience and judgment in the specification of the appropriate O90 size for any given application.

The largest hole sizes and largest particle sizes are assessed by consideration of the largest elements of the fabric and soil. Measuring the largest particles of a soil is achieved by passing the soil through standard sieves. In order to assess a realistic indication of the larger particle diameters, a notional size is adopted of the sieve size through which 90% of the soil passes. This dimension is known as the D90 by convention. Similarly, an indication of the largest holes in a textile is taken as the 90% of the biggest holes in the fabric, the O90.

Even under ideal conditions, if the O90 pore size is bigger than 5D90, then so-called piping will take place. The textile O90 pore size should be reduced from 5D90 towards D90 as the ground and hydraulic conditions deteriorate.

14.3.3 Chemical resistance

Although the chemical mechanisms involved in fibre degradation are complex,[8] there are four main agents of deterioration: organic, inorganic, light exposure and time change within the textile fibres.

Organic agents include attack by micro- and macrofaunas. This is not considered to be a major source of deterioration per se. Geotextiles may be damaged secondarily by animals, but not primarily. For example, few animals will eat them specifically, but in limited instances, when the textile is buried in the ground, it may be destroyed by animals burrowing through. Microorganisms may damage the textiles by living on or within the fibres and producing detrimental by-products. Possibly the most demanding environment for geotextiles is in the surf zone of the sea where oxygenated water permits the breeding of micro- and macroorganisms and where moving water provides a demanding physical stress.

Inorganic attack is generally restricted to extreme pH environments. Under most practical conditions, geotextile polymers are effectively inert. There are particular instances, such as polyester being attacked by pH levels greater than 11 (e.g. the byproducts of setting cement), but these are rare and identifiable.

Geotextiles can fail in their filtration function by virtue of organisms multiplying and blocking the pores, or by chemical precipitation from saturated mineral waters blocking the pores. In particular, water egressing from old mine workings can be heavily saturated with iron oxide which can rapidly block filters, whether textile or granular.

Ultraviolet light will deteriorate geotextile fibres if exposed for significant periods of time, but laboratory testing has shown that fibres will deteriorate on their own with time, even if stored under dry dark cool conditions in a laboratory. Therefore, time itself is a damaging agent as a consequence of ambient temperature and thermal degradation, which will deteriorate a geotextile by an unknown amount.

14.4 Conclusions

Geotextiles are part of a wider group of civil engineering membranes called geosynthetics. They are extremely diverse in their construction and appearance. However, they are generally made from a limited number of polymers (polypropylene, polyethylene and polyester), and are mostly of five basic types: woven, heat-bonded, needlepunched, knitted and direct soil mixed fibres.

The physical properties of this diverse group of products vary accordingly, with ultimate strengths reaching up to 2000 $kN\,m^{-1}$, but commonly between 10 and 200 $kN\,m^{-1}$. Ultimate strains vary up to more than 100%, but the usable range for engineers is generally between 3 and 10%. Similarly, the filtration potential and permeability of different geotextiles vary enormously.

Geotextiles are used in civil engineering earthworks to reinforce vertical and steep banks of soil, to construct firm bases for temporary and permanent roads and highways, to line ground drains, so that the soil filters itself and prevents soil from

filling up the drainpipes and to prevent erosion behind rock and stone facing on river banks and the coast. They have been developed since the mid 1970s, but the advent of knitted and composite fabrics has led to a revival in attempts to improve textile construction in a designed fashion. Better physical properties can be achieved by using more than one fabric and by utilising the best features of each.

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14

Textiles in civil engineering. Part 2 – natural fibre geotextiles

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14.5 Introduction

Processes for the selection, specification, production and utilisation of synthetic geotextiles are well established in developed countries. In many ground engineering situations, for example temporary haul roads, basal reinforcement, consolidation drains, and so on, geotextiles are only required to function for a limited time period whereas suitable synthetic materials often have a long life. Hence, the user is paying for something which is surplus to requirement. Also, conventional geotextiles are usually prohibitively expensive for developing countries. However, many of these countries have copious supplies of cheap indigenous vegetable fibres (such as jute, sisal and coir) and textile industries capable of replicating common geotextile forms. Although, there are numerous animal and mineral natural fibres available, these lack the required properties essential for geotextiles, particularly when the emphasis of use is on reinforcing geotextiles.

Synthetic geotextiles not only are alien to the ground, but have other adverse problems associated with them, in that some synthetic products are made from petroleum-based solutions. As a result of the finite nature of oil, the oil crisis in 1973, the conflict with Kuwait and Iraq in 1991, and the potentially political volatile state of some of the world's other oil producing countries, both the cost and the public awareness of using oil-based products have considerably increased. Natural fibre products of vegetable origin will be much more environmentally friendly than their synthetic equivalents and the fibres themselves are a renewable resource and biodegradable.

14.6 Development of natural materials as geotextiles

The exploitation of natural fibres in construction can be traced back to the 5th and 4th millennia BC as described in the Bible (Exodus 5, v 6–9) wherein dwellings were

14.7 Woven mat and plaited rope reeds used as reinforcement in the Ziggurat at Dur Kurigatzu.

formed from mud/clay bricks reinforced with reeds or straw. Two of the earliest surviving examples of material strengthening by natural fibres are the ziggurat in the ancient city of Dur-Kurigatzu (now known as Agar-Quf) and the Great Wall of China.[1] The Babylonians 3000 years ago constructed this ziggurat using reeds in the form of woven mats and plaited ropes as reinforcement (Fig. 14.7). The Great Wall of China, completed circa 200 BC, utilised tamarisk branches to reinforce mixtures of clay and gravel.[1,2] These types of construction however, are more comparable to reinforced concrete than today's reinforced earth techniques, because of the rigid way in which stress was transferred to the tensile elements and the 'cemented' nature of the fill.

Preconceived ideas over the low apparent tensile strength of natural materials and the perception that they have a short working life when in contact with soil limited their uses, especially for strengthening soil, in geotechnical engineering at this early stage. Also, the lack of reliable methods of joining individual textile components to form tensile fabrics presented a major limitation to their usage.

The first use of a textile fabric structure for geotechnical engineering was in 1926, when the Highways Department in South Carolina USA[3] undertook a series of tests using woven cotton fabrics as a simple type of geotextile/geomembrane, to help reduce cracking, ravelling and failures in roads construction. The basic system of construction was to place the cotton fabric on the previously primed earth base and to cover it with hot asphalt; this however made the fabric perform more like a geomembrane than a geotextile. Although published results were favourable, especially for a fabric that had been in service for nine years, further widescale development of this fabric as a geotextile did not take place. This was probably due to the high extensibility and degradable nature of this particular natural fibre together with the advent of chemical fibres.

The earliest example of jute woven fabric geotextiles for subgrade support was in the construction of a highway in Aberdeen in the 1930s.[4] The British Army also

used a special machine to lay canvas or fascines over beaches and dunes for the invasion of Normandy in 1944.[5]

For thousands of years the textile industry has been spinning fibres to make yarns which in turn can be woven into fabrics. Up until the mid 1930s, these fibres were all naturally occurring, either vegetable or animal. At the beginning of this century the use of natural polymers based on cellulose was discovered, and this was quickly followed by production of chemical or synthetic products made from petroleum-based solutions.

The use of chemical fibre-based geotextiles in ground engineering started to develop in the late 1950s, the earliest two references being (i) a permeable woven fabric employed underneath concrete block revetments for erosion control in Florida[6] and (ii) in the Netherlands in 1956, where Dutch engineers commenced testing geotextiles formed from hand-woven nylon strips, for the 'Delta Works Scheme'.[7]

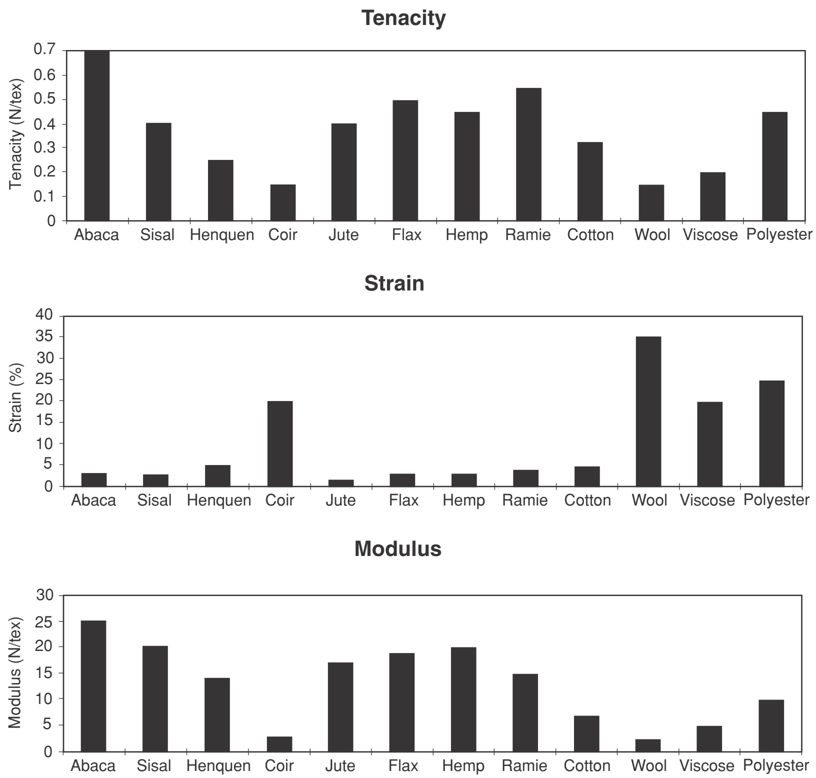
In the early 1960s, the excess capacity of synthetic products caused the manufacturers to develop additional outlets such as synthetic geotextiles for the construction industry. The manufacturers refined their products to suit the requirements of the engineer, rather than the engineer using the available materials to perform the requisite functions, because to a certain extent, fibre fineness and cross-sectional area can be modified to determine satisfactory tensile properties in terms of modulus, work of rupture, creep, relaxation, breaking force and extension. This led to the prolific production of synthetic materials for use in the geotextile industry. These synthetic geotextiles have monopolised the market irrespective of the cost both in economical and ecological terms. This put severe pressure on the manufacturers of ropes and cordage made from natural fibres, almost to the point of their extinction. In 1973, three fundamental applications were identified for the use of geotextiles, namely, reinforcement, separation and filtration,[8] with drainage applications (fluid transmission) also being a significant area. During the 1990s over 800 million m^2 of synthetic geotextiles have been produced worldwide,[9] making it the largest and fastest growing market in the industrial/technical fabrics industry.[10]

Although natural fibres have always been available, no one visualised their potential as a form of geotextile until synthetic fibres enabled diverse use and applications of geotextiles to emerge. Manufacturers are now attempting to produce synthetic fibres which will mimic the properties of natural fibres, but at a greater expense.

14.7 Natural fibres

The general properties of chemical fibres compared to natural fibres still tend to fall into distinct categories. Natural fibres possess high strength, modulus and moisture uptake and low elongation and elasticity. Regenerated cellulose fibres have low strength and modulus, high elongation and moisture uptake and poor elasticity. Synthetic fibres have high strength, modulus and elongation with a reasonable amount of elasticity and relatively low moisture uptake.

Natural fibres can be of vegetable, animal or mineral origin. Vegetable fibres have the greatest potential for use in geotextiles because of their superior engineering properties, for example animal fibres have a lower strength and modulus and higher



14.8 Typical strength, elongation and modulus values of natural fibres relative to those of synthetic fibres.

elongation than vegetable fibres. Mineral fibres are very expensive, brittle and lack strength and flexibility. Figure 14.8 shows typical strength, elongation and modulus values of natural fibres relative to those of synthetic fibres.

The pertinent factor for a geotextile, especially for reinforcement, is that it must possess a high tensile strength. It is known that the best way of obtaining this criterion is in the form of fibres which have a high ratio of molecular orientation. This is achieved naturally by vegetable fibres, but for synthetic polymers the molecules have to be artificially orientated by a process known as stretching or drawing, thus an increase in price is incurred. Hence nature provides ideal fibres to be used in geotextiles. In strength terms vegetable fibres compare very well with chemical fibres, in that the tenacity for cotton is in the region of $0.35\,\text{N}\,\text{tex}^{-1}$ and for flax, abaca and sisal it is between $0.4–0.6\,\text{N}\,\text{tex}^{-1}$ when dry, increasing when wet to the strength of high tenacity chemical fibres – the tenacity of ordinary chemical fibres is around $0.4\,\text{N}\,\text{tex}^{-1}$ (polyester). The Institute Textile de France showed (prior to 1988) that individual flax fibres (separated from their stems within the laboratory, using a process that does not weaken them) have a strength of $2 \times 10^6\,\text{kN}\,\text{m}^{-1}$ and modulus of $80 \times 10^6\,\text{kN}\,\text{m}^{-1}$, that is, of the same order as Kevlar,[11] a chemically modified polyamide, with exceptionally high strength compared to other synthetic fibres.

Natural fibre plants may be cultivated mainly for their fibre end-use (e.g. jute, sisal and abaca), but vegetable fibres are often a byproduct of food/crop produc-

tion. Flax fibre can be extracted from the linseed plant. Also, hemp fibre is extracted for paper pulp or textile use whilst the soft inner core of the stem is used for livestock bedding. The cultivation of flax and hemp fibre allows farmers to grow the fibre crops on set-aside land (land out of food production as part of a European Union policy to decrease surpluses) which would otherwise be standing idle.

Nature provides plants with bundles of fibres interconnected together by natural gums and resins to form a load-bearing infrastructure. These fibres are pliable, have good resistance to damage by abrasion and can resist both heat and sunlight to a much greater extent than most synthetic fibres. Some fibres can also withstand the hostile nature of the marine environment. However, all natural fibres will biodegrade in the long term as a result of the action of the microorganisms. In certain situations this biodegradation may be advantageous.

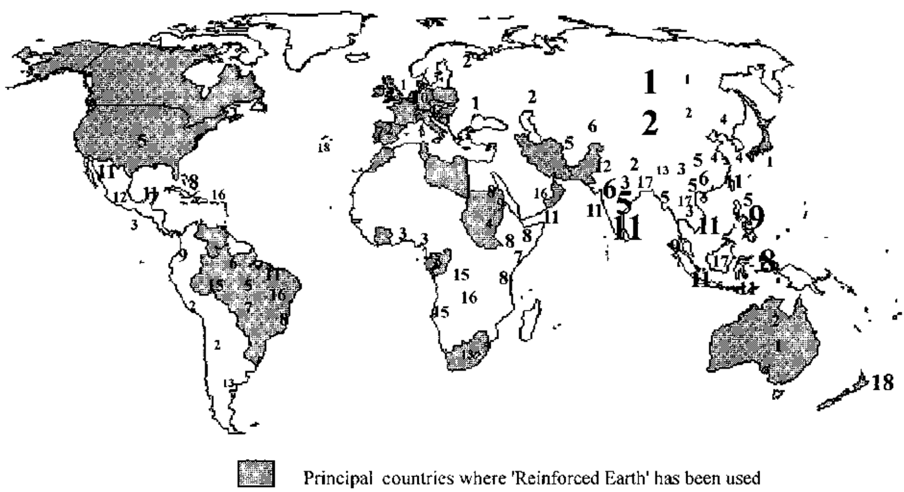
Vegetable fibres contain a basic constituent, cellulose, which has the elements of an empirical formula $(C_6H_{10}O_5)_n$. They can be classed morphologically, that is according to the part of the plant from which they are obtained:

1 *Bast* or *phloem fibres* (often designated as soft fibres) are enclosed in the inner bast tissue or bark of the stem of the dicotyledonous plants, helping to hold the plant erect. Retting is employed to free the fibres from the cellular and woody tissues, i.e. the plant stalks are rotted away from the fibres. Examples of the most common of these are flax, hemp and jute.
2 *Leaf fibres* (often designated as hard fibres) run hawser-like within the leaves of monocotyledonous plants. These fibres are part of the fibrovascular system of the leaves. The fibres are extracted by scraping the pulp from the fibres with a knife either manually or mechanically. Examples of these are abaca and sisal.
3 *Seed and fruit fibres* are produced by the plant, not to give structural support, but to serve as protection for the seed and fruit that are the most vulnerable parts of the plant normally attacked by predators. Examples of these are coir and cotton. With coir fibre, the coconut is dehusked then retted, enabling the fibre to be extracted.

A natural fibre normally has a small cross-sectional area, but has a long length. This length is naturally formed by shorter fibres (often referred to as the cell length) joined together by a natural substance, such as gum or resin (the exception to this is the fibre from the seeds of the plant, vis-à-vis cotton and kapok where the length of the fibre is the ultimate fibre length).

Of the 1000 to 2000 fibre-yielding plants throughout the world,[12] there are some 15–25 plants that satisfy the criteria for commercial fibre exploitation although a number of these are only farmed on a small scale. These main fibres are flax, hemp, jute, kenaf, nettle, ramie, roselle, sunn, urena (bast fibres) abaca, banana, cantala, date palm, henequen, New Zealand flax, pineapple, sisal, (leaf fibre) coir, cotton and kapok (seed/fruit fibres). Figure 14.9 indicates the principal centres of fibre production. The main factors affecting the production/extraction of vegetable fibres are:

1 The quantity of the fibre yield from the plant must be adequate to make fibre extraction a viable proposition.
2 There must be a practical and economical procedure for extracting the fibres, without causing damage to them, if they are to be of any value as a textile material.



14.9 Principal centres of fibre production. 1 Flax, 2 hemp, 3 sunn, 4 ramie, 5 jute, 6 kenaf, 7 roselle, 8 sisal, 9 abaca, 10 nettle, 11 coir, 12 cantala, 13 henequen, 14 kapok, 15 urena, 16 pineapple, 17 banana, 18 New Zealand flax. The size of the numbers indicates the most important countries for the production of fibre.

3 The pertinent properties of the fibre must be equivalent or superior to the existing chemical fibres used for the same given purpose in terms of both end production and machinability.
4 The annual yield of the fibre must be 'repeatable' and sufficiently large, i.e. if a plant has a high yield of fibre, say only every five years, then its marketability declines. Consideration must also be given to the time of harvest, i.e. late harvest yields lower quality fibres.
5 Whether there is a demand for the fibre properties on the market.
6 If there are problems of plant diseases and insect attack – protection from which has seen major improvements in the 20th century.

Advantages of developing such indigenous geotextiles would be:

- robust fibre
- environmental friendliness
- low unit cost
- strength/durability of some natural fibres, which are superior to chemical products
- reinforcing material is on the doorstep of developing countries
- increase in demand for the grower, therefore more money entering the country
- good drapability
- biodegradability
- additional use of byproducts or new use for waste.

14.7.1 Vegetable fibre properties

When selecting the most suitable vegetable fibres for geotextiles, consideration must be given to the general properties of available natural fibres in terms of strength,

elongation, flexibility, durability, availability, variability and their production forms, from the civil engineering and textile aspects. Also, factors affecting the economics of fibre cultivation and extraction on a large commercial scale should be taken into account. Allowing for the above factors, six vegetable fibres have been selected as the most promising to form geotextiles: flax, hemp, jute, abaca, sisal and coir (not in the order of priority). A generalised description of these plants/fibres is given in Tables 14.2 to 14.7, with typical values of their physical, mechanical, chemical and morphological characteristics shown in Tables 14.8 to 14.11.

Hemp and flax can be cultivated in the climatic conditions experienced in temperate countries such as the UK. Hemp does not require any pesticide treatment whilst growing. Both hemp and flax are very similar types of plant and are grown/cultivated in virtually identical conditions, producing almost similar properties in terms of fibre. However, hemp requires a licence from the Home Office for its cultivation, which imposes disadvantages compared to flax. Jute has emerged from its infancy in geotechnical engineering and has found a potential market in the erosion control industry, but may lack durability for other end-uses.

Strength properties of abaca may be superior to those of sisal, but the overall properties/economics of sisal may just outweigh those of abaca, that is, abaca is only cultivated in two countries throughout the world, with a production of less than one-fifth of sisal fibre. However, with leaf fibres retting has to be conducted within 48 hours of harvesting because otherwise the plant juices become gummy, and therefore fibre extraction is more difficult and unclean fibre is produced.

In certain categories, coir does not perform to the same standards as other fibres (i.e. low strength and high elongation), but general factors related to coir overshadow most of the other fibres for specific applications. The energy required to break the coir fibres is by far the highest of all the vegetable fibres, indicating its ability to withstand sudden shocks/pulls. Also, it is one of the best fibres in terms of retention of strength properties and biodegradation rates (in both water and sea water).

Further prioritisation of these six vegetable fibres will ultimately depend on the utilisation/end application of the geotextile.

14.8 Applications for natural geotextiles

The use of geotextiles for short-term/temporary applications to strengthen soil has a particular niche in geotechnical engineering. Geotextiles are used extensively in developed countries to combat numerous geotechnical engineering problems safely, efficiently and economically. They have several functions which can be performed individually or simultaneously, but this versatility relies upon the structure, physical, mechanical and hydraulic properties of the geotextile. Details of the general properties required to perform the functions of the geotextiles for various applications are given in Table 14.12.

14.8.1 Soil reinforcement

Soil is comparatively strong in compression, but very weak in tension. Therefore, if a tensile inclusion (geotextile) is added to the soil and forms intimate contact with it, a composite material can be formed which has superior engineering

Table 14.2 General description of flax plant/fibre

Fibre names and family	Flax	(Liniaceae)
Genus and species	*Linum usitatissimum*	(Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 16–32 mm, stem length 0.9–1.2 m. Harvested after 90 days of growth when stems are green-yellow. 30 bundles of fibre in stem, each bundle contains 10–14 individual (ultimate) fibres. Low input crop fits well on a rotation scheme (6–7 years)[13]	
Countries of cultivation	Russia (80%), China, Egypt, Turkey, Philippines, Malaysia, Sri Lanka, Japan, New Zealand, UK, Poland, France, Belgium, Netherlands, USA, Canada, Argentina, West Indies, Japan and Taiwan	
Environmental – climate requirements	90% of the world's production is grown between 49° to 53°N, but can be cultivated between 22° to 65°N and 30° to 45°S	
Soil type	Rich deep loams, slightly acidic[13]	
Components of yield	One quarter of stem consists of fibre. Stem is pulled out of ground not cut, therefore longer fibres are obtained. 5–7 tonnes of flax per hectare, of which 15–20% can be extracted as long fibre, 8–10% as short fibre or tow, 5–10% seed, 45–50% woody core or shives.[13] There has been little flax produced in the UK because until recently there was no processing industry, however there is now an EC subsidy for seed flax to produce linseed oil[13]	
Uses	Linen, twines, ropes fishing nets, bags, canvas & tents. Tow fibre; high grade paper, i.e. cigarette paper and banknotes. Linseed oil and linseed flax fibre	
World annual production (tonnes)	830 000[14] 3rd most important fibre in terms of cash and acreage. Ranks 4th for the total fibre production (1st cotton, 2nd jute, 3rd kenaf)	
£ per tonne	Long line 800–2000, tow 300–700[15]	
Fibre extraction – retting	Retting affects the colour, 85% by dew retting (3–7 wks) fibre grey in colour, producing cheaper better fibre by less labour intensive way than dam, tank and chemical retting. After retting, fibre is broken away from the stems and combed	
Effects from water, sea water, pests, etc.	Fibre strength increases when wet. Pests; flea, beetles and thrips, however in general flax is not very vulnerable[13]	
Cross-section bundles	Roundish elongated irregular[16]	
Ultimate fibre	Nodes at many points, cell wall thick and polygonal in cross-section. Cell long and transparent	
Longitudinal view	Cross-marking nodes and fissures[16]	
Fibre cell ends	Ends taper to a point or round[17]	
Properties compared to other fibres	Physical and chemical properties are superior to cotton	
General fibre detail, colour, etc.	Yellowish-white, soft and lustrous in appearance. High degree of rigidity and resists bending. Russian flax weak but very fine	
General	Inextensible fibre, more elongation obtained when dry. One of the highest tensile strength and modulus of elasticity of the natural vegetable fibres. Density same as polymers, thus used as alternative reinforcement to glass, aramid and carbon in composites. Good conductor of heat and can be cottonised	

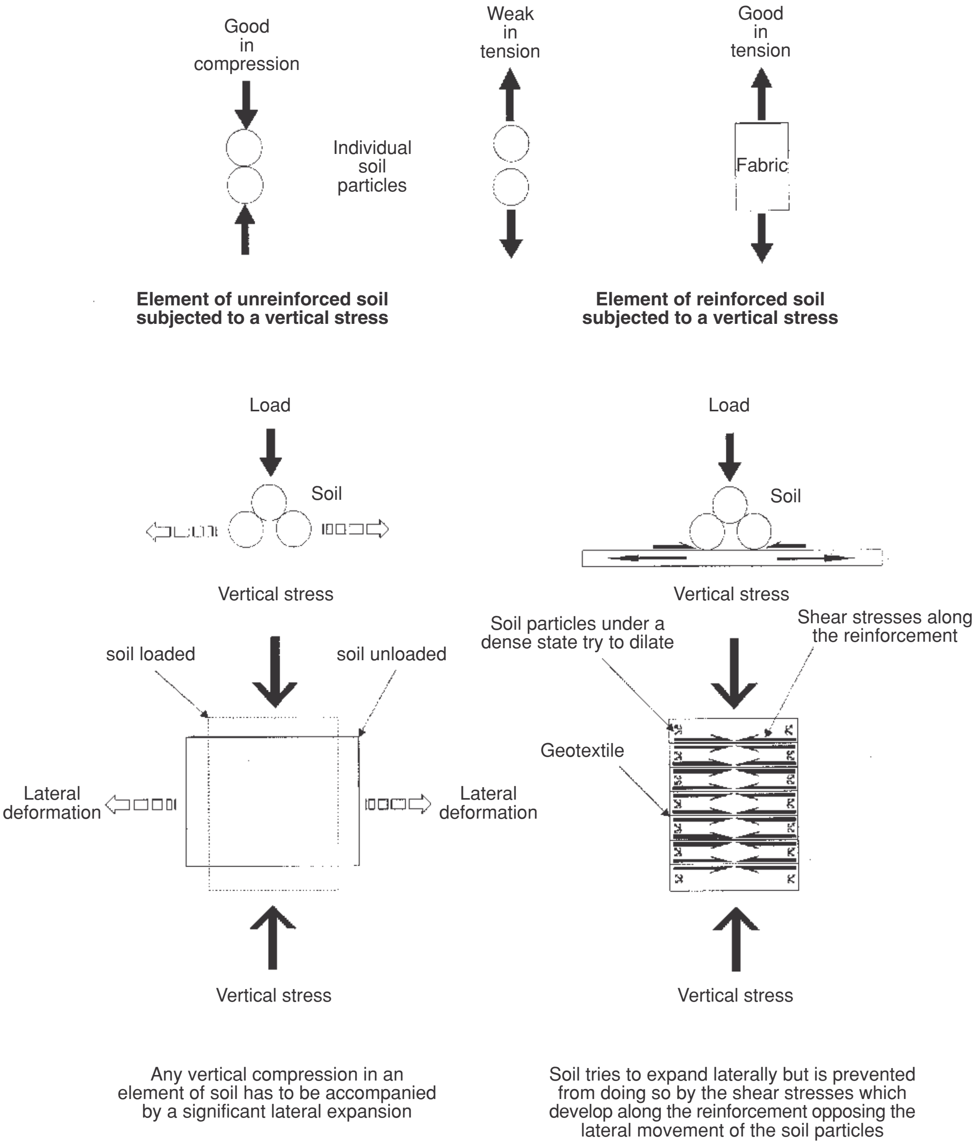
Table 14.3 Generalised description of hemp plant/fibre

Fibre names and family	Hemp	(Moraceae)
Genus and species	*Cannabis sativa*	(Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 4–20 mm, stem length 4.5–5 m. Harvested after 90 days	
Countries of cultivation	Russia, Italy, China, Yugoslavia, Romania, Hungry, Poland, France, Netherlands, UK and Australia	
Environmental – climate requirements	Annual rainfall >700 mm mild climate with high humidity	
Soil type	Best results from deep, medium heavy loams well-drained and high in organic matter. Poor results from mucky or peat soils and should not be grown on the same soil yearly	
Components of yield	Not hard to grow. Hemcore Ltd in 1994 grew 2000 acreage in East Anglia	
Uses	Ropes, marine cordage, ships sails, carpets, rugs, paper, livestock bedding and drugs	
World annual production (tonnes)	214 000[14] Ranks 6th in importance of vegetable fibre	
£ per tonne	300–500[15]	
Fibre extraction – retting	Same process as flax, at 15–20°C retting takes 10 to 15 days. Separation of the fibre from the straw can be carried out mechanically; this is commercially known as green hemp	
Effects from water, sea water, pests, etc.	Not weakened or quickly rotted by water or salt water. No pesticide protection required for growth	
Cross-section bundles	Similar to flax[16]	
Ultimate fibre	Similar to flax, polygonal in cross-section	
Longitudinal view	Similar to flax[16]	
Fibre cell ends	Rounded tips, ends of cell are blunt	
Properties compared to other fibres	Stronger, more durable, stiffer and more rigid and coarser than most vegetable fibres	
General fibre detail, colour, etc.	Harsh, stiff and strong fine white lustrous and brittle. Suitable for weaving of coarse fabric	
General	30 varieties, narcotic drug terrahydrocannabinol (THC), in some countries cultivation illegal (cultivated now <0.3% THC thus no narcotic value). Lacks flexibility and elasticity, i.e. brittle fibre. One hectare of hemp produces as much pulp as 4 acres of forest. Can be cottonised, i.e. up to 50% hemp, does not spin easily but produces useful yarns	

characteristics to soil alone. Load on the soil produces expansion. Thus, under load at the interface between the soil and reinforcement (assuming no slippage occurs, i.e. there is sufficient shear strength at the soil/fabric interface) these two materials must experience the same extension, producing a tensile load in each of the reinforcing elements that in turn is redistributed in the soil as an internal confining stress. Thus the reinforcement acts to prevent lateral movement because of the lateral shear stress developed (Fig. 14.10). Hence, there is an inbuilt additional lateral confining stress that prevents displacement. This method of reinforcing the soil can be extended to slopes and embankment stabilisation. The following exam-

Table 14.4 Generalised description of jute plant/fibre

Fibre names and family	Jute (Tiliaceae)
Genus and species	*Corchorus capsularus* and *Corchorus olitorius* (Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 20 mm, stem length 2.5–3.5 m. Harvested after 90 days, small pod stage best fibre yield
Countries of cultivation	India, Bangladesh, China, Thailand, Nepal, Indonesia, Burma, Brazil, Vietnam, Taiwan, Africa, Asia and Central and South America
Environmental – climate requirements	Annual rainfall >1800 mm required >500 mm during the growing season, high humidity between 70–90%, temperature between 70–100 °F, i.e. hot damp climates
Soil type	Rich loam soils produce best results, well-drained soils obtain reasonable results, with rocky – sandy soils producing poor results
Components of yield	Easily cultivated and harvested. Line sowing increases yield by 25–50% and reduces cost of cultivation by 25%
Uses	Ropes, bags, sacks, cloths. Erosion control applications; geojute, soil-saver, anti-wash, etc.
World annual production (tonnes)	2 300 000[14] 2nd most important fibre in terms of cash and acreage
£ per tonne	300–500[15]
Fibre extraction – retting	Same process as flax. Late harvest requires prolonged retting. 1–5% oil & water emulsion is added to soften the fibre for spinning into yarns
Effects from water, sea water, pests, etc.	Fibre deteriorates rapidly when exposed to moisture. Plant; damage by excessive: heat, drought, rainfall and floods. Pests; semilooper, mite, hairy, caterpillar and apion
Cross-section bundles	Varying size roundish or elongated[16]
Ultimate fibre	Sharply polygonal, rounded (5–6 sides) corners; wall thickness varies
Longitudinal view	Fissures and cross marking are unlikely. Lumen varies in size along each fibre
Fibre cell ends	Round tips partly pointed and tapered
Properties compared to other fibres	Not as strong as hemp and flax nor as durable
General fibre detail, colour, etc.	White, yellow, red or grey; silt like and easy to spin. Difficult to bleach and can never be made pure white owing to its lack of strength. If kept dry will last indefinitely, if not will deteriorate in time
General	Holds 5 times its weight of water. Cheap and used in great quantities, high initial modulus, but very little recoverable/elasticity (woody fibre); exhibiting brittle fracture, having small extension at break. Poor tensile strength, good luster (silky), high lignin content. Individual fibres vary greatly in strength owing to irregularities in the thickness of the cell wall



14.10 Principle of reinforced earth.

ples illustrate typical applications where geotextiles are employed to strengthen soil for a limited amount of time.

14.8.1.1 Long-term embankments

Many developing countries have engineering situations where geotextiles could be employed to great benefit, for example hillside stabilisation, embankment and flood bank strengthening and construction over soft ground. Such countries often have copious, renewable supplies of natural fibres. Labour is also abundant in these developing countries, therefore it is more desirable to construct inexpensive short-term projects, monitor and assess their stability periodically and rebuild them

Table 14.5 Generalised description of abaca plant/fibre

Fibre names and family	Abaca or Manila hemp	(Musaceace)
Genus and species	*Musa textilis*	(leaf fibre)
Plant type – harvesting	Perennial plant, 12–30 stems per plant, leaves 2–4 m, stem diameter 130–300 mm, stems length 7.5 m. Stem contains 90% water/sap with 2–5% fibre the rest soft cellular tissue. Plant life 10–20 years without replanting, fertilisation or rotation, thus impoverishes the soil. Productivity life 7–8 years, harvest 3 stalks every 4–5 months	
Countries of cultivation	Philippines (85%) & Ecuador (15%)	
Environmental – climate requirements	Warm climate, shade, abundant moisture and good drainage. Altitude <900 m heavy rainfall (2500–3000 mm per year) uniformly distributed throughout the year and high humidity are most advantageous. Too much heat causes excessive evaporation from the leaves, thus damages them and the fibres. Also immersion in water injures the plant	
Soil type	Needs little cultivation, best grown in very fertile and well-drained soils	
Components of yield	Fibre obtained from the stem of the leaves not the expanded portion of the leaf. After efflorescence plant dies. Yield up to 1 tonne of dry fibre per acre. Maximum production between 4–8 years. 100 kg of fresh leaves produce 1–3 kg of fibre	
Uses	Marine cordage (naturally buoyant), fishing nets, mission ropes, well-drilling cables, paper and tea bags	
World annual production (tonnes)	70 000[14]	
£ per tonne	680–1150	
Fibre extraction – retting	Within 48 hours if not the plant juices become gummy thus fibre extraction is more difficult and unclean fibre is produced also waste water is acidic. Fibre extracted by separating the ribbons (tuxies) of the fibre from the layers of pulp by a knife to remove the residual pulp then hung to dry (this process can be carried out by machines)	
Effects from water, sea water, pests, etc.	Good water-resisting properties, hydroscopic, not affected by salt water. Pests; brown aphids, corm weevil, slug caterpillar	
Cross-section bundles	Roundish, slightly indented or round to elliptical[16]	
Ultimate fibre	Cells are uniform, smooth and regular surface, thus poor interlock, i.e. hard to make into a yarn. Polygonal, slightly rounded corners[16]	
Longitudinal view	Smooth cross-markings rare[16]	
Fibre cell ends	Thin smooth walls and sharp or pointed ends tapered. Cell diameter 3–4 times thicker than the cell wall. Cylindrical, long and regular in width	
Properties compared to other fibres	Superior to flax, better than hemp for marine ropes and hawers	
General fibre detail, colour, etc.	Cream and glossy, stiff and tenacious; even texture, very light weight	
General	Strong and sufficiently flexible to provide a degree of give when used in ropes where strength, durability and flexibility are essential. There are 4 groups of fibre yielded from this plant, depending on where the leaves have come from; (i) Outside sheaths (*Primera baba*) dark brown/light purple & green strips (i.e. exposure to sun) Grade 4–5. (ii) Next to outside (*segunda baba*) light green and purple, Grade 3. (iii) Middle (Media), Grade 2. (iv) Innermost (Ubod), Grade 1. The grade also depends on knife type to extract the fibre	

Table 14.6 Generalised description of sisal plant/fibre

Fibre names and family	Sisal
Genus and species	*Agave sisalana* (Leaf fibres)
Plant type – harvesting	Perennial plant, leaves 1–2 m long each containing about 1000 fibres
Countries of cultivation	Central America, Mexico, Brazil, Philippines, India, Florida, Africa, Venezuela, Tanzania, Kenya, Madagascar, Mozambique, Angola and Ethiopia
Environmental – climate requirements	If rainfall is erratic growth is spasmodic, thus low annual yield. Temperature between 27–32 °C (<16 °C), frost damages leaves, optimum rainfall 1200–1800 mm, but can withstand droughts, when other plants would perish, requires substantial amounts of strong sunlight
Soil type	Grows on dry, porous, rocky, not too acidic or low in nutrients free draining soils. Hardy plant can grow in mimimum rainfall 250–375 mm per year. Waterlogging and salinity are fatal to sisal
Components of yield	If the leaves are in the shade poor quality fibre is produced. Also cold, frost and hail can damage the leaves (fibre). There are spines at the tips of leaves. The leaves are harvested after 2–4 years of growth and then at intervals, after efflorescence plant dies, 45 kg of leaves produce approximately 2 kg of long and tow fibre
Uses	Twines, ropes, rugs, sacking, carpets, cordage and agricultural. Tow (waste product) used for upholstery
World annual production (tonnes)	378 000[14]
£ per tonne	450–1100[15]
Fibre extraction – retting	Within 48 hours if not the plant juices become gummy, thus fibre extraction is more difficult and unclean fibre is produced. Machines are used which scrape the pulpy material from the fibre, after washing, the fibre is dried and bleached in the sun, or oven-dried
Effects from water, sea water, pests, etc.	It was once believed that sisal deteriorated rapidly in salt water; experience has shown that this is not the case. Sisal is widely used for marine ropes.
Cross-section bundles	(i) Crescent to horse-shoe often split.[16] (ii) Few or no hemi-concentrical bundles with cavities.[16] (iii) Round ellipt[16]
Ultimate fibre	Polygonal wall, thick to medium.[16] Stiff in texture, wide central cavity (may be wider than the cell wall), marked towards the middle
Longitudinal view	Smooth[16]
Fibre cell ends	Same thickness as abaca, but half as long. Rounded tips, seldom forked – pointed[16]
Properties compared to other fibres	Shorter, coarser and not quite as strong as abaca. Also lower breaking load and tends to break suddenly without warning. Can be spun as fine as jute. Sisal can be grown under a wider range of conditions then henequen
General fibre detail, colour, etc.	Light yellow in colour, smooth, straight, very long and strong fibre. Number of different types of cells inside a sisal plant; normal fibre cell straight, stiff, cylindrical and often striated
General	Blooms once in its lifetime then dies. Cheap, stiff, inflexible, high strength and good lustre. Sisal fibre is equivalent hand or machine stripped. Dark bluish-green leaves, having a waxy surface to reduce water loss

Table 14.7 Generalised description of coir plant/fibre

Fibre names and family	Coir	(Coconut fibre)
Genus and species	*Cocos nucifera*	(Seed/fruit fibre)
Plant type – harvesting	Perennial plant 70–100 nuts per year, fruit picked every alternate month throughout the year. Best crop between May & June, economic life 60 years. Two types of coir; brown and white. Brown coir obtained from slightly ripened nuts. White coir obtained from immature nuts (green coconuts) fibre being finer and lighter in colour	
Countries of cultivation	India (22%), Indonesia (20%), Sri Lanka (9%), Thailand, Malaysia, Brazil, Philippines, Mexico, Kenya, Tanzania, Asia, Africa, Kerala State, Latin America and throughout the Pacific regions	
Environmental – climate requirements	20°N to 20°S latitude, planted below an altitude of 300 m. Temperature 27–32 °C, diurnal variations <7 °C, rainfall between 1000–2500 mm, >2000 hours of sunshine i.e. high humidity and plenty of sunlight	
Soil type	Wide range of soils. Best results are from well-drained, fertile alluvial and volcanic soils	
Components of yield	Husk to nut ratio, size of nuts, fibre quality, huskability, pests and diseases. Harvesting: men climb trees, from ground, or use a knife on the end of a bamboo pole, monkeys (*Macacus nemestrima*) also climb trees to collect the nuts	
Uses	Known as the tree of life, because source of many raw materials; leaves used for roofs and mats, trunks for furniture, coconut meat for food, soap and cooking oil, roots for dyes and traditional medicines, husk for ropes, cordage and sailcloths; in marine environments	
World annual production (tonnes)	100 000[14]	
£ per tonne	200–800[15]	
Fibre extraction – retting	Retting pits (brown fibre up to 9 months, white fibre 2–6 weeks). Dehusked manually or mechanically (brown fibre only)	
Effects from water, sea water, pests, etc.	Coir is resistant to degradation by sea water, endures sudden pulls, that would snap the otherwise much stronger ropes, made from hemp or other hard fibres	
Cross-section bundles	Round mostly, with cavities, hemi-concentrical bundles[16]	
Ultimate fibre	Polygonal to round, also oblong walls, medium thickness. Round and elliptical in cross-section[16]	
Longitudinal view	Smooth[16]	
Fibre cell ends	Blunt or rounded[16]	
Properties compared to other fibres	Mature brown coir fibre contains more lignin and less cellulose than fibres such as flax and cotton	
General fibre detail, colour, etc.	Reddish-brown strong, elastic filaments of different lengths, thicker in middle and tapers gradually towards the ends. Naturally coarse, suitable for use in sea water, high lignin content makes it resistant to weathering	
General	Extremely abrasive and rot resistant (high % of lignin) under wet and dry conditions and retains a high percentage in tensile strength. Surface covered with pores, but relatively waterproof, being the main natural fibre resistant to damage by salt water	

Table 14.8 Typical values of chemical, mechanical, morphological and physical characteristics of vegetable fibres

Chemical composition of plant fibres							
Fibre type	Cellulose (%)	Hemi-cellulose (%)	Pectin (%)	Lignin (%)	Water-soluble (%)	Fat and Wax (%)	Moisture (%)
Flax	64.1	16.7	1.8	2.0	3.9	1.5	10.0
Jute	64.4	12.0	0.2	11.8	1.1	0.5	10.0
Hemp	67.0	16.1	0.8	3.3	2.1	0.7	10.0
Sisal	65.8	12.0	0.8	9.9	1.2	0.3	10.0
Abaca	63.2	19.6	0.5	5.1	1.4	0.2	10.0
Coir	35–45	1.25–2.5		30–46		1.3–1.8	20

Figures in Tables 14.8 to 14.11 are obtained from reference sources Lewin and Pearce,[17] McGovern,[18] van Dam,[19] and Mandal.[20]

Table 14.9 Mechanical parameters from stress–strain for vegetable fibres

Fibre type	Tensile ($kN\,m^{-2} \times 10^6$)	Tenacity ($N\,tex^{-1}$)	Initial modulus ($N\,tex^{-1}$)	Extension at break (%)	Work of rupture ($N\,tex^{-1}$)
Flax	0.9	0.54–0.57	17.85–18.05	1.6–3	0.0069–0.0095
Jute	0.2–0.5	0.41–0.52	19.75	1.7	0.005
Hemp	0.3–0.4	0.47–0.6	17.95–21.68	2.0–2.6	0.0039–0.0058
Sisal	0.1–0.8	0.36–0.44	25.21	1.9–4.5	0.0043
Abaca	1.0	0.35–0.67	17.17	2.5–3	0.0077
Coir	0.1–0.2	0.18	4.22	16	0.0157

Table 14.10 Morphological plant fibre characteristics

Fibre type	Long length (mm)	Diameter (mm)	Fineness (Denier)	Cell length (mm)	Cell diameter (um)
Flax	200–1400	0.04–0.62	1.7–18	4–77	5–76
Jute	1500–3600	0.03–0.14	13–27	0.8–6	5–25
Hemp	1000–3000	0.16	3–20	5–55	10–51
Sisal	600–1000	0.1–0.46	9–406	0.8–8	7–47
Abaca	1000–2000	0.01–0.28	38–400	3–12	6–46
Coir	150–350	0.1–0.45		0.3–1.0	15–24

Table 14.11 Physical plant fibre characteristics

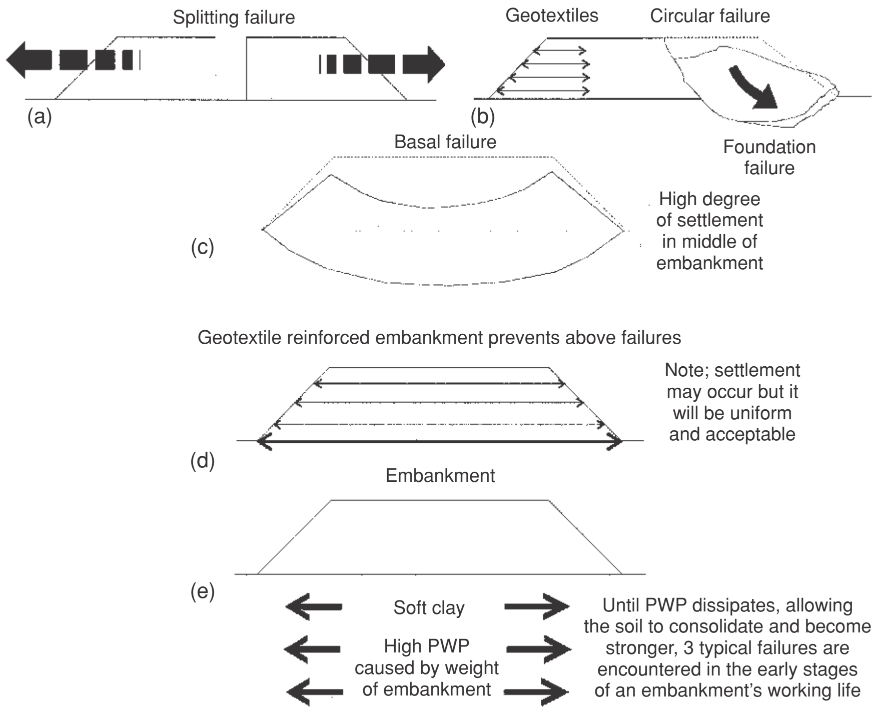
Fibre type	Specific gravity (%)	Specific heat ($cal\,g^{-1}\,°C^{-1}$)	Moisture regain (%) 65% RH 20°C	Absorption (%)	Volume swelling (%)	Specific heat ($cal\,g^{-1}\,°C^{-1}$)	Porosity (%)	Apparent density ($g\,cm^{-3}$)	True density ($g\,cm^{-3}$)
Flax	1.54		12	7	30		10.7	1.38	1.54
Jute	1.5	0.324	13.8	10–12.5	45	0.324	14–15	1.23	1.44
Hemp	1.48	0.323	12	8		0.323			1.5
Sisal	1.2–1.45	0.317	14	11	40	0.317	17	1.2	1.45
Abaca	1.48		14	9.5			17–21	1.2	1.45
Coir	1.15–1.33			10					1.15

able 14.12 Functional requirements for geotextiles

eotextiles nctions	Tensile strength	Elongation	Chemical resistance	Biodegradability	Flexibility	Friction properties	Interlock	Tear resistance	Penetration	Puncture resistance
einforcement	iii	iii	ii–iii	iii	i	iii	iii	i	i	i
ltration	i–ii	i–ii	iii	iii	i–ii	i–ii	iii	iii	ii	ii
eparation	ii	iii	iii	iii	iii	i	ii	iii	iii	ii
rainage	na	i–ii	iii	iii	i–ii	na	ii	ii–iii	iii	iii
rosion control	ii	ii–iii	i	iii	iii	ii	i	ii	ii	i–ii

eotextiles nctions	Creep	Permeability	Resistance to flow	Properties of soil	Water	Burial	UV light	Climate	Quality assurance & control	Costs
einforcement	iii	na-i	i	iii	iii	iii	ii	na	iii	iii
ltration	na	ii–iii	i	ii	iii	iii	na	iii	iii	iii
eparation	na	ii–iii	i	na	iii	iii	na	i	ii	iii
rainage	na	iii	i	na	iii	iii	na	iii	iii	iii
rosion control	na	ii	iii	na	iii	na	iii	iii	i	iii

= Highly important, ii = important, i = moderately important, na = not applicable.

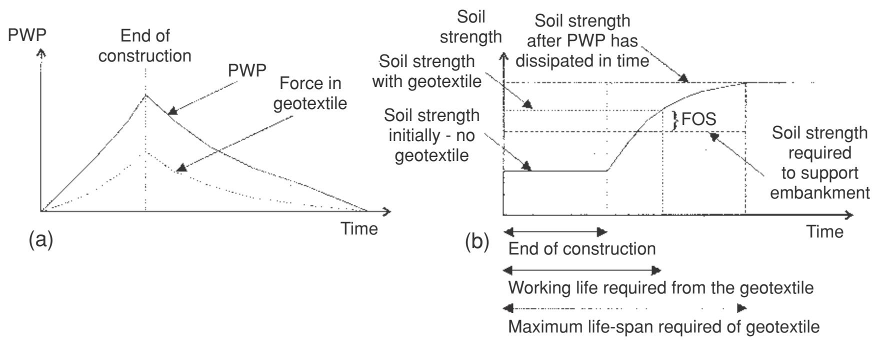


14.11 Short-term applications for geotextiles in embankments.

after a number of years if necessary (i.e. when the natural material has lost sufficient strength owing to the degradation process that it can no longer withstand the applied tensile forces). Furthermore, this procedure enriches the soil thereby improving growing conditions without introducing harmful residues. Although, it is not suggested, these natural geotextiles would be a universal panacea; they would have a significant impact on the economy of developing countries.

14.8.1.2 Short-term embankments

Geotextiles provide an invaluable solution to the problem of constructing embankments over soft compressible ground where water fills the pores between the soil particles under the embankment. The load from the embankment fill increases the tendency for the embankment to fail. Figure 14.11(a) to (c) illustrates three typical modes of failure that may be encountered (splitting, circular and basal) caused because the underlying soft soil does not have sufficient strength to resist the applied shear stresses (water has no shear strength). The use of geotextiles at vertical increments in an embankment and/or at the bottom of it, between the underlying soft soil and embankment fill (Fig. 14.11(d)), would provide extra lateral forces that either prevent the embankment from splitting or introduce a moment to resist rotation. Compression of the soft soil beneath the embankment will occur, but this will be uniform, which is acceptable. The embankment loading increases the water pressure in the pores in the underlying ground, especially at the centre of the embankment, whilst the pore water pressure (PWP) in the soil at and preceding the



14.12 Stabilising force to be provided by the geotextile will diminish with time. FOS = factor of safety.

extremities of the embankment is low in comparison (Fig. 14.11(e)). Thus, there is a pressure gradient set-up and water migrates from beneath the embankment sideways so that the PWP falls. Stability of the embankment will improve in time (1–2 years) as the excess PWP from the underlying soft soil dissipates (Fig. 14.11(e) and Fig. 14.12(a)). Hence its strength will increase and the stabilising force that has to be provided by the geotextile will diminish with time as shown in Fig. 14.12(b). This decrease (in the required stabilising force) can be designed to correspond to the rate of deterioration of the vegetable fibre geotextile. If necessary the rate of dissipation of the excess PWP can be enhanced by the use of consolidation drains.

14.8.1.3 Specialist areas – short-term

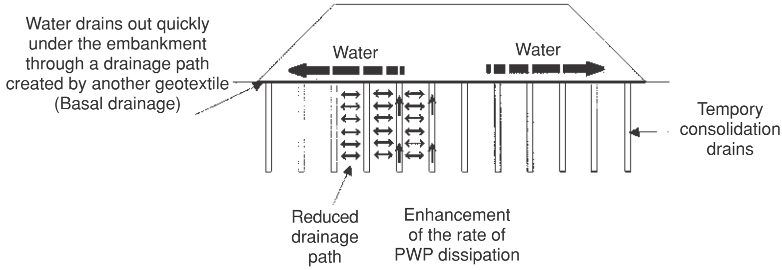
The armed forces often have to construct temporary roads/structures very quickly when they are dealing with confrontations. Also, these structures must be capable of being demolished if the soldiers have to retreat. By employing indigenous vegetable fibre materials as reinforcing geotextiles, the additional costs associated with the long life of synthetic geotextiles are not incurred. Decommissioning the reinforced structure is a low cost procedure – the structure can be destroyed by machinery or explosives and the natural geotextiles left to rot in the soil or set on fire, without leaving any resources for the enemy to exploit.

14.8.2 Drainage (fluid transmission)

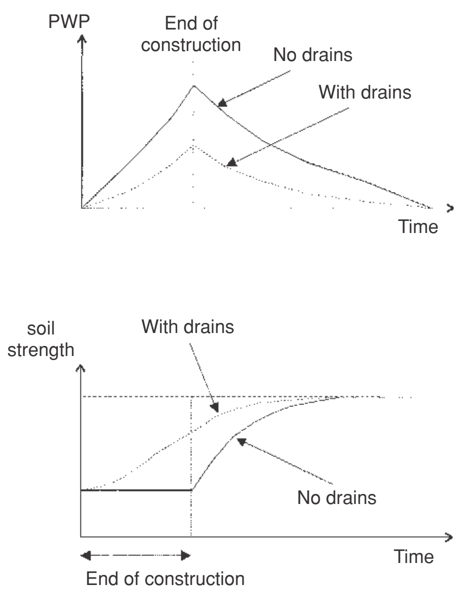
Normally the strength of soil is determined by its water content; as the water content decreases its strength increases and vice versa. A geotextile can convey fluids or gases within the plane of the geotextile to an egress point.

14.8.2.1 Consolidation/basal drains

The drainage system allows dissipation of excess pore water pressure, thus consolidation can take place and the soil strength is increased. The rate of dissipation of excess pore water pressure can be enhanced by using temporary drains in the soil so that the drainage path is reduced (Fig. 14.13). This type of drain is only required to perform for a limited time period, until consolidation has taken place (Fig. 14.14).



14.13 Temporary consolidation drains.



14.14 Comparison of time and strength of soil with and without consolidation drains.

14.8.3 Filtration

A geotextile acts as a filter by permitting the flow of liquid and gases, but preventing the passage of soil particles which can cause settlement due to loss of ground. The pore size within the geotextile is selected to avoid blocking, blinding and clogging.

Ground drains are used to prevent/intercept water flow, normally to reduce the risk of a rise in pore water pressure. Typically these drains are vertically sided trenches, lined with a geotextile and then filled with coarse gravel. Initial loss of soil particles will be high adjacent to the geotextile. This causes a zone (in the remaining soil particles) to bridge over the pores in the geotextile and retain smaller particles, which in turn retain even smaller particles. Thus a natural graded filter is formed which will prevent additional washout of fine particles, after which the geotextile becomes more-or-less redundant. If the geotextile was not used to encapsulate the coarse granular drainage material, too much wash-through of particles

would occur and this would either cause the drain to block or cavities to develop and lead ultimately to subsidence.

14.8.4 Separation

A geotextile acts as a separator by preventing the intermixing of coarse and fine soil materials whilst allowing the free flow of water across the geotextile. For instance, when a geotextile is placed between the subsoil and the granular sub-base of an unpaved road, it prevents the aggregate from being punched down into the soil during initial compaction and subsequently from the dynamic loading of vehicle axles. An example of a short-term use of a geotextile is in a temporary haul road that is formed during the construction of the permanent works, where it is only required to function for a limited amount of time before being removed. The temporary haul road is dug up and disposed of. A geotextile made from natural fibres, such as jute, coir, and so on, would be more suitable for such applications, because it would be biodegradable and hence more environmentally friendly.

14.8.5 Erosion control/absorption

A rapidly developing area for geotextiles is in the erosion control industry where they are employed for short-term effects. This usage differs from the other applications of geotextiles in that they are laid on the surface and not buried in the soil. The main aim is to control erosion whilst helping to establish vegetation which will control erosion naturally. The geotextile is then surplus to requirements and can degrade, enriching the soil. Geotextiles can reduce runoff, retain soil particles and protect soil which has not been vegetated, from the sun, rain and wind. They can also be used to suppress weeds around newly planted trees. Erosion control can be applied to riverbanks and coastlines to prevent undermining by the ebb and flow of the tide or just by wave motion.

14.9 Engineering properties of geotextiles

The physical and mechanical properties of soil are virtually unaffected by the environment over substantial periods. The natural fibre geotextiles could be used where the life of the fabrics is designed to be short. The definition of a short-term timescale varies from site to site and application to application. It depends ultimately on a number of factors, such as the size of the job, the construction period, the time of the year (weather), and so on. However, from the wealth of accumulated knowledge, a conservative design life expectancy of the geotextiles may be made for each given end-use. Applications exist where geotextiles are only required to perform for a few days after laying (drainage/filtration) or have to last up to a hundred years (reinforced earth abutments). The design life of natural fibre fabrics will be dictated by the type of fibre and the conditions to which they will be subjected. However, design lives of a few months to 4–5 years should be achieved for natural fibre geotextiles used in non-extreme situations, particularly since the need for the geotextile declines with the passage of time.

Natural materials such as timber have been used in the construction industry for a long time. However, the use of timber is limited because it is only used as a block,

that is, the individual components are not utilised. With natural fibres the stalks/stems can be stripped away to leave just the fibre which can be adapted to suit many different purposes in numerous forms and shapes with a wide range of properties. The key to developing geotextiles from natural fibres is the concept of designing by function, that is, to identify the functions and characteristics required to overcome a given problem and then manufacture the product accordingly. Provided the function can be satisfied technically and economically, these can compete with synthetic materials and in some situations they will have superior performance to their artificial counterparts.

14.10 Present state and uses of vegetable fibre geotextiles

The major use of vegetable fibre geotextiles is in the erosion control industry. Jute is readily biodegradable and ideally suited for the initial establishment of vegetation that in turn provides a natural erosion prevention facility. By the time natural vegetation has become well established the jute has started to rot/break down and disappear (6–12 months), without polluting the land.

Bangladesh, China, India and Thailand produce and sell jute geotextiles for erosion control. These are coarse mats, with open mesh woven structures made from 100% jute yarn produced on traditional jute machines. The jute geotextiles are laid on the surface of the slopes, where the weight and drapability of the mats encourage close contact with the soil. Between 1960 and 1980 a number of studies conducted by universities and highway departments demonstrated the effectiveness of jute geotextiles for surface erosion control.[21] Typical properties of a jute geotextiles[22] are:

- Pore size: 11 mm by 18 mm
- Open area ratio: 60–65%
- Water permeability: >500 litres $m^{-2} s^{-1}$ (100 mm head)
- Water absorption: 485%
- Breaking strength:
  warp 7.5 kN m^{-1}
  weft 5.2 kN m^{-1}

Some research has been directed towards reducing the degradation rate of jute, which can be made almost rot-proof by treating the fabric with a mixture of oxides and hydroxides of cobalt and manganese with copper pyroborate. Even after 21 days exposure in multiple-biological culture tanks, jute which had been subjected to this treatment had retained 96% of its original tensile strength. In soil incubation tests, the chemically treated jute had a 13-fold increase in lifetime over untreated jute.[23] Tests have been conducted on phenol formaldehyde-treated polypropylene–jute blended fabrics buried in soil to assess their susceptibility to microbial attack compared to untreated samples. It was concluded that the treated jute could withstand microbial attack more effectively than the untreated jute.[24] However, treated jute loses some of its ‘environmental friendliness’.

There has been no substantial research on the engineering properties of vegetable fibres for soil strengthening or on the development of new and novel geotextile structures made from vegetable fibres for exploiting the beneficial properties of the fibre, fabric and ground for short-term or temporary applications.

14.11 Performance of natural fibre geotextiles for soil strengthening

An area which may offer the most new and upcoming potential for the use of vegetable fibres as geotextiles is to strengthen soils, as demonstrated by Sarsby *et al.*[25] in 1992. Hence, the remainder of this chapter is devoted to the use of vegetable fibres for this specific application.

Factors affecting the suitability of vegetable fibres for reinforcing geotextiles can be identified as: durability, tensile properties, creep behaviour, manufacturing feasibility and soil/geotextile interaction. To be accepted these materials must satisfy/fulfil all of the above criteria to some degree. The aim of this section is not to 'design' for a specific limited application, but to determine whether acceptable balances of properties may be established. To achieve this, comparisons are made between different vegetable fibre yarns for long-term stability, that is, for biodegradation and creep. Also, nine different vegetable fibre geotextiles are compared with two synthetic products in terms of fabric stress–strain and shearing interactive properties.

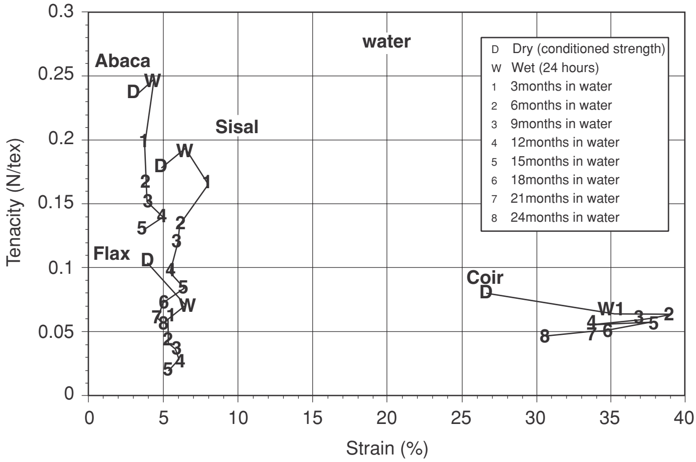
14.11.1 Long-term stability of natural fibre geotextiles

A geotextile should show the ability to maintain the requisite properties over the selected design life. One of the reasons for using vegetable fibre geotextiles is that they biodegrade when they have served their working life, but they must be sufficiently durable in different and aggressive ground conditions to last the prescribed duration. Only purely environmental deterioration will be considered, no damage to the geotextile caused by installation will be taken into account. The effects of biodegradation and creep will be considered for four vegetable fibre yarns which are particularly suitable for soil reinforcement: flax, abaca, sisal and coir.

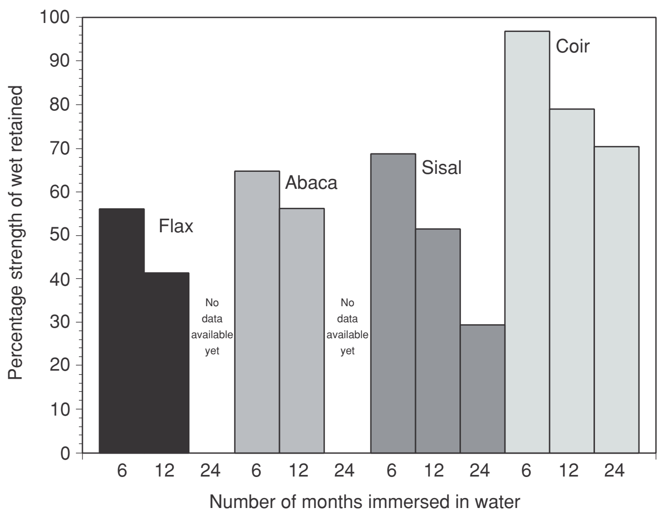
14.11.1.1 Durability/biodegradation rates

There are numerous factors which combine together to influence the rate of deterioration of vegetable fibres. However, to demonstrate simply the differences in the rates of deterioration, the change in strength and elongation of the four vegetable fibre yarns (fully immersed in water) is shown in Fig. 14.15.

The values shown are the average of five samples, tested after every three months. The samples were removed from the water and tested immediately, in other words the wet strength is given. This was chosen as representing the conditions most likely to be found in the ground. The original conditioned tex values were used at each testing stage to determine the yarns' tenacity. The initial strength of abaca and sisal (both leaf fibres) yarns increases by approximately 4% and 9%, respectively, when wet. However, with flax and coir (bast and seed/fruit fibres, respectively) there is a reduction in strength by 31% and 18%, respectively. This is in contrast to the earlier reference to the strength properties of flax increasing when wet. The reduction in strength could be accounted for by the yarn structure, rather than the fibre properties themselves. For the flax, abaca and sisal yarns there is a steady reduction in tenacity with time, with slight variations in strain. In contrast, the variations in the strength of coir yarn are minor, the difference between the groups of readings probably resulting from variations in the natural product itself. Figure 14.16 shows the



14.15 Effect of the deterioration process on the stress–strain properties of vegetable fibre yarns.

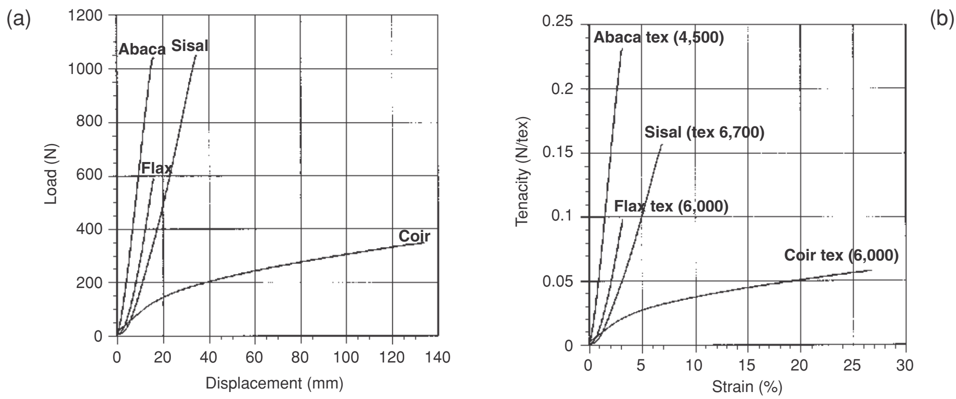


14.16 Percentage strength retained for vegetable fibre yarns in water for 6, 12 and 24 months.

percentage of the 24 hours wet strength retained for 6, 12 and 24 months. It can be seen that coir has retained by far the highest amount of strength. This was also true for coir and jute ropes which were immersed in pulverised fuel ash (PFA) for 10 and 36 months[25] – the reduction in strength for the coir was 38% and 47%, respectively whereas for jute it was 75% and 100%.

14.11.1.2 Creep

Creep and stress relaxation of geotextiles are prime factors in serviceability failure over the fabric's design life. Creep is a time-dependant increase in strain under



14.17 (a) Load–displacement and (b) stress–strain properties of the four vegetable fibre yarns.

constant load (e.g. reinforced walls), whereas stress relaxation is the reduction in tensile stress with time when subjected to constant strain (e.g. basal embankment reinforcement).

The main variables influencing creep for vegetable fibres geotextiles could be related to:

1 The fibre cell structure (e.g. abaca contains spiral molecules which are in a parallel configuration to each other, producing low extension).
2 Yarn type (e.g. between adjacent flax fibres cohesion is present, however with sisal no cohesion is present, the fibres are held together by twist only).
3 Fabric structure forms (e.g. crimp in woven structures).

Laboratory tests have been carried out in which the variables were load and time, with temperature and relative humidity being kept constant at 20 °C and 65%, respectively. Uniform loads of 40%, 20% and 10% of the maximum load (representing factors of safety of 2.5, 5 and 10) were applied to the four different vegetable fibre yarns and a gauge length of 500 mm was monitored.

Figure 14.17 illustrates typical short term load/extension curves at constant strain for flax, abaca, sisal and coir yarns, with the values of total strain and creep strain given in Table 14.13. Total strain includes the initial strain the sample undergoes when the load is applied plus the creep strain (this latter is the increase in change in length due to the passage of time, after the initial elongation).

14.12 Geotextile structure forms

Table 14.14 indicates the eleven different types of geotextile structure and fibre type together with their standard properties.

The creation of reinforcing geotextiles made from vegetable fibres introduces new manufacturing restraints, compared with the use of synthetic fibres and structures on existing textile machines. Numbers 1 to 5 of these structures have been designed, developed and produced in the Textile Centre at Bolton Institute from novel structure runs with selected natural fibres, namely flax, sisal and coir, to enable

Table 14.13 Total strain and creep strain of vegetable fibre yarns

Type of yarn	Max. load (kN)	Max. strain (%)	40% load (kN)	Strain at 40% load	20% load (kN)	Strain at 20% load	10% load (kN)	Strain at 10% load
Sisal	1.05	6.90	0.42	3.50	0.21	2.30	0.11	1.50
Abaca	1.04	3.19	0.42	1.40	0.21	0.80	0.10	0.50
Coir	0.35	26.71	0.14	3.70	0.07	1.50	0.04	0.70
Flax	0.68	4.02	0.27	2.30	0.14	1.50	0.07	0.90

Total strain for 10 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.6	2.7	1.5
Abaca	1.8	1.3	0.6
Coir	5.1	2.0	1.7
Flax	2.4	1.5	0.9

Creep strain for 10 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.1	0.4	0.0
Abaca	0.4	0.5	0.1
Coir	1.4	0.5	1.0
Flax	0.1	0.0	0.0

Total strain for 100 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.6	2.8	1.6
Abaca	1.9	1.4	0.7
Coir	6.0	2.3	1.8
Flax	2.6	1.5	1.0

Creep strain for 100 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.1	0.5	0.1
Abaca	0.5	0.6	0.2
Coir	2.3	0.8	1.1
Flax	0.3	0.0	0.1

Total strain for 1000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.8	3.0	1.8
Abaca	2.0	1.4	0.7
Coir	6.9	2.7	2.0
Flax	2.8	1.5	1.1

Creep strain for 1000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.3	0.7	0.3
Abaca	0.6	0.6	0.2
Coir	3.2	1.2	1.3
Flax	0.5	0.0	0.2

Total strain for 10 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	5.0	3.2	2.0
Abaca	2.1	1.5	0.8
Coir	7.9	3.1	2.1
Flax	2.9	1.6	1.2

Creep strain for 10 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.5	0.9	0.5
Abaca	0.7	0.7	0.3
Coir	4.2	1.6	1.4
Flax	0.6	0.1	0.3

Total strain for 100 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	5.2	3.3	2.1
Abaca	2.2	1.5	0.8
Coir	8.8	3.4	2.3
Flax	3.1	1.7	1.2

Creep strain for 100 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	–	1.0	0.6
Abaca	–	0.7	0.3
Coir	5.1	1.9	1.6
Flax	–	0.2	0.3

Table 14.14 Standard properties of vegetable fibres and commercially available geotextiles

	Average of 5 fabric samples for all test results shown	Disp. at max. load (mm)	Load at max. (kN)	% Strain at max. load	Stress at max. load (MPa) ($N\,mm^{-2}$)	Load/Width at max. load ($kN\,m^{-1}$)	Modulus ($kN\,m^{-1}$)	Toughness (MPa) ($N\,mm^{-2}$)	Mass ($g\,m^{-2}$)	Thickness (mm) weight 100 g
1	Knitted flax sisal inlay (strength direction)	16.35	10.33	8.18	38.98	206.60	4657.64	3.85	1753.23	5.3
	Knitted flax sisal inlay (*x*-strength direction)	80.04	1.03	40.02	3.74	20.57	93.02	0.50		
2	Knitted grid flax sisal (strength direction)	14.88	7.88	7.44	32.63	143.58	2647.04	3.88	1613.81	4.4
	Knitted grid flax sisal (*x*-strength direction)	97.76	1.09	48.88	4.35	19.15	84.26	0.47		
3	Plain weave sisal warp flax weft (warp direction)	19.28	8.99	9.64	49.94	179.80	2604.24	4.34	1289.95	3.6
	Plain weave sisal warp flax weft (weft direction)	58.07	0.22	29.04	1.22	4.40	50.65	0.06		
4	Plain weave sisal warp coir weft (warp direction)	32.68	5.65	16.34	14.86	113.00	683.24	1.59	1895.48	7.6
	Plain weave sisal warp coir weft (weft direction)	51.70	1.32	25.85	3.48	26.42	256.73	0.73		
5	6 × 1 woven weft rib sisal warp coir weft (warp direction)	16.69	8.53	8.35	14.10	170.60	2947.56	0.96	3051.75	12.1
	6 × 1 woven weft rib sisal warp coir weft (weft direction)	68.16	5.58	34.08	9.23	111.70	710.27	2.87		
6	Plain weave coir geotextile (warp direction)	56.23	0.99	28.12	2.47	19.74	114.56	0.50	1110.99	8.0
	Plain weave coir geotextile (weft direction)	44.01	0.89	22.00	2.23	17.86	142.40	0.41		
7	Knotted coir geotextile (long direction)	105.90	0.92	52.95	5.93	18.38	56.11	1.87	605.37	3.1
	Knotted coir geotextile (width direction)	389.60	0.33	194.80	2.12	6.56	12.80	0.90		
8	Nonwoven hemp (machine direction)	112.70	0.11	56.37	0.48	2.15	2.48	0.16	683.16	4.5
	Nonwoven hemp (*x*-machine direction)	85.47	0.17	42.74	0.76	3.43	4.14	0.22		
9	Nonwoven coir latex (machine direction)	12.26	0.20	6.13	0.74	4.07	107.58	0.07	1018.24	5.5
	Nonwoven coir latex (*x*-machine direction)	11.18	0.15	5.59	0.54	2.95	72.05	0.05		
10	Plain weave synthetic polyester (warp direction)	16.35	2.07	8.17	51.62	41.30	768.72	2.94	432.09	0.8
	Plain weave synthetic polyester (weft direction)	19.62	2.30	9.81	57.50	46.00	669.36	3.52		
11	Synthetic warp knitted polyester (warp direction)	55.78	2.32	27.89	27.31	46.42	446.42	4.18	430.13	1.7
	Synthetic warp knitted polyester (weft direction)	102.87	0.11	51.43	1.31	2.23	70.64	0.26		

the creation of the most suitable compositions of fabrics. They have been created with the fundamental properties required to form geotextiles to reinforce soil, in that they have been designed to provide:

1 The highest possible strength in one direction, combined with ease of handling and laying on site
2 Soil particle interlock with the fabric to such an extent that the soil/fabric interface exhibits greater shearing resistance than the surrounding soil, i.e. the soil/fabric coefficient of interaction (α) is greater than one
3 A degree of protection to the high strength yarns during installation
4 A tensile strength in the range of 100–200 $kN\,m^{-1}$.
5 Ease of manufacture on conventional textile machines.

Numbers 1 and 2 are the most novel structures developed, being of weft knitting origin. The knitted structure is formed from a flax yarn (tex ≈ 400) encapsulating high strength sisal yarns (tex ≈ 6700). Knitted flax and inlay sisal yarns can be substituted by other natural fibres yarns.

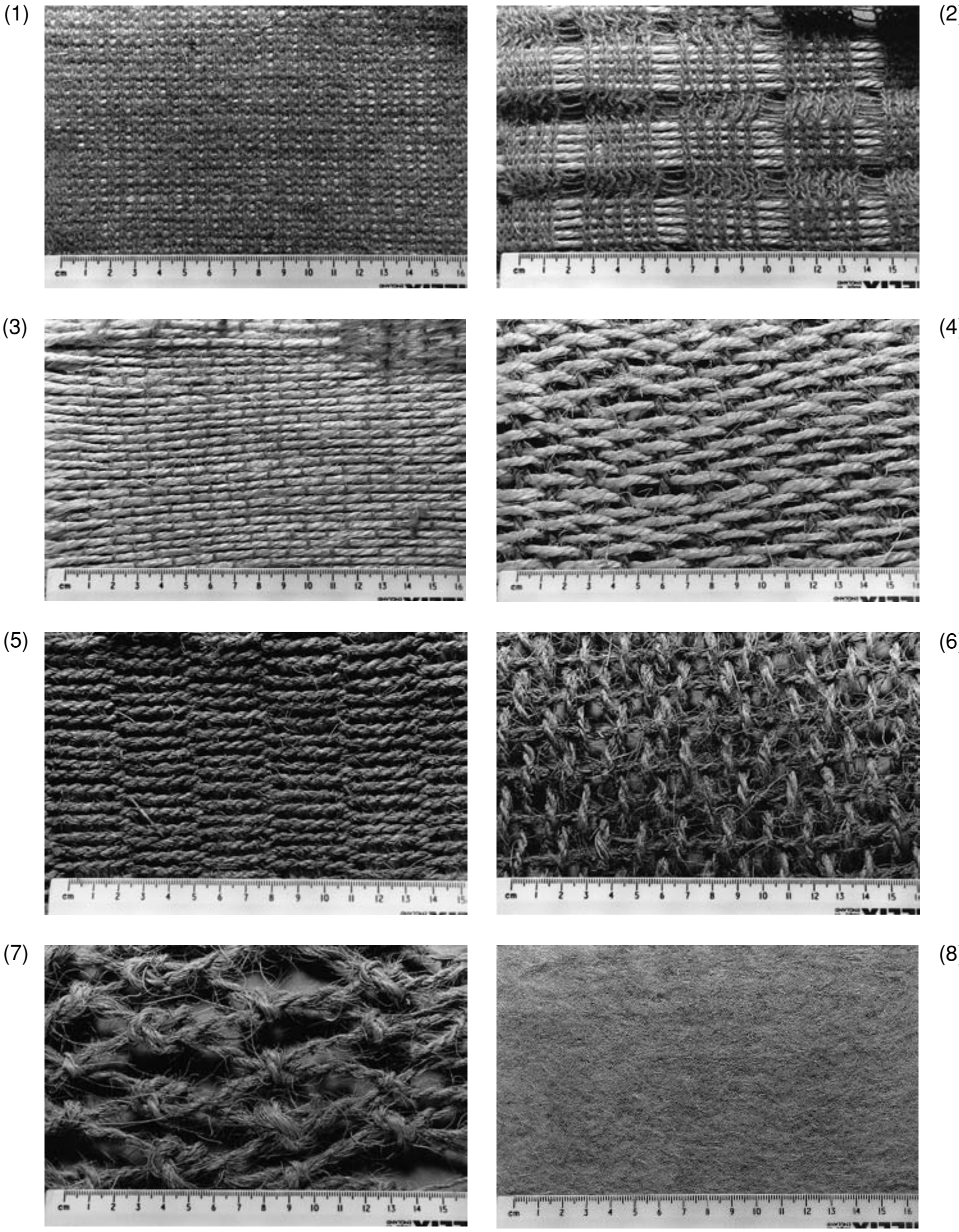
The knitted flax/sisal inlay number 1 (Fig. 14.18) has as many straight inlay yarns as possible in one direction which gives the geotextile its high strength, without introducing crimp into these yarns. Thus a fabric is produced which has low extensibility compared with conventional woven structures. The knitted loops hold the inlay yarn in a parallel configuration during transportation and laying on site; under site conditions it would be impractical to lay numerous individual sisal yarns straight onto the ground. The knitted loops also provide some protection for the sisal inlay yarns during installation/backfilling. The most advantageous use of the knitted loops in this structure is that they form exactly the same surface on both sides of the fabric and the sand is in contact not only with the knitted loops but with the inlay yarns as well. Thus the shear stress from the sand is transmitted directly to both the inlay yarns and the knitted skeleton.

With the grid flax/sisal geotextile number 2 (Fig. 14.18), at predetermined intervals needles were omitted and the sisal inlay yarn left out, to produce large apertures in the geotextile. This is similar in form to the Tensar Geogrid (commercial polymer grids designed for soil reinforcement), which allows large gravel particles to penetrate into the structure thereby 'locking' the gravel in this zone and forcing it to shear against the gravel above and below the geotextile, rather than just relying on the surface characteristics.

Structures 3 to 5 employed traditional woven patterns, but exploited combinations of different types of yarn and thickness to produce advantageous fabric properties for reinforcing geotextiles.

The plain weave sisal warp/flax weft geotextile number 3 (Fig. 14.18) allows the maximum possible number of the high strength sisal yarns to be laid in one direction, whilst the flax weft yarns hold the sisal yarns together during transportation and laying on site. By only using very thin weft yarns compared to the warp yarns no crimp is introduced in these warp yarns. This structure is not as stable as the knitted structures and the flax weft yarns offer no protection for the sisal warp yarns during installation.

The plain weave sisal warp/coir weft geotextile number 4 (Fig. 14.18) provides the sisal strength yarn in one direction whilst using the coir weft yarn to form ridges in the structures caused by its coarseness, thus creating abutments which the soil has to shear around. By using a thick weft yarn, crimp is introduced into the warp

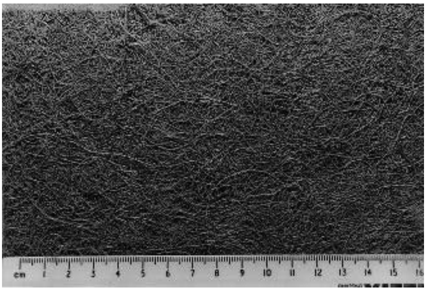


14.18 Photographs of different fabric structures used for tensile and shear interactive tests. (1) Knitted flax/sisal inlay, (2) knitted grid flax/sisal, (3) plain weave sisal warp/flax weft, (4) plain weave sisal warp/coir weft, (5) 6×1 woven weft rib sisal warp/coir weft, (6) plain weave coir warp/coir weft, (7) knotted coir grid, (8) nonwoven hemp, (9) nonwoven coir latex, (10) plain weave synthetic polyester, (11) synthetic warp-knitted polyester.

yarn and this in turn creates a more extensible geotextile, as well as providing no protection for the sisal strength yarns.

The woven 6×1 weft rib geotextile number 5 (Fig. 14.18) was designed to provide the ultimate protection for the high strength sisal yarns but without introducing any

(9)



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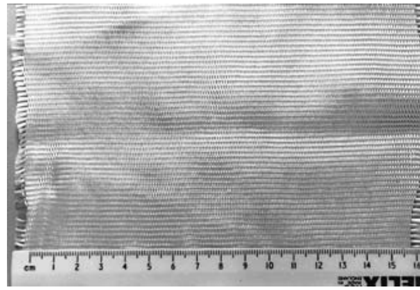

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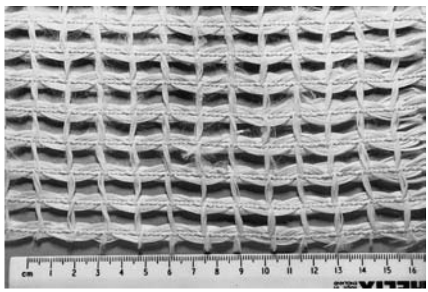


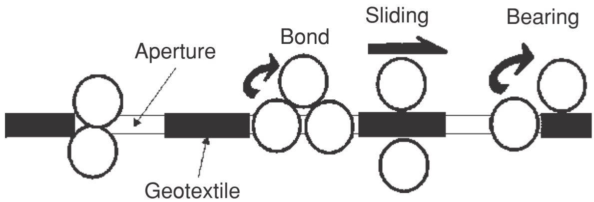
14.18 *Continued.*

crimp. However, this structure has comparatively lower productivity because of the high weft cover factor and thus it is more costly.

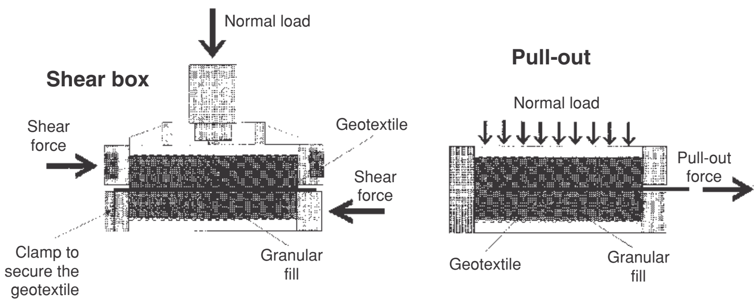
Numbers 6 to 11 are all commercially available geotextile products, with 6 to 9 being of a natural fibre origin. The coir knotted geotextile (Fig. 14.18) was chosen to study the effect of larger particle interlock with the fabric and large abutments formed by the knots. This geotextile was obtained from India (Aspinwall & Co. Ltd.) where the knots are produced by hand. The nonwoven samples 8 and 9 (Fig. 14.18) were obtained from Thulica AB, Sweden, for a comparison with the knitted and woven natural fibre structures. However, geotextiles 10 and 11 are of a synthetic origin from the midrange of synthetic products commercially available. These were used for a direct comparison with the natural fibre geotextiles using exactly the same tests and procedures. Both of these synthetic geotextiles were made of polyester, number 10 was a plain weave structure and number 11 was a warp-knitted grid (Fig. 14.18).

14.13 Frictional resistance of geotextiles

The frictional shearing resistance at the interface between the soil and the geotextile is of paramount importance since it enables the geotextile to resist pull-out failure and allows tensile forces to be carried by the soil/geotextile composite. The resistance offered by the fabric structure can be attributed to the surface roughness characteristics of the geotextile (soil sliding) and the ability of the soil to penetrate the fabric, that is, the aperture size of the geotextile in relation to the particle size of the soil, which affects bond and bearing resistance (Fig. 14.19). Bond resistance is created when soil particles interlock with the geotextile and permit these 'locked'



14.19 Forms of shearing resistance; sliding, bond and bearing.



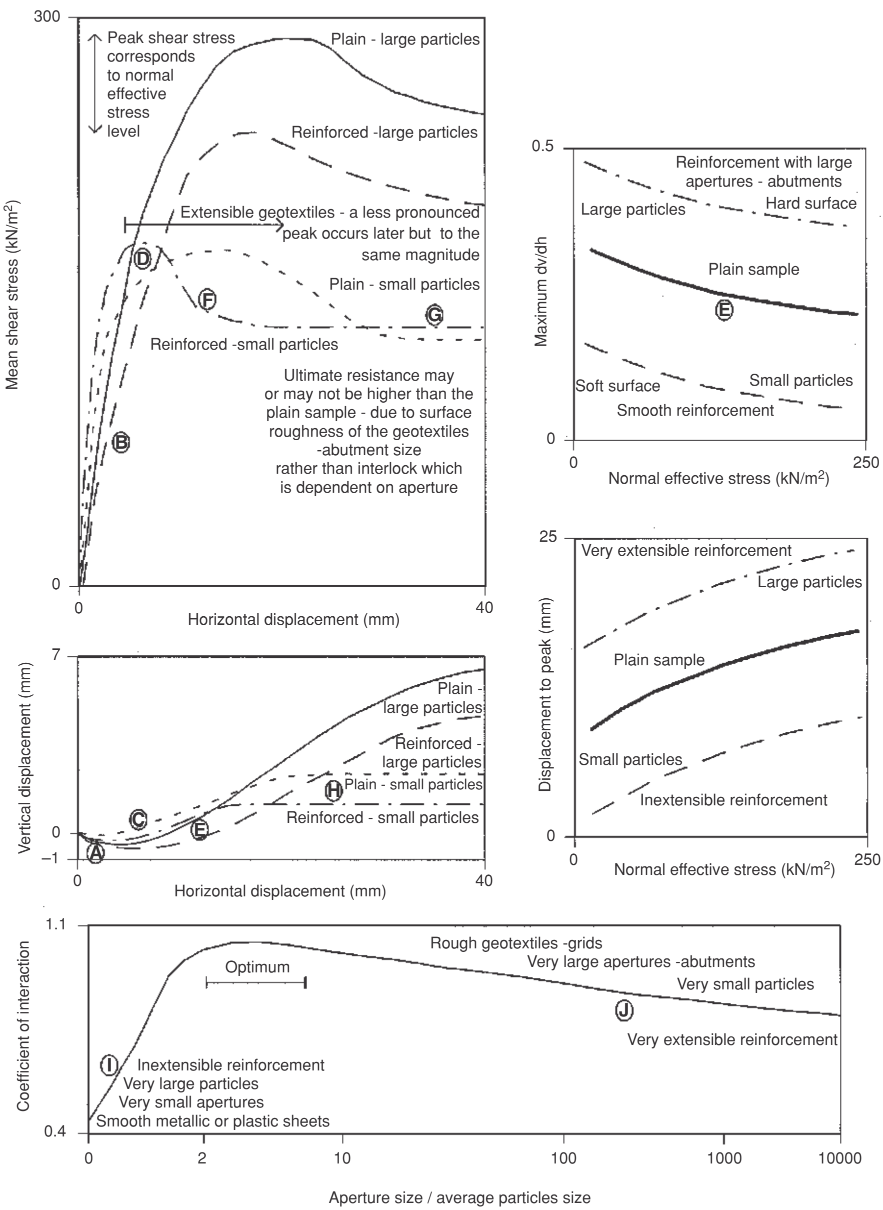
14.20 Laboratory tests to determine the frictional resistance of a geotextile.

particles in the apertures to shear against ambient soil in close vicinity above and below the geotextile surface, whereas bearing resistance, which can only really be assessed by pull-out tests, is the effect of soil having to shear around abutments in the geotextiles, or at the end of the apertures, in the direction of shear. This mode of resistance is very similar to that encountered in reinforced anchors and is determined by relating the pull-out force to the sum of projected area of the transverse members in the geotextile.

The efficiency of geotextiles in developing shearing resistance at the soil–fabric interface is indicated by the coefficient of interaction (α) defined as the ratio of the friction coefficient between soil and fabric ($\tan\delta$) and the friction coefficient for soil sliding on soil ($\tan\phi$). There are two conventional laboratory tests to determine the frictional resistance of a geotextile; the direct shear box and the pull-out test (Fig. 14.20). The main distinction between these tests is that in the direct shear box test, the soil is strained against the fabric, whereas in the pull-out test, strain is applied to the fabric thereby mobilising different degrees of shearing resistance along the fabric corresponding to a relative position of the fabric from the applied load and the extensibility of the fabric.

14.13.1 Performance of vegetable fibre geotextiles during shear

The stress–strain response and volumetric behaviour for all the geotextiles in both sand and gravel are typical of a densely packed granular dilating medium. Figure 14.21 illustrates typical curves that should be expected, relating the physical properties of the geotextiles to that of the fill. Initial volumetric compression (A) would occur to a higher degree than in plain soil as a result of the soil bedding in the geotextile. At relatively small strains, the stress level would increase rapidly more-or-



14.21 Typical shearing interactive curves, relating the physical properties of the geotextiles to that of the fill. Values indicated on these proposed charts are only shown as an estimate of the range of typical values which may lie within, for dense sand and gravel fills.

less linearly with strain (B). The stress increase will be at a higher rate than in plain soil if the geotextile limits the movement between adjacent soil particles caused by soil interlocking with the fabric. Volumetric expansion will develop at the same time, that is the soil will be dilating (C). At maximum shearing resistance the stress–strain response should produce a well-defined peak in the shear stress (D), more pro-

nounced than in plain soil, because of the 'locked' nature of the soil particles. This should correspond to the rate of maximum volume change (E), which is likely to be greater in reinforced samples than in plain soil, particularly if introduction of the geotextile produces 'abutments' around which the soil has to shear. At this stage all the available shearing resistance, under the given vertical pressure, has been mobilised and the shear stress at the soil–fabric interface is equal to the shear strength. This stage is followed by a reduction in shearing resistance, as particle interlocking is 'released', (F) towards the final state (G), where constant volume is maintained (H). Thus a thin rupture zone of the soil at critical density is produced. By increasing the particle size in the direct shear box the behaviour will be modified slightly, because the nature ratio of the soil–fabric contact will be reduced. The opportunity for movement between ambient soil particles will be reduced as will the soil–fabric interlock as the size of the apertures in the geotextile approach the diameter of the particles (I). With very small particles or large apertures the converse will apply (J), in that the ratio of particles to aperture size will be large and thus will permit additional freedom of movement between sand grains in the shearing zone. Furthermore, the use of larger particles will produce a less rapid stress/strain response, i.e. considerably more horizontal shear displacement is needed, more effort is therefore required, to enable a gravel particle to ride over another gravel particle than it would for corresponding sand particles. Therefore no constant volume shearing zones will be expected in a sample with large particles. The extensibility of the fabric is of paramount importance for producing different degrees of soil strain. The geotextile is required to strain sufficiently to permit maximum soil strength to be mobilised, but not to the extent that serviceability failure occurs.

14.13.2 Coefficient of interaction

Values of the shearing angle and coefficient of interaction, α, of the geotextiles sheared in sand and gravel are shown, together with a summary of their stress–strain values, in Table 14.15. The results for the nonwoven samples were not as favourable as the other geotextiles, for tensile strength and shearing interactive properties, indicating that these structures are not as suitable for soil reinforcement. Some of the α values are more than 1 for the sand, indicating that by introducing the geotextile in the sand it actually strengthens the ambient sand. This could possibly be due to the surface texture of some of these geotextiles, because the sand grains can interlock with the fabric and reduce movement. This scenario can be described as if sand were sheared against sandpaper producing a higher frictional resistance than shearing sand against sand. As a result of sand shearing against sand, the sand grains above and below the failure plane are free to move, but with the sandpaper the sand grains grains are unable to move. In a practical situation if α is more than 1, the failure surface would just be pushed up away from the geotextile into the region of sand against sand. The fabric structure can be further assessed by applying a flow rule analysis to the soil/fabric interface data, as demonstrated by Pritchard,[26] to enable an assessment of whether a higher shearing resistance was developed from the surface roughness characteristics of the geotextile (smoothness of the fabric) or as a result of interlock, that is, from a higher dilational component (the effect from the apertures and abutments in the fabric).

able 14.15 Shearing interactive values of vegetable fibre geotextiles compared to two synthetic geotextiles

	Geotextiles	($kN\,m^{-1}$)	% Strain at max.	θ′max Sand	∝ for θ′max	θ′r Sand	∝ for θ′r	θ′max Gravel	∝ for θ′max
	Fill vs Fill			40.5°	1.00	33.1°	1.00	54.7°	1.00
1	Knitted flax sisal inlay	207	8	40.9°	1.01	33.0°	1.00	50.5°	0.86
2	Knitted grid flax sisal	144	7	38.8°	0.94	32.5°	0.98	50.9°	0.87
3	Plain weave sisal warp flax weft	180	10	40.0°	0.98	32.4°	0.97	49.8°	0.84
4	Plain weave sisal warp coir weft	113	16	42.1°	1.06	33.1°	1.00	53.4°	0.95
5	6 × 1 Woven weft rib sisal coir	170	8	42.0°	1.05	33.2°	1.00	50.9°	0.87
6	Plain weave coir geotextile	20	28	41.9°	1.05	33.1°	1.00	51.2°	0.88
7	Knotted coir geotextile	18	53	43.5°	1.11	36.7°	1.21	51.8°	0.90
8	Nonwoven hemp	2	56	39.3°	0.96	34.8°	1.07	44.6°	0.70
9	Nonwoven coir latex	4	6	34.7°	0.81	–	–	36.4°	0.52
0	Plain weave synthetic (polyester)	41	8	40.4°	1.00	31.9°	0.95	46.6°	0.75
1	Warp knitted grid synthetic (polyester)	46	28	38.4°	0.93	31.8°	0.95	51.3°	0.88

ests conditions are: 300 × 300 mm shear box. Fill; Leighton Buzzard sand and limestone gravel (average particle diameter 0.8 mm and 6 mm, respectively). Nominal ormal stress; 200, 150, 100 and 50 $kN\,m^{-2}$. Nominal unit weight of 96% and 94% of the maximum nominal dry unit weight for the sand and gravel, respectively. Accu-cy of ±0.01 $Mg\,m^{-3}$ from the mean dry density in subsequent shear box tests. Leading side of the bottom half of the shear box had the geotextile clamped to it.
max = maximum shear angle.

14.14 Conclusions

Vegetable fibre geotextiles offer environmentally friendly, sustainable, cost effective, geotechnical solutions to many ground engineering problems, in both developed and less developed countries. The main area where they have been employed is in the erosion control industry, but new and novel structures are being produced which exploit advantageous fabric/ground interaction properties. One of the main areas, with the largest potential for development, is to use these natural products temporarily to strengthen the ground, during and just after construction, until the soil consolidates and becomes stronger. These reinforcing geotextiles then biodegrade leaving no alien residue in the ground.

From the extensive research conducted on vegetable fibres, the six most promising fibres for geotextiles are flax, hemp, jute (bast), sisal, abaca (leaf) and coir (seed/fruit). These can be refined down to the four most suitable fibres, flax, abaca, sisal and coir, when taking into account the relevant properties required for soil reinforcement.

It has been shown that coir yarns are far more durable than any of the other vegetable fibre yarns when tested in water. Also, the coir rope exhibited excellent durability qualities compared to that of the jute rope when subjected to a hostile environment of PFA. However, the coir yarn exhibited significantly higher creep rates than flax, abaca and sisal at increased load levels.

Vegetable fibre geotextiles have been found to have superior properties to the mid-range reinforcing synthetic geotextiles for soil reinforcement, when considering tensile strength (between 100–200 $kN\,m^{-1}$) and frictional resistance (α approximately 1). The high degree of frictional resistance of the vegetable fibre geotextiles probably develops from both the coarseness of the natural yarns and the novel structure forms.

Finally it must be pointed out that the success of synthetic geotextiles is due to excess manufacturing capacity and the large amount of research and development that has been carried out in relation to their production, properties and application and not simply because they are superior to fabrics made from natural fibres.

14.15 Relevant British Standards

BS 2576: 1986 Determination of breaking strength and elongation (strip method) of woven fabrics.
BS 6906: Part 1: 1987 Determination of the tensile properties using a wide width strip.
BS 6906: Part 2: 1987 Determination of the apparent pore size distribution by dry sieving.
BS 6906: Part 3: 1987 Determination of the water flow normal to the plane of the geotextile under a constant head.
BS 6906: Part 4: 1987 Determination of the puncture resistance (CBR (California bearing ratio) puncture test).
BS 6906: Part 5: 1987 Determination of creep.
BS 6906: Part 6: 1987 Determination of resistance to perforation (cone drop test).
BS 6906: Part 7: 1987 Determination of in-plane flow.
BS 6906: Part 8: 1987 Determination of geotextile frictional behaviour by direct shear.

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14

Textiles in civil engineering. Part 1 – geotextiles

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14.1 Introduction to geotextiles

Although skins, brushwood and straw–mud composites have been used to improve soft ground for many thousands of years, it is not realistic to refer to these as 'geotextiles'. The important factor that separates them from modern geotextiles is that they cannot be made with specific and consistent properties. When modern polymers were developed in the mid 20th century, it became possible to create textiles with designed forecastable performance and to produce them in large quantities with statistically consistent and repeatable properties. Once this was achieved, the science of geotextiles became possible. In essence, the difference between geotextiles and skins is their numerical or engineering capability.

In the early 1960s and 1970s, some pioneering engineers wondered if textiles could be used to control soils under difficult conditions. For example, very wet soils need draining and textiles were used to line drains, to prevent mud and silt from clogging up the drains. Similarly, engineers tried to use textiles beneath small access roads constructed over very soft wet soils. It was found that these textiles helped to increase the life and performance of roads. Also, early work was being undertaken in the laying of textiles on the coast to prevent erosion by wave action. A number of limited but historical publications were published.[1–2]

However, in those early days, it was not known exactly how these textiles performed their functions. How did they actually filter? How did a relatively weak textile apparently support heavy vehicles and improve road performance? This was a dangerous period for engineers, because it was quite possible that the experience-based employment of geotextiles could lead to their use in unsuitable constructions. It was likely that before long, an engineer would use textiles in a structure that was too large, too demanding or too stressful for the product; a significant failure could result. It was therefore vital that study and research should be undertaken to provide theories and preliminary design equations against which to test site results.

In 1977 Rankilor produced what was probably the first 'design' manual for a commercial product[3] and this was followed by a textbook written in 1980[4] which built on the extensive experience that had been amassed by this time. As is so typical of scientific development, many engineers were soon working worldwide on the development of geotextiles. Another significant textbook by Koerner and Welsh was published in 1980,[5] showing that work in the USA was at an advanced stage. The French, Japanese, Germans, Dutch and workers in other countries were equally active in the utilisation of textiles in civil engineering earthworks at that time.

During the last 20 years of the 20th century, the use of geotextiles spread geographically worldwide and in area terms their use increased almost exponentially. It is expected that their use will continue to increase into the 21st century unabated.

Once textiles were recognised as being numerically capable materials, engineers developed new types of textile and new composites to solve more difficult problems. Woven and nonwoven textiles were joined into composite products; nonwoven products were combined with plastic cores to form fin drains, and woven products were developed from stronger polymers such as polyester to extend the mechanical range of textiles and their uses in soil reinforcement. It is probable that the Dutch were the first to weave heavy steel wires into polypropylene textiles for incorporation into their major coastal land reclamation schemes. During the period 1984–85, Raz and Rankilor explored and developed the design and use of warp knitted fabrics for civil engineering ground uses.[6,7] Rankilor coined the term 'DSF' geotextiles – directionally structured fabric geotextiles; Raz specified the 'DOS' group within the main DSF range – directionally orientated structures.

Within a few years, more than six major manufacturers were producing warp knitted textiles for civil engineering earthworks. Currently, many are commercially available.

It can be considered that the 'first generation' of geotextiles were textiles that were being manufactured for other purposes (such as carpet or industrial sackings) but which were diverted and used for geotechnical purposes. The second generation of geotextiles became generated by manufacturers choosing specific textiles suitable for geotechnical purposes, but using conventional manufacturing techniques. The third generation textiles were actually designed and developed anew specifically for the purpose of geotechnical application – in particular DSF, DOS and composite products.

The development of geotextiles has always been an 'industry-led' science. Academic institutions have almost universally lagged well behind industry, with industrial designers acquiring experience at an ever-increasing rate. Currently, for example, in the USA, there are only a small number of universities teaching geotextile design as part of their main core programmes. In the UK, there are even fewer. Nonetheless, research publications from British academic institutions are of a high quality, showing specialised interests such as weathering,[8,9] filtration,[10] soil reinforcement[11,12] and computer applications.[13]

The establishment of the International Geotextile Society in 1978 led to a coordinated and coherent approach to international development of geotextile design and utilisation. The Society's four-yearly international symposium has been emulated by many other groups and countries, such that the rate of publication of papers is now very high, providing widespread exposure of developments to all interested engineers.

There are some interesting commercial aspects related to geotextiles that are specific to the industry. For example, availability must be considered in the light of the extreme size range of operations into which geotextiles are incorporated. About one-third of all geotextiles are used in small batches of three rolls or less, but a significantly large proportion are used in very large projects incorporating hundreds of thousands of square metres. Supply must therefore be available on call for one or two rolls from local stock and, simultaneously, must be available through agents or directly from the manufacturer in large quantities over a short space of time.

Delivery period is particularly onerous for textile suppliers. The majority of delivery requirements are of a standard industrial nature, but geotextile suppliers have to be able to supply large quantities within a short period for major engineering undertakings. This aspect has deterred many potential geotextile manufacturers from entering the field.

Price is also of interest, in that the cost of the polymer and manufacture can be irrelevant in certain cases. In civil engineering, a textile can be used to 'replace' a more conventional material such as sand in a granular filter. In this case, the cost of the product would be relevant and would be compared to the cost of the sand. Taken into account would be other marginal factors such as time saved in the laying of the textile as opposed to that of laying the sand. If the balance was in favour of the textile, then it might be adopted. However, in different circumstances the same textile might be worth considerably more as a sand replacement, for example, if sand were required to be placed under rapidly moving water or waves. In this case, if the textile could be placed where sand could not, then the comparison is not simply a matter of cost, but of the textile actually allowing construction to take place when the sand could not. Considerably more could be charged for a textile in these circumstances than in the former. Therefore, the cost of textiles is enhanced where they are sold and used as part of a 'system'.

Quality has to be controlled in much the same way as with other textiles – quality variation within the fabric and quality variations over time – but the implications of failure can be so much greater than with normal industrial products. If a major dam were to fail because the textile filter clogged, it would not just be a matter of apologising and replacing the filter with new product! The manufacturer does not take responsibility for the use of fabrics in the ground, but the design consultant does. He will not therefore be willing to certify the use of a textile if he is not satisfied that quality can be maintained at all levels of the process.

It is certainly necessary for modern-day geotextiles to be produced by manufacturers having ISO 9000 certification and it is ideal for this to include 9001, 9002 and 9003. The full range of these certifications covers the manufacturer's operation from raw material supplier through manufacture to storage and delivery.

14.2 Geosynthetics

In the field of civil engineering, membranes used in contact with, or within the soil, are known generically as 'geosynthetics'. This term encompasses permeable textiles, plastic grids, continuous fibres, staple fibres and impermeable membranes. Textiles were the first products in the field, extending gradually to include additional products, but have remained by far the most important of the range. Grids are formed from sheets of plastic that are punched and stretched; meshes are formed from

melted extruded polymer; neither can be categorised as textiles. Geomembranes are continuous sheets of impermeable plastic and are not textiles. The more difficult areas of the geosynthetic range to categorise are those where discrete staple fibres or continuous filament fibres are mixed directly with soil. These are polymer textile fibres and therefore, as such, are included within the definition of geotextiles.

14.2.1 Geotextile types

Geotextiles basically fall into five categories – woven, heat-bonded nonwoven, needlepunched nonwoven, knitted and by fibre/soil mixing.

Woven fabrics are made on looms which impart a regular rectilinear construction to them, but which can vary in terms of the component fibres and the weave construction. They have a surprisingly wide range of applications and they are used in lighter weight form as soil separators, filters and erosion control textiles. In heavy weights, they are used for soil reinforcement in steep embankments and vertical soil walls; the heavier weight products also tend to be used for the support of embankments built over soft soils. The beneficial property of the woven structure in terms of reinforcement, is that stress can be absorbed by the warp and weft yarns and hence by fibres, without much mechanical elongation. This gives them a relatively high modulus or stiffness.

Heat-bonded nonwoven textiles are generally made from continuous filament fine fibres that have been laid randomly onto a moving belt and passed between heated roller systems. These fabrics acquire their coherence and strength from the partial melting of fibres between the hot rollers, resulting in the formation of a relatively thin sheet of textile.

Needlepunched nonwoven fabrics are made from blended webs of continuous or staple filaments that are passed through banks of multiple reciprocating barbed needles. The fabrics derive mechanical coherence from the entangling of fibres caused by the barbs on the reciprocating needles; these fabrics thus resemble wool felts.

In the case of needlepunched textiles, considerable thicknesses (up to more than 10 mm) and weights greater than 2000 $g\,m^{-2}$ can be achieved, whereas the heat-bonding process is limited in its efficacy as thickness increases. If sufficient heat is applied to melt the internal fibres of a thick fabric adequately, then the outer fibres will tend to be overheated and overmelted. Conversely, if appropriate heat is applied to the external fibres, then insufficient heat may be applied to the centre of the sheet, resulting in inadequate bonding and potential delamination in use.

Knitted fabrics, as used in the field of geotextiles, are restricted to warp-knitted textiles, generally specially produced for the purpose. Warp-knitting machines can produce fine filter fabrics, medium meshes and large diameter soil reinforcing grids. However, it is generally found that only the high strength end of the product range is cost effective, usually for soil reinforcement and embankment support functions.

14.2.2 The main geotextile fibre-forming polymers

The two most common fibre polymers used for the manufacture of geotextiles are polypropylene and polyethylene, but polyester is almost inevitably used when high strengths are required. There are other higher strength polymers available on the market, but geotextiles have to be produced in large quantities (some polymers are not available in large volumes) and economically (specialist polymers tend to be

very expensive). On the overall balance of cost against performance, polyester is the present day optimum, while polypropylene and polyethylene vie for being the most chemically resistant.

Care must be taken when considering the properties of geotextile polymers that consideration is restricted to polymers as they are actually produced and used for geotextile manufacturing purposes; they are not in their chemically pure form. For example, raw polyethylene in its colourless translucent form is quite susceptible to light degradation. However, it is not used in this form in geotextiles, but usually contains carbon black as an ultraviolet (UV) light stabiliser. In this black form, it is arguably the most light-resistant polymer.

Also, it must be recognised that real in situ field testing of geotextile polymers is limited. Publications and authorities may quote accelerated laboratory results for xenon UV exposure, high temperature degradation testing, and similar, but these cannot take account of additional degradation factors such as biological attack, or synergistic reactions that may take place. The difficulty, therefore, arises that accelerated laboratory testing may well be pessimistic in one regard and optimistic in the other when used for ranking purposes.

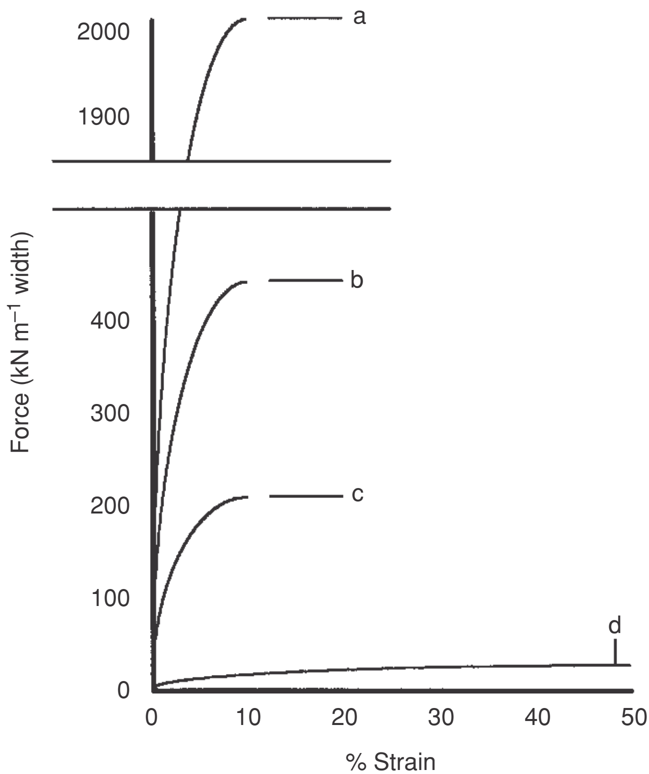
Although polyamide is a common fibre-forming and textile material, nonetheless, it is rarely used in geotextiles, where its cost and overall performance render it inferior to polyester. Some woven materials, for example, have used polyamide in the weft direction, more as a 'fill', where its properties are not critical. Its main asset is its resistance to abrasion, but it displays softening when exposed to water, which appears to have made it unpopular for geosynthetic use. Polyvinylidene chloride fibre is used in Japan and in one or two products in the United States, but not in Europe.

14.3 Essential properties of geotextiles

The three main properties which are required and specified for a geotextile are its mechanical responses, filtration ability and chemical resistance. These are the properties that produce the required working effect. They are all developed from the combination of the physical form of the polymer fibres, their textile construction and the polymer chemical characteristics. For example, the mechanical response of a geotextile will depend upon the orientation and regularity of the fibres as well as the type of polymer from which it is made. Also, the chemical resistance of a geotextile will depend upon the size of the individual component fibres in the fabric, as well as their chemical composition – fine fibres with a large specific surface area are subject to more rapid chemical attack than coarse fibres of the same polymer.

Mechanical responses include the ability of a textile to perform work in a stressed environment and its ability to resist damage in an arduous environment. Usually the stressed environment is known in advance and the textile is selected on the basis of numerical criteria to cope with the expected imposed stresses and its ability to absorb those stresses over the proposed lifetime of the structure without straining more than a predetermined amount. Figure 14.1 compares the tensile behaviours of a range of geotextiles.

On the other hand, damage can be caused on site during the construction period (e.g. accidental tracking from vehicles) or in situ during use (e.g. punching through geotextiles by overlying angular stone). Clearly, in both cases, damage is caused by



14.1 Typical ultimate stress–strain failure levels (a) of high strength and (b) of medium strength polyester woven geotextiles used for embankment support and soil reinforcement, (c) of geogrids and lower strength polyester woven geotextiles used for soil reinforcement and (d) of low strength, highly extensible nonwoven geotextiles used for separation and filtration. (c) represents the current maximum strength capacity of polyethylene geogrids.

an undesirable circumstance which is particularly difficult to remove by design. However, in the latter case, it is possible to perform advanced field testing and to allow appropriate safety factors in calculations.

The ability to perform work is fundamentally governed by the stiffness of the textile in tension and its ability to resist creep failure under any given load condition. The ability to resist damage is complex, clearly being a function of the fibre's ability to resist rupture and the construction of the fabric, which determines how stresses may be concentrated and relieved. In practical terms, geotextiles can be manufactured in a composite form, utilising the protective nature of one type of construction to reduce damage on a working element. For example, a thick nonwoven fabric may be joined to a woven fabric; the woven textile performs the tensile work whilst the nonwoven acts as a damage protective cushion.

The filtration performance of a geotextile is governed by several factors. To understand this, it is essential to be aware that the function of the textile is not truly as a filter in the literal sense. In general, filters remove particles suspended in a fluid, for example, dust filters in air-conditioning units, or water filters, which are intended to remove impurities from suspension. Quite the opposite state of affairs exists with geotextile filters. The geotextile's function is to hold intact a freshly prepared soil

Table 14.1 Recommended time periods for maximum daylight exposure of geosynthetics. Beyond the limits shown damage may occur, depending upon sunlight intensity

	Temperate	Arctic	Desert	Tropical
April to Sept	8 Weeks	4 Weeks	2 Weeks	1 Week
Oct to March	12 Weeks	6 Weeks	2 Weeks	1 Week

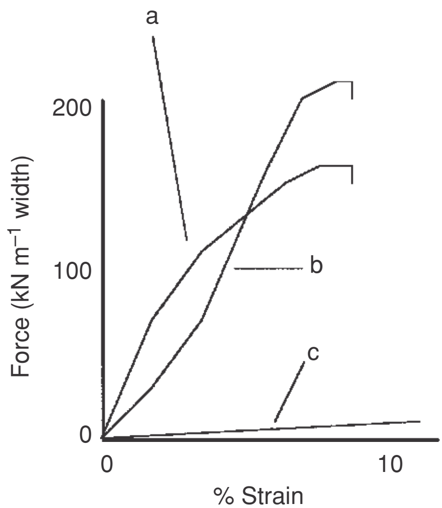
surface, so that water may exude from the soil surface and through the textile without breaking down that surface. If water is allowed to flow between the textile and the soil interface, with particles in suspension, it will tend to clog up the textile which will fail in its function. In practice, it has been found that, in conjunction with a textile, the soil will tend to filter itself, provided that the integrity of its external surface is maintained. The actual process taking place is the passage of a liquid from a solid medium that is held intact by a permeable textile. The process is not one of restraining the passage of solids that are suspended within a liquid medium.

Geotextiles are rarely called upon to resist extremely aggressive chemical environments. Particular examples of where they are, however, include their use in the basal layers of chemical effluent containers or waste disposal sites. This can happen if and when leaks occur, permitting effluent to pass through the impermeable liner, or if the textiles have been incorporated directly in the leachate disposal system above the impermeable liner. Another example might be the use of textiles in contact with highly acidic peat soils, where in tropical countries, pH values down to 2 have been encountered. In industrialised countries where infrastructure developments are being constructed through highly polluted and contaminated areas, geotextiles can also come into contact with adverse environments.

Ultraviolet light will tend to cause damage to most polymers, but the inclusion of additives, in the form of antioxidant chemicals and carbon black powder, can considerably reduce this effect. The only time when a geotextile is going to be exposed to sunlight is during the construction period. It is generally considered that contracts should specify the minimum realistic period of exposure during site installation works. However, this will vary with time of year and latitude. In brief, it can be considered that exposure in UK and northern European type climates can be eight weeks in the summer and twelve in the winter. In tropical countries, however, exposure should be limited to seven days at any time of year before noticeable damage occurs. Table 14.1 lists typical maximum exposure periods.

14.3.1 Mechanical properties

The weight or area density of the fabric is an indicator of mechanical performance only within specific groups of textiles, but not between one type of construction and another. For example, within the overall range of needlepunched continuous filament polyester fabrics, weight will correlate with tensile stiffness. However, a woven fabric with a given area density will almost certainly be much stiffer than an equivalent weight needlepunched structure. Clearly the construction controls the performance. Therefore, it is impossible to use weight alone as a criterion in specifying textiles for civil engineering use. However, in combination with other



14.2 Different stress–strain curve shapes exhibited by the three main types of geosynthetic construction. (a) Geogrids absorb the imposed stresses immediately, giving a high initial modulus. Later, the curve flattens. (b) Woven fabrics exhibit initial straightening of warp fibres which produces a low initial modulus. Later the modulus increases as the straightened polymer fibres take the stress directly. (c) Nonwovens give a curvilinear curve, because extension is primarily resisted by straightening and realignment of the random fibre directions.

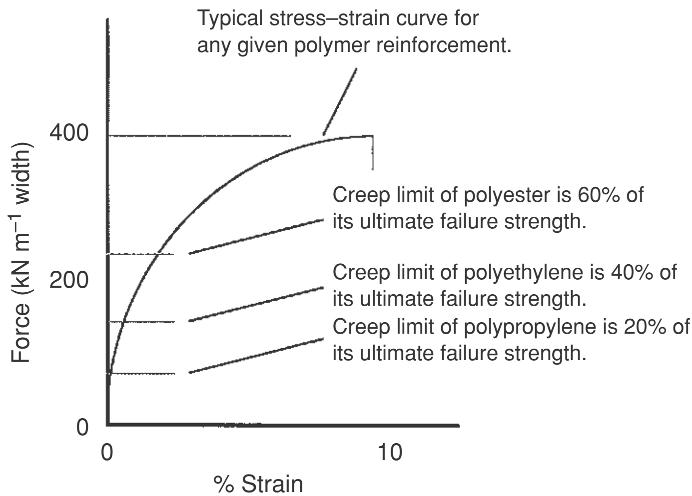
specified factors, weight is a useful indication of the kind of product required for a particular purpose.

The breaking strength of a standard width of fabric or 'ultimate strip tensile failure strength' is universally quoted in the manufacturers' literature to describe the 'strength' of their textiles. Again, this is of very limited use in terms of design. No designer actually uses the failure strength to develop a design. Rather, a strength at a given small strain level will be the design requirement. Therefore, the tensile resistance or modulus of the textile at say, 2%, 4%, and 6% strain is much more valuable. Ideally, continuous stress–strain curves should be provided for engineers, to enable them to design stress resisting structures properly.

Stress–strain curves, as shown in Fig. 14.1 and in Fig. 14.2 above, may well comprise a high strain sector, contributed by the textile structure straightening out, and a low strain sector, contributed by the straightened polymer taking the stress. Of course, the mechanical performance of the common geotextiles will be less as the ambient temperature rises. Because engineering sites are exposed to temperatures varying from –20 °C to 50 °C, this can have important consequences during installation and use.

Creep can cause the physical failure of a geotextile if it is held under too high a mechanical stress. It has been found that in practical terms, both polyester and polyethylene will stabilise against creep if stress levels can be maintained at a sufficiently low level. Although polypropylene does not seem to stabilise at any stress level, its creep rate is so low at small stresses that a 'no creep' condition may be considered to exist in practice.

The 'no creep' condition, measured as elongation, for any particular polymer



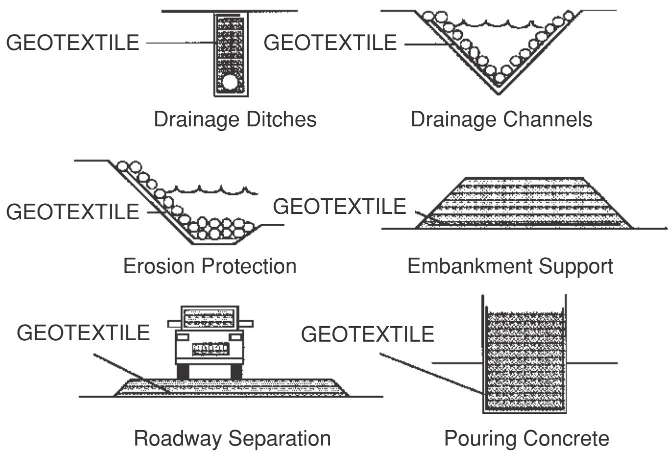
14.3 Approximate limits of creep resistance for different geosynthetic polymer constructions.

textile is defined (usually as a percentage) with respect to the textile's ultimate load-carrying capability. For polyester, it is approximately 60%, for polyethylene about 40% and for polypropylene around 20%. Therefore, for example, a polyester fabric with an ultimate tensile strength of 100 kN m^{-1} width cannot be loaded under a long term stress of more than 60 kN m^{-1}. The higher the level of imposed stress above this point, the more rapid will be the onset of creep failure. Figure 14.3 shows the safe loading limits for most commonly used geotextiles.

Wing tear, grab tear and puncture resistance tests may be valuable because they simulate on-site damage scenarios such as boulder dropping and direct over-running by machines. These tests are developed in standard form in a number of countries, with the standard geosynthetic test specification in the UK being BS 6906 which contains tests for:

1 tensile testing by means of a wide strip test
2 pore size testing by dry sieving
3 water flow testing normal to the plane of the textile
4 puncture resistance testing
5 creep testing
6 perforation susceptibility (cone) testing
7 water flow testing in the plane of the textile
8 testing of sand/geotextile frictional behaviour.

While not normally part of the mechanical requirements of a textile, the strength of joints between sheet edges is an important aspect of geotextile performance. When laying textiles on soft ground for supporting embankments, parallel sheets of textile have to be sewn together so that they do not separate under load. The strength of such sewn joints depends critically on the tensile strength of the sewing thread. Rarely will the sewn joint exceed 30% of the weft ultimate tensile strength. Research and field practice have shown that the strength of a sewn joint depends more upon the tenacity and tension of the sewing thread, the kind of sewing stitch



14.4 Some different drainage and filtration applications for geotextiles in civil engineering.

and the kind of textile lap than the strength of the textile. An erroneous but common concept of joint 'efficiency' has developed which expresses the strength of a sewn seam as a percentage of the textile strength. In fact, relatively weak textiles can be sewn such that the joint is as strong as the textile, thus giving a 100% efficiency. The stronger the textile, the less is the relative strength of the sewn joint, leading to falling efficiencies with stronger fabrics. Thus it is reasonable to request a 75% efficient sewn joint if the textiles being joined are relatively weak, say 20 kN ultimate strength, but it would be impossible to achieve with a textile of say 600 kN ultimate strength. Unfortunately, it is the stronger textiles that tend to need to be joined, in order to support embankments and the like.

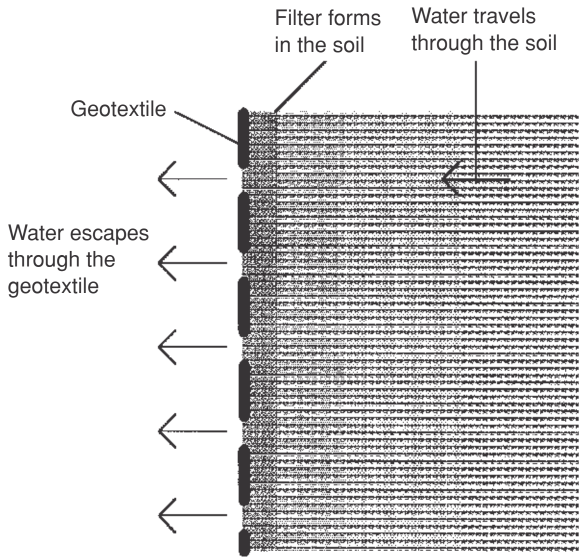
Adhesive joints, on the other hand, can be made using single-component adhesives whose setting is triggered by atmospheric moisture. These can be used to make joints which are as strong as the textile, even for high strength fabrics. Research is still needed on methods of application, but their use should become more widespread in the future.

Apart from tensile testing of joints, there is an urgent need to develop tests that give a meaningful description of the ways that textiles behave when stressed within a confining soil mass and additionally when stressed by a confining soil mass. The standard textile tests used in the past are not able to do this. Research work has been started along these lines but is so far insufficient to provide a basis for theoretical analysis.

14.3.2 Filtration properties

Filtration is one of the most important functions of textiles used in civil engineering earthworks. It is without doubt the largest application of textiles and includes their use in the lining of ditches, beneath roads, in waste disposal facilities, for building basement drainage and in many other ways (Fig. 14.4).

Of all the varied uses for geotextiles, only in a reinforced soil mass is there no beneficial filtration effect. In just about all other applications including drains, access



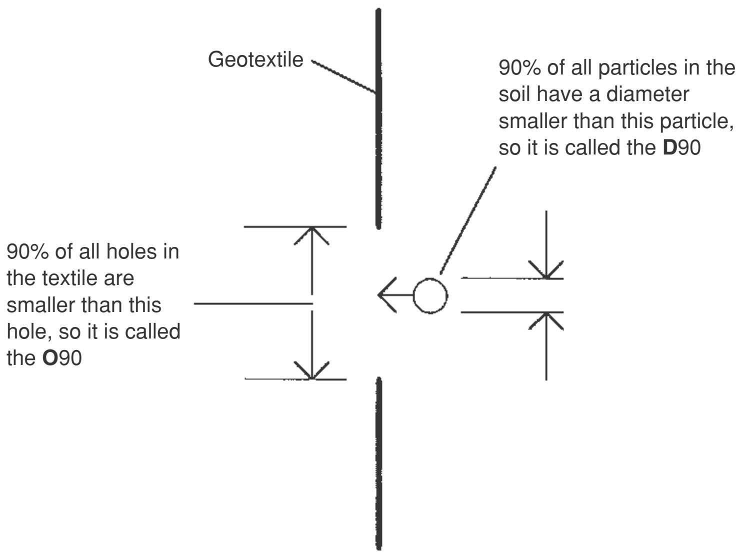
14.5 Internal soil filter zone generated by a geotextile.

roads, river defences, marine defences, embankment support and concrete pouring, the geotextile will play a primary or secondary filtering function.

The permeability of geotextiles can vary immensely, depending upon the construction of the fabric. Various national and international standards have been set up for the measurement of permeability that is required, most often at right angles to the plane of the textile (crossflow), but also along the plane of the textile (in-plane flow, called transmissivity). It is important in civil engineering earthworks that water should flow freely through the geotextile, thus preventing the build-up of unnecessary water pressure. The permeability coefficient is a number whose value describes the permeability of the material concerned, taking into account its dimension in the direction of flow; the units are rationalised in metres per second. Effectively the coefficient is a velocity, indicating the flow velocity of the water through the textile. Usually, this will be of the order of $0.001\,\mathrm{m\,s^{-1}}$. A commonly specified test measures a directly observed throughflow rate, which many feel is more practical than the permeability coefficient; this is the volume throughflow in litres per square metre per second at 100 mm head of pressure. Engineers also use a coefficient called the permittivity, which defines the theoretical permeability irrespective of the thickness of the fabric.

The filtration effect is achieved by placing the textile against the soil, in close contact, thus maintaining the physical integrity of the bare soil surface from which water is passing. Within the first few millimetres of soil, an internal filter is built up and after a short period of piping, stability should be achieved and filtration established (Fig. 14.5).

As previously discussed, filtration is normally achieved by making the soil filter itself, thus using a solid medium system, through which the liquid is flowing. There are, however, special cases where it is specifically required that the textile works in a slurry environment. Examples include tailing lagoons from mining operations and other industrial lagoons where water has to be cleared from slurries. Single textiles



14.6 Relationship between O90 and D90.

do not work well under these conditions, but experimental work has suggested that double layers of different types of textile acting as a composite unit can improve the ability of the individual components to effect filtration without clogging.

The simplest combination reported is a smooth woven textile over a thick needlepunched nonwoven fabric placed so that the former is between the needlepunched component and the slurry. It appears that the woven fabric acts as a 'shield', protecting the nonwoven from the liquid and emulating a soil surface, thus permitting the nonwoven to function more effectively as a filter. The drainage effect of the underlying nonwoven also possibly acts to induce high hydraulic gradients which, reciprocally, assist the woven to function.

The procedure for matching a textile to the soil, in order to achieve stability under difficult hydraulic conditions, is to use a textile whose largest holes are equal in diameter to the largest particles of the soil (see Fig. 14.6 where O90 = D90). Where hydraulic conditions are less demanding, the diameter of the largest textile holes can be up to five times larger than the largest soil particles (O90 = 5D90). Particularly difficult hydraulic conditions exist in the soil (i) when under wave attack, (ii) where the soil is loosely packed (low bulk density), (iii) where the soil is of uniform particle size, or (iv) where the hydraulic gradients are high. Lack of these features defines undemanding conditions. Between the two extremes lies a continuum of variation which requires the engineer to use experience and judgment in the specification of the appropriate O90 size for any given application.

The largest hole sizes and largest particle sizes are assessed by consideration of the largest elements of the fabric and soil. Measuring the largest particles of a soil is achieved by passing the soil through standard sieves. In order to assess a realistic indication of the larger particle diameters, a notional size is adopted of the sieve size through which 90% of the soil passes. This dimension is known as the D90 by convention. Similarly, an indication of the largest holes in a textile is taken as the 90% of the biggest holes in the fabric, the O90.

Even under ideal conditions, if the O90 pore size is bigger than 5D90, then so-called piping will take place. The textile O90 pore size should be reduced from 5D90 towards D90 as the ground and hydraulic conditions deteriorate.

14.3.3 Chemical resistance

Although the chemical mechanisms involved in fibre degradation are complex,[8] there are four main agents of deterioration: organic, inorganic, light exposure and time change within the textile fibres.

Organic agents include attack by micro- and macrofaunas. This is not considered to be a major source of deterioration per se. Geotextiles may be damaged secondarily by animals, but not primarily. For example, few animals will eat them specifically, but in limited instances, when the textile is buried in the ground, it may be destroyed by animals burrowing through. Microorganisms may damage the textiles by living on or within the fibres and producing detrimental by-products. Possibly the most demanding environment for geotextiles is in the surf zone of the sea where oxygenated water permits the breeding of micro- and macroorganisms and where moving water provides a demanding physical stress.

Inorganic attack is generally restricted to extreme pH environments. Under most practical conditions, geotextile polymers are effectively inert. There are particular instances, such as polyester being attacked by pH levels greater than 11 (e.g. the byproducts of setting cement), but these are rare and identifiable.

Geotextiles can fail in their filtration function by virtue of organisms multiplying and blocking the pores, or by chemical precipitation from saturated mineral waters blocking the pores. In particular, water egressing from old mine workings can be heavily saturated with iron oxide which can rapidly block filters, whether textile or granular.

Ultraviolet light will deteriorate geotextile fibres if exposed for significant periods of time, but laboratory testing has shown that fibres will deteriorate on their own with time, even if stored under dry dark cool conditions in a laboratory. Therefore, time itself is a damaging agent as a consequence of ambient temperature and thermal degradation, which will deteriorate a geotextile by an unknown amount.

14.4 Conclusions

Geotextiles are part of a wider group of civil engineering membranes called geosynthetics. They are extremely diverse in their construction and appearance. However, they are generally made from a limited number of polymers (polypropylene, polyethylene and polyester), and are mostly of five basic types: woven, heat-bonded, needlepunched, knitted and direct soil mixed fibres.

The physical properties of this diverse group of products vary accordingly, with ultimate strengths reaching up to $2000\,kN\,m^{-1}$, but commonly between 10 and $200\,kN\,m^{-1}$. Ultimate strains vary up to more than 100%, but the usable range for engineers is generally between 3 and 10%. Similarly, the filtration potential and permeability of different geotextiles vary enormously.

Geotextiles are used in civil engineering earthworks to reinforce vertical and steep banks of soil, to construct firm bases for temporary and permanent roads and highways, to line ground drains, so that the soil filters itself and prevents soil from

filling up the drainpipes and to prevent erosion behind rock and stone facing on river banks and the coast. They have been developed since the mid 1970s, but the advent of knitted and composite fabrics has led to a revival in attempts to improve textile construction in a designed fashion. Better physical properties can be achieved by using more than one fabric and by utilising the best features of each.

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14

Textiles in civil engineering. Part 2 – natural fibre geotextiles

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14.5 Introduction

Processes for the selection, specification, production and utilisation of synthetic geotextiles are well established in developed countries. In many ground engineering situations, for example temporary haul roads, basal reinforcement, consolidation drains, and so on, geotextiles are only required to function for a limited time period whereas suitable synthetic materials often have a long life. Hence, the user is paying for something which is surplus to requirement. Also, conventional geotextiles are usually prohibitively expensive for developing countries. However, many of these countries have copious supplies of cheap indigenous vegetable fibres (such as jute, sisal and coir) and textile industries capable of replicating common geotextile forms. Although, there are numerous animal and mineral natural fibres available, these lack the required properties essential for geotextiles, particularly when the emphasis of use is on reinforcing geotextiles.

Synthetic geotextiles not only are alien to the ground, but have other adverse problems associated with them, in that some synthetic products are made from petroleum-based solutions. As a result of the finite nature of oil, the oil crisis in 1973, the conflict with Kuwait and Iraq in 1991, and the potentially political volatile state of some of the world's other oil producing countries, both the cost and the public awareness of using oil-based products have considerably increased. Natural fibre products of vegetable origin will be much more environmentally friendly than their synthetic equivalents and the fibres themselves are a renewable resource and biodegradable.

14.6 Development of natural materials as geotextiles

The exploitation of natural fibres in construction can be traced back to the 5th and 4th millennia BC as described in the Bible (Exodus 5, v 6–9) wherein dwellings were

14.7 Woven mat and plaited rope reeds used as reinforcement in the Ziggurat at Dur Kurigatzu.

formed from mud/clay bricks reinforced with reeds or straw. Two of the earliest surviving examples of material strengthening by natural fibres are the ziggurat in the ancient city of Dur-Kurigatzu (now known as Agar-Quf) and the Great Wall of China.[1] The Babylonians 3000 years ago constructed this ziggurat using reeds in the form of woven mats and plaited ropes as reinforcement (Fig. 14.7). The Great Wall of China, completed circa 200 BC, utilised tamarisk branches to reinforce mixtures of clay and gravel.[1,2] These types of construction however, are more comparable to reinforced concrete than today's reinforced earth techniques, because of the rigid way in which stress was transferred to the tensile elements and the 'cemented' nature of the fill.

Preconceived ideas over the low apparent tensile strength of natural materials and the perception that they have a short working life when in contact with soil limited their uses, especially for strengthening soil, in geotechnical engineering at this early stage. Also, the lack of reliable methods of joining individual textile components to form tensile fabrics presented a major limitation to their usage.

The first use of a textile fabric structure for geotechnical engineering was in 1926, when the Highways Department in South Carolina USA[3] undertook a series of tests using woven cotton fabrics as a simple type of geotextile/geomembrane, to help reduce cracking, ravelling and failures in roads construction. The basic system of construction was to place the cotton fabric on the previously primed earth base and to cover it with hot asphalt; this however made the fabric perform more like a geomembrane than a geotextile. Although published results were favourable, especially for a fabric that had been in service for nine years, further widescale development of this fabric as a geotextile did not take place. This was probably due to the high extensibility and degradable nature of this particular natural fibre together with the advent of chemical fibres.

The earliest example of jute woven fabric geotextiles for subgrade support was in the construction of a highway in Aberdeen in the 1930s.[4] The British Army also

used a special machine to lay canvas or fascines over beaches and dunes for the invasion of Normandy in 1944.[5]

For thousands of years the textile industry has been spinning fibres to make yarns which in turn can be woven into fabrics. Up until the mid 1930s, these fibres were all naturally occurring, either vegetable or animal. At the beginning of this century the use of natural polymers based on cellulose was discovered, and this was quickly followed by production of chemical or synthetic products made from petroleum-based solutions.

The use of chemical fibre-based geotextiles in ground engineering started to develop in the late 1950s, the earliest two references being (i) a permeable woven fabric employed underneath concrete block revetments for erosion control in Florida[6] and (ii) in the Netherlands in 1956, where Dutch engineers commenced testing geotextiles formed from hand-woven nylon strips, for the 'Delta Works Scheme'.[7]

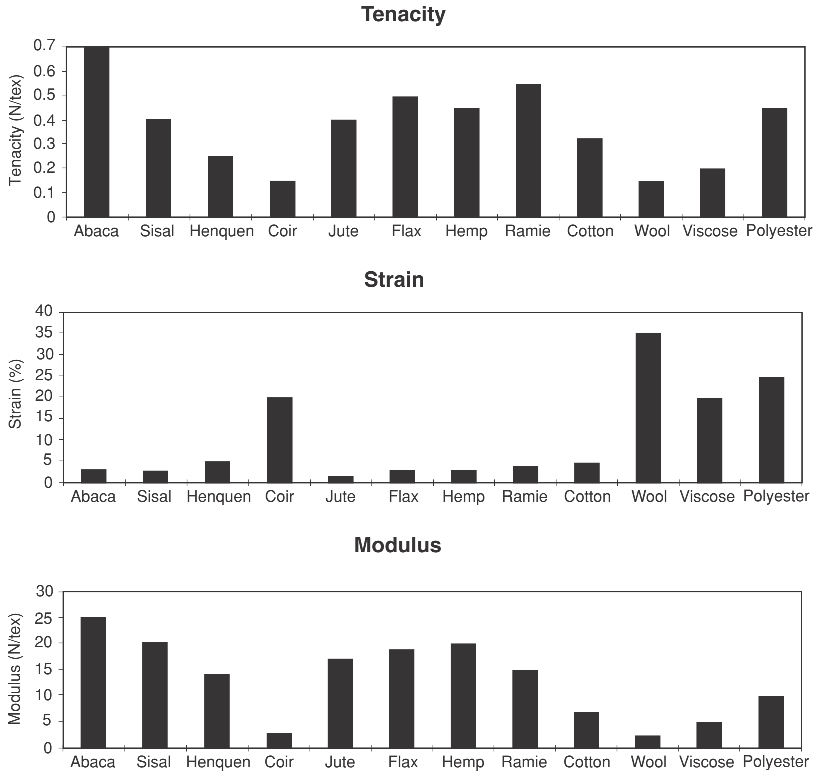
In the early 1960s, the excess capacity of synthetic products caused the manufacturers to develop additional outlets such as synthetic geotextiles for the construction industry. The manufacturers refined their products to suit the requirements of the engineer, rather than the engineer using the available materials to perform the requisite functions, because to a certain extent, fibre fineness and cross-sectional area can be modified to determine satisfactory tensile properties in terms of modulus, work of rupture, creep, relaxation, breaking force and extension. This led to the prolific production of synthetic materials for use in the geotextile industry. These synthetic geotextiles have monopolised the market irrespective of the cost both in economical and ecological terms. This put severe pressure on the manufacturers of ropes and cordage made from natural fibres, almost to the point of their extinction. In 1973, three fundamental applications were identified for the use of geotextiles, namely, reinforcement, separation and filtration,[8] with drainage applications (fluid transmission) also being a significant area. During the 1990s over 800 million m^2 of synthetic geotextiles have been produced worldwide,[9] making it the largest and fastest growing market in the industrial/technical fabrics industry.[10]

Although natural fibres have always been available, no one visualised their potential as a form of geotextile until synthetic fibres enabled diverse use and applications of geotextiles to emerge. Manufacturers are now attempting to produce synthetic fibres which will mimic the properties of natural fibres, but at a greater expense.

14.7 Natural fibres

The general properties of chemical fibres compared to natural fibres still tend to fall into distinct categories. Natural fibres possess high strength, modulus and moisture uptake and low elongation and elasticity. Regenerated cellulose fibres have low strength and modulus, high elongation and moisture uptake and poor elasticity. Synthetic fibres have high strength, modulus and elongation with a reasonable amount of elasticity and relatively low moisture uptake.

Natural fibres can be of vegetable, animal or mineral origin. Vegetable fibres have the greatest potential for use in geotextiles because of their superior engineering properties, for example animal fibres have a lower strength and modulus and higher



14.8 Typical strength, elongation and modulus values of natural fibres relative to those of synthetic fibres.

elongation than vegetable fibres. Mineral fibres are very expensive, brittle and lack strength and flexibility. Figure 14.8 shows typical strength, elongation and modulus values of natural fibres relative to those of synthetic fibres.

The pertinent factor for a geotextile, especially for reinforcement, is that it must possess a high tensile strength. It is known that the best way of obtaining this criterion is in the form of fibres which have a high ratio of molecular orientation. This is achieved naturally by vegetable fibres, but for synthetic polymers the molecules have to be artificially orientated by a process known as stretching or drawing, thus an increase in price is incurred. Hence nature provides ideal fibres to be used in geotextiles. In strength terms vegetable fibres compare very well with chemical fibres, in that the tenacity for cotton is in the region of $0.35\,\mathrm{N\,tex^{-1}}$ and for flax, abaca and sisal it is between 0.4–$0.6\,\mathrm{N\,tex^{-1}}$ when dry, increasing when wet to the strength of high tenacity chemical fibres – the tenacity of ordinary chemical fibres is around $0.4\,\mathrm{N\,tex^{-1}}$ (polyester). The Institute Textile de France showed (prior to 1988) that individual flax fibres (separated from their stems within the laboratory, using a process that does not weaken them) have a strength of $2 \times 10^6\,\mathrm{kN\,m^{-1}}$ and modulus of $80 \times 10^6\,\mathrm{kN\,m^{-1}}$, that is, of the same order as Kevlar,[11] a chemically modified polyamide, with exceptionally high strength compared to other synthetic fibres.

Natural fibre plants may be cultivated mainly for their fibre end-use (e.g. jute, sisal and abaca), but vegetable fibres are often a byproduct of food/crop produc-

tion. Flax fibre can be extracted from the linseed plant. Also, hemp fibre is extracted for paper pulp or textile use whilst the soft inner core of the stem is used for livestock bedding. The cultivation of flax and hemp fibre allows farmers to grow the fibre crops on set-aside land (land out of food production as part of a European Union policy to decrease surpluses) which would otherwise be standing idle.

Nature provides plants with bundles of fibres interconnected together by natural gums and resins to form a load-bearing infrastructure. These fibres are pliable, have good resistance to damage by abrasion and can resist both heat and sunlight to a much greater extent than most synthetic fibres. Some fibres can also withstand the hostile nature of the marine environment. However, all natural fibres will biodegrade in the long term as a result of the action of the microorganisms. In certain situations this biodegradation may be advantageous.

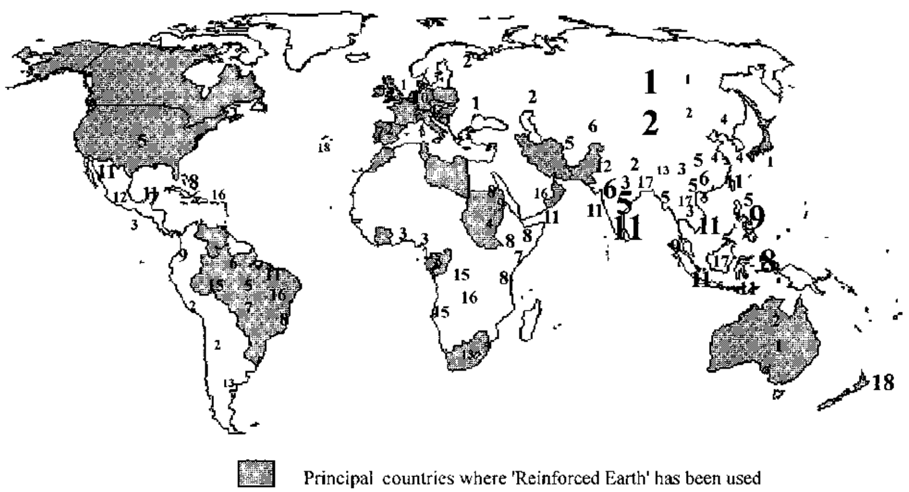
Vegetable fibres contain a basic constituent, cellulose, which has the elements of an empirical formula $(C_6H_{10}O_5)_n$. They can be classed morphologically, that is according to the part of the plant from which they are obtained:

1 *Bast* or *phloem fibres* (often designated as soft fibres) are enclosed in the inner bast tissue or bark of the stem of the dicotyledonous plants, helping to hold the plant erect. Retting is employed to free the fibres from the cellular and woody tissues, i.e. the plant stalks are rotted away from the fibres. Examples of the most common of these are flax, hemp and jute.
2 *Leaf fibres* (often designated as hard fibres) run hawser-like within the leaves of monocotyledonous plants. These fibres are part of the fibrovascular system of the leaves. The fibres are extracted by scraping the pulp from the fibres with a knife either manually or mechanically. Examples of these are abaca and sisal.
3 *Seed and fruit fibres* are produced by the plant, not to give structural support, but to serve as protection for the seed and fruit that are the most vulnerable parts of the plant normally attacked by predators. Examples of these are coir and cotton. With coir fibre, the coconut is dehusked then retted, enabling the fibre to be extracted.

A natural fibre normally has a small cross-sectional area, but has a long length. This length is naturally formed by shorter fibres (often referred to as the cell length) joined together by a natural substance, such as gum or resin (the exception to this is the fibre from the seeds of the plant, vis-à-vis cotton and kapok where the length of the fibre is the ultimate fibre length).

Of the 1000 to 2000 fibre-yielding plants throughout the world,[12] there are some 15–25 plants that satisfy the criteria for commercial fibre exploitation although a number of these are only farmed on a small scale. These main fibres are flax, hemp, jute, kenaf, nettle, ramie, roselle, sunn, urena (bast fibres) abaca, banana, cantala, date palm, henequen, New Zealand flax, pineapple, sisal, (leaf fibre) coir, cotton and kapok (seed/fruit fibres). Figure 14.9 indicates the principal centres of fibre production. The main factors affecting the production/extraction of vegetable fibres are:

1 The quantity of the fibre yield from the plant must be adequate to make fibre extraction a viable proposition.
2 There must be a practical and economical procedure for extracting the fibres, without causing damage to them, if they are to be of any value as a textile material.



14.9 Principal centres of fibre production. 1 Flax, 2 hemp, 3 sunn, 4 ramie, 5 jute, 6 kenaf, 7 roselle, 8 sisal, 9 abaca, 10 nettle, 11 coir, 12 cantala, 13 henequen, 14 kapok, 15 urena, 16 pineapple, 17 banana, 18 New Zealand flax. The size of the numbers indicates the most important countries for the production of fibre.

3 The pertinent properties of the fibre must be equivalent or superior to the existing chemical fibres used for the same given purpose in terms of both end production and machinability.
4 The annual yield of the fibre must be 'repeatable' and sufficiently large, i.e. if a plant has a high yield of fibre, say only every five years, then its marketability declines. Consideration must also be given to the time of harvest, i.e. late harvest yields lower quality fibres.
5 Whether there is a demand for the fibre properties on the market.
6 If there are problems of plant diseases and insect attack – protection from which has seen major improvements in the 20th century.

Advantages of developing such indigenous geotextiles would be:

- robust fibre
- environmental friendliness
- low unit cost
- strength/durability of some natural fibres, which are superior to chemical products
- reinforcing material is on the doorstep of developing countries
- increase in demand for the grower, therefore more money entering the country
- good drapability
- biodegradability
- additional use of byproducts or new use for waste.

14.7.1 Vegetable fibre properties

When selecting the most suitable vegetable fibres for geotextiles, consideration must be given to the general properties of available natural fibres in terms of strength,

elongation, flexibility, durability, availability, variability and their production forms, from the civil engineering and textile aspects. Also, factors affecting the economics of fibre cultivation and extraction on a large commercial scale should be taken into account. Allowing for the above factors, six vegetable fibres have been selected as the most promising to form geotextiles: flax, hemp, jute, abaca, sisal and coir (not in the order of priority). A generalised description of these plants/fibres is given in Tables 14.2 to 14.7, with typical values of their physical, mechanical, chemical and morphological characteristics shown in Tables 14.8 to 14.11.

Hemp and flax can be cultivated in the climatic conditions experienced in temperate countries such as the UK. Hemp does not require any pesticide treatment whilst growing. Both hemp and flax are very similar types of plant and are grown/cultivated in virtually identical conditions, producing almost similar properties in terms of fibre. However, hemp requires a licence from the Home Office for its cultivation, which imposes disadvantages compared to flax. Jute has emerged from its infancy in geotechnical engineering and has found a potential market in the erosion control industry, but may lack durability for other end-uses.

Strength properties of abaca may be superior to those of sisal, but the overall properties/economics of sisal may just outweigh those of abaca, that is, abaca is only cultivated in two countries throughout the world, with a production of less than one-fifth of sisal fibre. However, with leaf fibres retting has to be conducted within 48 hours of harvesting because otherwise the plant juices become gummy, and therefore fibre extraction is more difficult and unclean fibre is produced.

In certain categories, coir does not perform to the same standards as other fibres (i.e. low strength and high elongation), but general factors related to coir overshadow most of the other fibres for specific applications. The energy required to break the coir fibres is by far the highest of all the vegetable fibres, indicating its ability to withstand sudden shocks/pulls. Also, it is one of the best fibres in terms of retention of strength properties and biodegradation rates (in both water and sea water).

Further prioritisation of these six vegetable fibres will ultimately depend on the utilisation/end application of the geotextile.

14.8 Applications for natural geotextiles

The use of geotextiles for short-term/temporary applications to strengthen soil has a particular niche in geotechnical engineering. Geotextiles are used extensively in developed countries to combat numerous geotechnical engineering problems safely, efficiently and economically. They have several functions which can be performed individually or simultaneously, but this versatility relies upon the structure, physical, mechanical and hydraulic properties of the geotextile. Details of the general properties required to perform the functions of the geotextiles for various applications are given in Table 14.12.

14.8.1 Soil reinforcement

Soil is comparatively strong in compression, but very weak in tension. Therefore, if a tensile inclusion (geotextile) is added to the soil and forms intimate contact with it, a composite material can be formed which has superior engineering

Table 14.2 General description of flax plant/fibre

Fibre names and family	Flax	(Liniaceae)
Genus and species	*Linum usitatissimum*	(Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 16–32 mm, stem length 0.9–1.2 m. Harvested after 90 days of growth when stems are green-yellow. 30 bundles of fibre in stem, each bundle contains 10–14 individual (ultimate) fibres. Low input crop fits well on a rotation scheme (6–7 years)[13]	
Countries of cultivation	Russia (80%), China, Egypt, Turkey, Philippines, Malaysia, Sri Lanka, Japan, New Zealand, UK, Poland, France, Belgium, Netherlands, USA, Canada, Argentina, West Indies, Japan and Taiwan	
Environmental – climate requirements	90% of the world's production is grown between 49° to 53°N, but can be cultivated between 22° to 65°N and 30° to 45°S	
Soil type	Rich deep loams, slightly acidic[13]	
Components of yield	One quarter of stem consists of fibre. Stem is pulled out of ground not cut, therefore longer fibres are obtained. 5–7 tonnes of flax per hectare, of which 15–20% can be extracted as long fibre, 8–10% as short fibre or tow, 5–10% seed, 45–50% woody core or shives.[13] There has been little flax produced in the UK because until recently there was no processing industry, however there is now an EC subsidy for seed flax to produce linseed oil[13]	
Uses	Linen, twines, ropes fishing nets, bags, canvas & tents. Tow fibre; high grade paper, i.e. cigarette paper and banknotes. Linseed oil and linseed flax fibre	
World annual production (tonnes)	830 000[14] 3rd most important fibre in terms of cash and acreage. Ranks 4th for the total fibre production (1st cotton, 2nd jute, 3rd kenaf)	
£ per tonne	Long line 800–2000, tow 300–700[15]	
Fibre extraction – retting	Retting affects the colour, 85% by dew retting (3–7 wks) fibre grey in colour, producing cheaper better fibre by less labour intensive way than dam, tank and chemical retting. After retting, fibre is broken away from the stems and combed	
Effects from water, sea water, pests, etc.	Fibre strength increases when wet. Pests; flea, beetles and thrips, however in general flax is not very vulnerable[13]	
Cross-section bundles	Roundish elongated irregular[16]	
Ultimate fibre	Nodes at many points, cell wall thick and polygonal in cross-section. Cell long and transparent	
Longitudinal view	Cross-marking nodes and fissures[16]	
Fibre cell ends	Ends taper to a point or round[17]	
Properties compared to other fibres	Physical and chemical properties are superior to cotton	
General fibre detail, colour, etc.	Yellowish-white, soft and lustrous in appearance. High degree of rigidity and resists bending. Russian flax weak but very fine	
General	Inextensible fibre, more elongation obtained when dry. One of the highest tensile strength and modulus of elasticity of the natural vegetable fibres. Density same as polymers, thus used as alternative reinforcement to glass, aramid and carbon in composites. Good conductor of heat and can be cottonised	

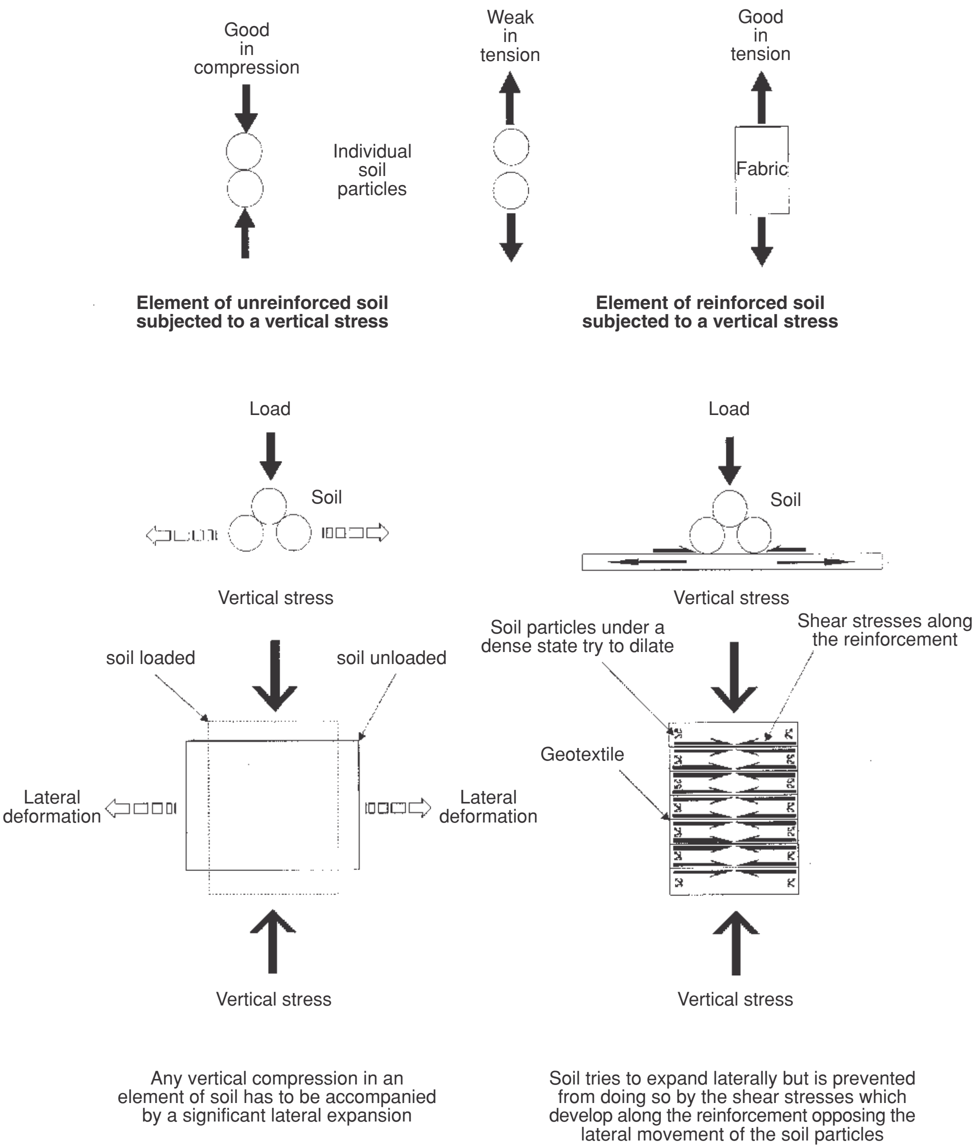
Table 14.3 Generalised description of hemp plant/fibre

Fibre names and family	Hemp	(Moraceae)
Genus and species	*Cannabis sativa*	(Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 4–20 mm, stem length 4.5–5 m. Harvested after 90 days	
Countries of cultivation	Russia, Italy, China, Yugoslavia, Romania, Hungry, Poland, France, Netherlands, UK and Australia	
Environmental – climate requirements	Annual rainfall >700 mm mild climate with high humidity	
Soil type	Best results from deep, medium heavy loams well-drained and high in organic matter. Poor results from mucky or peat soils and should not be grown on the same soil yearly	
Components of yield	Not hard to grow. Hemcore Ltd in 1994 grew 2000 acreage in East Anglia	
Uses	Ropes, marine cordage, ships sails, carpets, rugs, paper, livestock bedding and drugs	
World annual production (tonnes)	214 000[14] Ranks 6th in importance of vegetable fibre	
£ per tonne	300–500[15]	
Fibre extraction – retting	Same process as flax, at 15–20°C retting takes 10 to 15 days. Separation of the fibre from the straw can be carried out mechanically; this is commercially known as green hemp	
Effects from water, sea water, pests, etc.	Not weakened or quickly rotted by water or salt water. No pesticide protection required for growth	
Cross-section bundles	Similar to flax[16]	
Ultimate fibre	Similar to flax, polygonal in cross-section	
Longitudinal view	Similar to flax[16]	
Fibre cell ends	Rounded tips, ends of cell are blunt	
Properties compared to other fibres	Stronger, more durable, stiffer and more rigid and coarser than most vegetable fibres	
General fibre detail, colour, etc.	Harsh, stiff and strong fine white lustrous and brittle. Suitable for weaving of coarse fabric	
General	30 varieties, narcotic drug terrahydrocannabinol (THC), in some countries cultivation illegal (cultivated now <0.3% THC thus no narcotic value). Lacks flexibility and elasticity, i.e. brittle fibre. One hectare of hemp produces as much pulp as 4 acres of forest. Can be cottonised, i.e. up to 50% hemp, does not spin easily but produces useful yarns	

characteristics to soil alone. Load on the soil produces expansion. Thus, under load at the interface between the soil and reinforcement (assuming no slippage occurs, i.e. there is sufficient shear strength at the soil/fabric interface) these two materials must experience the same extension, producing a tensile load in each of the reinforcing elements that in turn is redistributed in the soil as an internal confining stress. Thus the reinforcement acts to prevent lateral movement because of the lateral shear stress developed (Fig. 14.10). Hence, there is an inbuilt additional lateral confining stress that prevents displacement. This method of reinforcing the soil can be extended to slopes and embankment stabilisation. The following exam-

Table 14.4 Generalised description of jute plant/fibre

Fibre names and family	Jute (Tiliaceae)
Genus and species	*Corchorus capsularus* and *Corchorus olitorius* (Bast fibre)
Plant type – harvesting	Annual plant, stem diameter 20 mm, stem length 2.5–3.5 m. Harvested after 90 days, small pod stage best fibre yield
Countries of cultivation	India, Bangladesh, China, Thailand, Nepal, Indonesia, Burma, Brazil, Vietnam, Taiwan, Africa, Asia and Central and South America
Environmental – climate requirements	Annual rainfall >1800 mm required >500 mm during the growing season, high humidity between 70–90%, temperature between 70–100 °F, i.e. hot damp climates
Soil type	Rich loam soils produce best results, well-drained soils obtain reasonable results, with rocky – sandy soils producing poor results
Components of yield	Easily cultivated and harvested. Line sowing increases yield by 25–50% and reduces cost of cultivation by 25%
Uses	Ropes, bags, sacks, cloths. Erosion control applications; geojute, soil-saver, anti-wash, etc.
World annual production (tonnes)	2 300 000[14] 2nd most important fibre in terms of cash and acreage
£ per tonne	300–500[15]
Fibre extraction – retting	Same process as flax. Late harvest requires prolonged retting. 1–5% oil & water emulsion is added to soften the fibre for spinning into yarns
Effects from water, sea water, pests, etc.	Fibre deteriorates rapidly when exposed to moisture. Plant; damage by excessive: heat, drought, rainfall and floods. Pests; semilooper, mite, hairy, caterpillar and apion
Cross-section bundles	Varying size roundish or elongated[16]
Ultimate fibre	Sharply polygonal, rounded (5–6 sides) corners; wall thickness varies
Longitudinal view	Fissures and cross marking are unlikely. Lumen varies in size along each fibre
Fibre cell ends	Round tips partly pointed and tapered
Properties compared to other fibres	Not as strong as hemp and flax nor as durable
General fibre detail, colour, etc.	White, yellow, red or grey; silt like and easy to spin. Difficult to bleach and can never be made pure white owing to its lack of strength. If kept dry will last indefinitely, if not will deteriorate in time
General	Holds 5 times its weight of water. Cheap and used in great quantities, high initial modulus, but very little recoverable/ elasticity (woody fibre); exhibiting brittle fracture, having small extension at break. Poor tensile strength, good luster (silky), high lignin content. Individual fibres vary greatly in strength owing to irregularities in the thickness of the cell wall



14.10 Principle of reinforced earth.

ples illustrate typical applications where geotextiles are employed to strengthen soil for a limited amount of time.

14.8.1.1 Long-term embankments

Many developing countries have engineering situations where geotextiles could be employed to great benefit, for example hillside stabilisation, embankment and flood bank strengthening and construction over soft ground. Such countries often have copious, renewable supplies of natural fibres. Labour is also abundant in these developing countries, therefore it is more desirable to construct inexpensive short-term projects, monitor and assess their stability periodically and rebuild them

Table 14.5 Generalised description of abaca plant/fibre

Fibre names and family	Abaca or Manila hemp	(Musaceace)
Genus and species	*Musa textilis*	(leaf fibre)
Plant type – harvesting	Perennial plant, 12–30 stems per plant, leaves 2–4 m, stem diameter 130–300 mm, stems length 7.5 m. Stem contains 90% water/sap with 2–5% fibre the rest soft cellular tissue. Plant life 10–20 years without replanting, fertilisation or rotation, thus impoverishes the soil. Productivity life 7–8 years, harvest 3 stalks every 4–5 months	
Countries of cultivation	Philippines (85%) & Ecuador (15%)	
Environmental – climate requirements	Warm climate, shade, abundant moisture and good drainage. Altitude <900 m heavy rainfall (2500–3000 mm per year) uniformly distributed throughout the year and high humidity are most advantageous. Too much heat causes excessive evaporation from the leaves, thus damages them and the fibres. Also immersion in water injures the plant	
Soil type	Needs little cultivation, best grown in very fertile and well-drained soils	
Components of yield	Fibre obtained from the stem of the leaves not the expanded portion of the leaf. After efflorescence plant dies. Yield up to 1 tonne of dry fibre per acre. Maximum production between 4–8 years. 100 kg of fresh leaves produce 1–3 kg of fibre	
Uses	Marine cordage (naturally buoyant), fishing nets, mission ropes, well-drilling cables, paper and tea bags	
World annual production (tonnes)	70 000[14]	
£ per tonne	680–1150	
Fibre extraction – retting	Within 48 hours if not the plant juices become gummy thus fibre extraction is more difficult and unclean fibre is produced also waste water is acidic. Fibre extracted by separating the ribbons (tuxies) of the fibre from the layers of pulp by a knife to remove the residual pulp then hung to dry (this process can be carried out by machines)	
Effects from water, sea water, pests, etc.	Good water-resisting properties, hydroscopic, not affected by salt water. Pests; brown aphids, corm weevil, slug caterpillar	
Cross-section bundles	Roundish, slightly indented or round to elliptical[16]	
Ultimate fibre	Cells are uniform, smooth and regular surface, thus poor interlock, i.e. hard to make into a yarn. Polygonal, slightly rounded corners[16]	
Longitudinal view	Smooth cross-markings rare[16]	
Fibre cell ends	Thin smooth walls and sharp or pointed ends tapered. Cell diameter 3–4 times thicker than the cell wall. Cylindrical, long and regular in width	
Properties compared to other fibres	Superior to flax, better than hemp for marine ropes and hawers	
General fibre detail, colour, etc.	Cream and glossy, stiff and tenacious; even texture, very light weight	
General	Strong and sufficiently flexible to provide a degree of give when used in ropes where strength, durability and flexibility are essential. There are 4 groups of fibre yielded from this plant, depending on where the leaves have come from; (i) Outside sheaths (*Primera baba*) dark brown/light purple & green strips (i.e. exposure to sun) Grade 4–5. (ii) Next to outside (*segunda baba*) light green and purple, Grade 3. (iii) Middle (Media), Grade 2. (iv) Innermost (Ubod), Grade 1. The grade also depends on knife type to extract the fibre	

Table 14.6 Generalised description of sisal plant/fibre

Fibre names and family	Sisal
Genus and species	*Agave sisalana* (Leaf fibres)
Plant type – harvesting	Perennial plant, leaves 1–2 m long each containing about 1000 fibres
Countries of cultivation	Central America, Mexico, Brazil, Philippines, India, Florida, Africa, Venezuela, Tanzania, Kenya, Madagascar, Mozambique, Angola and Ethiopia
Environmental – climate requirements	If rainfall is erratic growth is spasmodic, thus low annual yield. Temperature between 27–32 °C (<16 °C), frost damages leaves, optimum rainfall 1200–1800 mm, but can withstand droughts, when other plants would perish, requires substantial amounts of strong sunlight
Soil type	Grows on dry, porous, rocky, not too acidic or low in nutrients free draining soils. Hardy plant can grow in mimimum rainfall 250–375 mm per year. Waterlogging and salinity are fatal to sisal
Components of yield	If the leaves are in the shade poor quality fibre is produced. Also cold, frost and hail can damage the leaves (fibre). There are spines at the tips of leaves. The leaves are harvested after 2–4 years of growth and then at intervals, after efflorescence plant dies, 45 kg of leaves produce approximately 2 kg of long and tow fibre
Uses	Twines, ropes, rugs, sacking, carpets, cordage and agricultural. Tow (waste product) used for upholstery
World annual production (tonnes)	378 000[14]
£ per tonne	450–1100[15]
Fibre extraction – retting	Within 48 hours if not the plant juices become gummy, thus fibre extraction is more difficult and unclean fibre is produced. Machines are used which scrape the pulpy material from the fibre, after washing, the fibre is dried and bleached in the sun, or oven-dried
Effects from water, sea water, pests, etc.	It was once believed that sisal deteriorated rapidly in salt water; experience has shown that this is not the case. Sisal is widely used for marine ropes.
Cross-section bundles	(i) Crescent to horse-shoe often split.[16] (ii) Few or no hemi-concentrical bundles with cavities.[16] (iii) Round ellipt[16]
Ultimate fibre	Polygonal wall, thick to medium.[16] Stiff in texture, wide central cavity (may be wider than the cell wall), marked towards the middle
Longitudinal view	Smooth[16]
Fibre cell ends	Same thickness as abaca, but half as long. Rounded tips, seldom forked – pointed[16]
Properties compared to other fibres	Shorter, coarser and not quite as strong as abaca. Also lower breaking load and tends to break suddenly without warning. Can be spun as fine as jute. Sisal can be grown under a wider range of conditions then henequen
General fibre detail, colour, etc.	Light yellow in colour, smooth, straight, very long and strong fibre. Number of different types of cells inside a sisal plant; normal fibre cell straight, stiff, cylindrical and often striated
General	Blooms once in its lifetime then dies. Cheap, stiff, inflexible, high strength and good lustre. Sisal fibre is equivalent hand or machine stripped. Dark bluish-green leaves, having a waxy surface to reduce water loss

Table 14.7 Generalised description of coir plant/fibre

Fibre names and family	Coir	(Coconut fibre)
Genus and species	*Cocos nucifera*	(Seed/fruit fibre)
Plant type – harvesting	Perennial plant 70–100 nuts per year, fruit picked every alternate month throughout the year. Best crop between May & June, economic life 60 years. Two types of coir; brown and white. Brown coir obtained from slightly ripened nuts. White coir obtained from immature nuts (green coconuts) fibre being finer and lighter in colour	
Countries of cultivation	India (22%), Indonesia (20%), Sri Lanka (9%), Thailand, Malaysia, Brazil, Philippines, Mexico, Kenya, Tanzania, Asia, Africa, Kerala State, Latin America and throughout the Pacific regions	
Environmental – climate requirements	20°N to 20°S latitude, planted below an altitude of 300 m. Temperature 27–32 °C, diurnal variations <7 °C, rainfall between 1000–2500 mm, >2000 hours of sunshine i.e. high humidity and plenty of sunlight	
Soil type	Wide range of soils. Best results are from well-drained, fertile alluvial and volcanic soils	
Components of yield	Husk to nut ratio, size of nuts, fibre quality, huskability, pests and diseases. Harvesting: men climb trees, from ground, or use a knife on the end of a bamboo pole, monkeys (*Macacus nemestrima*) also climb trees to collect the nuts	
Uses	Known as the tree of life, because source of many raw materials; leaves used for roofs and mats, trunks for furniture, coconut meat for food, soap and cooking oil, roots for dyes and traditional medicines, husk for ropes, cordage and sailcloths; in marine environments	
World annual production (tonnes)	100 000[14]	
£ per tonne	200–800[15]	
Fibre extraction – retting	Retting pits (brown fibre up to 9 months, white fibre 2–6 weeks). Dehusked manually or mechanically (brown fibre only)	
Effects from water, sea water, pests, etc.	Coir is resistant to degradation by sea water, endures sudden pulls, that would snap the otherwise much stronger ropes, made from hemp or other hard fibres	
Cross-section bundles	Round mostly, with cavities, hemi-concentrical bundles[16]	
Ultimate fibre	Polygonal to round, also oblong walls, medium thickness. Round and elliptical in cross-section[16]	
Longitudinal view	Smooth[16]	
Fibre cell ends	Blunt or rounded[16]	
Properties compared to other fibres	Mature brown coir fibre contains more lignin and less cellulose than fibres such as flax and cotton	
General fibre detail, colour, etc.	Reddish-brown strong, elastic filaments of different lengths, thicker in middle and tapers gradually towards the ends. Naturally coarse, suitable for use in sea water, high lignin content makes it resistant to weathering	
General	Extremely abrasive and rot resistant (high % of lignin) under wet and dry conditions and retains a high percentage in tensile strength. Surface covered with pores, but relatively waterproof, being the main natural fibre resistant to damage by salt water	

Table 14.8 Typical values of chemical, mechanical, morphological and physical characteristics of vegetable fibres

Chemical composition of plant fibres							
Fibre type	Cellulose (%)	Hemi-cellulose (%)	Pectin (%)	Lignin (%)	Water-soluble (%)	Fat and Wax (%)	Moisture (%)
Flax	64.1	16.7	1.8	2.0	3.9	1.5	10.0
Jute	64.4	12.0	0.2	11.8	1.1	0.5	10.0
Hemp	67.0	16.1	0.8	3.3	2.1	0.7	10.0
Sisal	65.8	12.0	0.8	9.9	1.2	0.3	10.0
Abaca	63.2	19.6	0.5	5.1	1.4	0.2	10.0
Coir	35–45	1.25–2.5		30–46		1.3–1.8	20

Figures in Tables 14.8 to 14.11 are obtained from reference sources Lewin and Pearce,[17] McGovern,[18] van Dam,[19] and Mandal.[20]

Table 14.9 Mechanical parameters from stress–strain for vegetable fibres

Fibre type	Tensile ($kN\,m^{-2} \times 10^6$)	Tenacity ($N\,tex^{-1}$)	Initial modulus ($N\,tex^{-1}$)	Extension at break (%)	Work of rupture ($N\,tex^{-1}$)
Flax	0.9	0.54–0.57	17.85–18.05	1.6–3	0.0069–0.0095
Jute	0.2–0.5	0.41–0.52	19.75	1.7	0.005
Hemp	0.3–0.4	0.47–0.6	17.95–21.68	2.0–2.6	0.0039–0.0058
Sisal	0.1–0.8	0.36–0.44	25.21	1.9–4.5	0.0043
Abaca	1.0	0.35–0.67	17.17	2.5–3	0.0077
Coir	0.1–0.2	0.18	4.22	16	0.0157

Table 14.10 Morphological plant fibre characteristics

Fibre type	Long length (mm)	Diameter (mm)	Fineness (Denier)	Cell length (mm)	Cell diameter (um)
Flax	200–1400	0.04–0.62	1.7–18	4–77	5–76
Jute	1500–3600	0.03–0.14	13–27	0.8–6	5–25
Hemp	1000–3000	0.16	3–20	5–55	10–51
Sisal	600–1000	0.1–0.46	9–406	0.8–8	7–47
Abaca	1000–2000	0.01–0.28	38–400	3–12	6–46
Coir	150–350	0.1–0.45		0.3–1.0	15–24

Table 14.11 Physical plant fibre characteristics

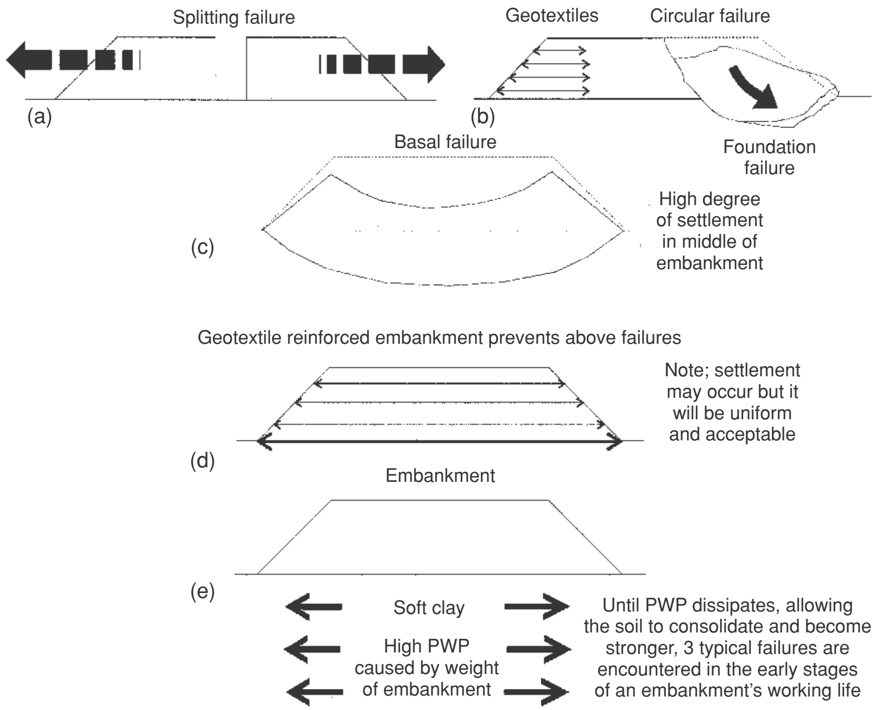
Fibre type	Specific gravity (%)	Specific heat ($cal\,g^{-1}\,°C^{-1}$)	Moisture regain (%) 65% RH 20 °C	Absorption (%)	Volume swelling (%)	Specific heat ($cal\,g^{-1}\,°C^{-1}$)	Porosity (%)	Apparent density ($g\,cm^{-3}$)	True density ($g\,cm^{-3}$)
Flax	1.54		12	7	30		10.7	1.38	1.54
Jute	1.5	0.324	13.8	10–12.5	45	0.324	14–15	1.23	1.44
Hemp	1.48	0.323	12	8		0.323			1.5
Sisal	1.2–1.45	0.317	14	11	40	0.317	17	1.2	1.45
Abaca	1.48		14	9.5			17–21	1.2	1.45
Coir	1.15–1.33			10					1.15

able 14.12 Functional requirements for geotextiles

eotextiles unctions	Tensile strength	Elongation	Chemical resistance	Biodegradability	Flexibility	Friction properties	Interlock	Tear resistance	Penetration	Puncture resistance
einforcement	iii	iii	ii–iii	iii	i	iii	iii	i	i	i
ltration	i–ii	i–ii	iii	iii	i–ii	i–ii	iii	iii	ii	ii
eparation	ii	iii	iii	iii	iii	i	ii	iii	iii	ii
rainage	na	i–ii	iii	iii	i–ii	na	ii	ii–iii	iii	iii
rosion control	ii	ii–iii	i	iii	iii	ii	i	ii	ii	i–ii

eotextiles unctions	Creep	Permeability	Resistance to flow	Properties of soil	Water	Burial	UV light	Climate	Quality assurance & control	Costs
einforcement	iii	na-i	i	iii	iii	iii	ii	na	iii	iii
ltration	na	ii–iii	i	ii	iii	iii	na	iii	iii	iii
eparation	na	ii–iii	i	na	iii	iii	na	i	ii	iii
rainage	na	iii	i	na	iii	iii	na	iii	iii	iii
rosion control	na	ii	iii	na	iii	na	iii	iii	i	iii

= Highly important, ii = important, i = moderately important, na = not applicable.

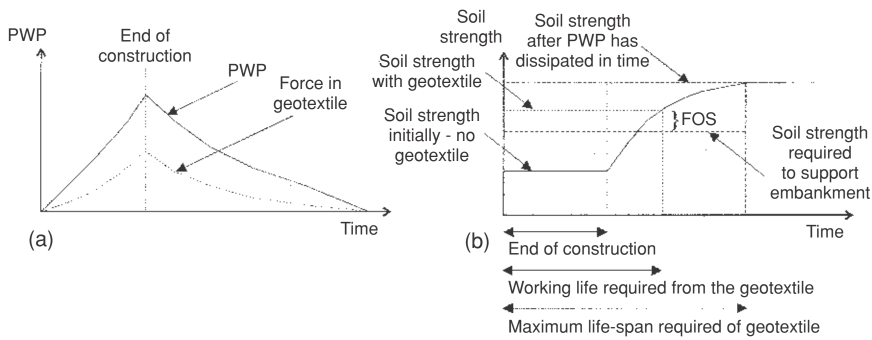


14.11 Short-term applications for geotextiles in embankments.

after a number of years if necessary (i.e. when the natural material has lost sufficient strength owing to the degradation process that it can no longer withstand the applied tensile forces). Furthermore, this procedure enriches the soil thereby improving growing conditions without introducing harmful residues. Although, it is not suggested, these natural geotextiles would be a universal panacea; they would have a significant impact on the economy of developing countries.

14.8.1.2 Short-term embankments

Geotextiles provide an invaluable solution to the problem of constructing embankments over soft compressible ground where water fills the pores between the soil particles under the embankment. The load from the embankment fill increases the tendency for the embankment to fail. Figure 14.11(a) to (c) illustrates three typical modes of failure that may be encountered (splitting, circular and basal) caused because the underlying soft soil does not have sufficient strength to resist the applied shear stresses (water has no shear strength). The use of geotextiles at vertical increments in an embankment and/or at the bottom of it, between the underlying soft soil and embankment fill (Fig. 14.11(d)), would provide extra lateral forces that either prevent the embankment from splitting or introduce a moment to resist rotation. Compression of the soft soil beneath the embankment will occur, but this will be uniform, which is acceptable. The embankment loading increases the water pressure in the pores in the underlying ground, especially at the centre of the embankment, whilst the pore water pressure (PWP) in the soil at and preceding the



14.12 Stabilising force to be provided by the geotextile will diminish with time. FOS = factor of safety.

extremities of the embankment is low in comparison (Fig. 14.11(e)). Thus, there is a pressure gradient set-up and water migrates from beneath the embankment sideways so that the PWP falls. Stability of the embankment will improve in time (1–2 years) as the excess PWP from the underlying soft soil dissipates (Fig. 14.11(e) and Fig. 14.12(a)). Hence its strength will increase and the stabilising force that has to be provided by the geotextile will diminish with time as shown in Fig. 14.12(b). This decrease (in the required stabilising force) can be designed to correspond to the rate of deterioration of the vegetable fibre geotextile. If necessary the rate of dissipation of the excess PWP can be enhanced by the use of consolidation drains.

14.8.1.3 Specialist areas – short-term

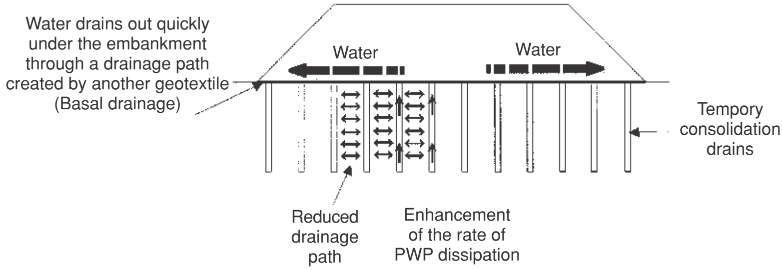
The armed forces often have to construct temporary roads/structures very quickly when they are dealing with confrontations. Also, these structures must be capable of being demolished if the soldiers have to retreat. By employing indigenous vegetable fibre materials as reinforcing geotextiles, the additional costs associated with the long life of synthetic geotextiles are not incurred. Decommissioning the reinforced structure is a low cost procedure – the structure can be destroyed by machinery or explosives and the natural geotextiles left to rot in the soil or set on fire, without leaving any resources for the enemy to exploit.

14.8.2 Drainage (fluid transmission)

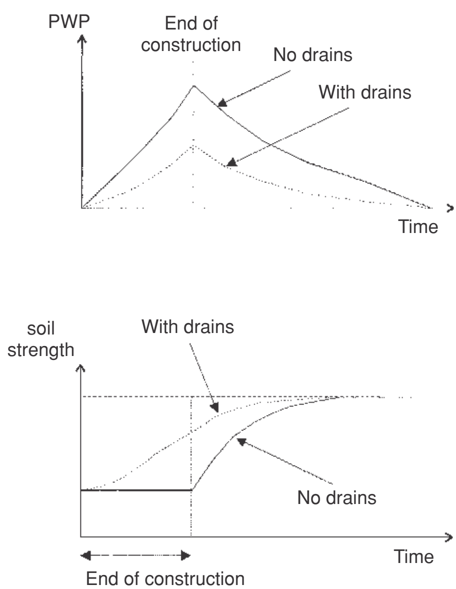
Normally the strength of soil is determined by its water content; as the water content decreases its strength increases and vice versa. A geotextile can convey fluids or gases within the plane of the geotextile to an egress point.

14.8.2.1 Consolidation/basal drains

The drainage system allows dissipation of excess pore water pressure, thus consolidation can take place and the soil strength is increased. The rate of dissipation of excess pore water pressure can be enhanced by using temporary drains in the soil so that the drainage path is reduced (Fig. 14.13). This type of drain is only required to perform for a limited time period, until consolidation has taken place (Fig. 14.14).



14.13 Temporary consolidation drains.



14.14 Comparison of time and strength of soil with and without consolidation drains.

14.8.3 Filtration

A geotextile acts as a filter by permitting the flow of liquid and gases, but preventing the passage of soil particles which can cause settlement due to loss of ground. The pore size within the geotextile is selected to avoid blocking, blinding and clogging.

Ground drains are used to prevent/intercept water flow, normally to reduce the risk of a rise in pore water pressure. Typically these drains are vertically sided trenches, lined with a geotextile and then filled with coarse gravel. Initial loss of soil particles will be high adjacent to the geotextile. This causes a zone (in the remaining soil particles) to bridge over the pores in the geotextile and retain smaller particles, which in turn retain even smaller particles. Thus a natural graded filter is formed which will prevent additional washout of fine particles, after which the geotextile becomes more-or-less redundant. If the geotextile was not used to encapsulate the coarse granular drainage material, too much wash-through of particles

would occur and this would either cause the drain to block or cavities to develop and lead ultimately to subsidence.

14.8.4 Separation

A geotextile acts as a separator by preventing the intermixing of coarse and fine soil materials whilst allowing the free flow of water across the geotextile. For instance, when a geotextile is placed between the subsoil and the granular sub-base of an unpaved road, it prevents the aggregate from being punched down into the soil during initial compaction and subsequently from the dynamic loading of vehicle axles. An example of a short-term use of a geotextile is in a temporary haul road that is formed during the construction of the permanent works, where it is only required to function for a limited amount of time before being removed. The temporary haul road is dug up and disposed of. A geotextile made from natural fibres, such as jute, coir, and so on, would be more suitable for such applications, because it would be biodegradable and hence more environmentally friendly.

14.8.5 Erosion control/absorption

A rapidly developing area for geotextiles is in the erosion control industry where they are employed for short-term effects. This usage differs from the other applications of geotextiles in that they are laid on the surface and not buried in the soil. The main aim is to control erosion whilst helping to establish vegetation which will control erosion naturally. The geotextile is then surplus to requirements and can degrade, enriching the soil. Geotextiles can reduce runoff, retain soil particles and protect soil which has not been vegetated, from the sun, rain and wind. They can also be used to suppress weeds around newly planted trees. Erosion control can be applied to riverbanks and coastlines to prevent undermining by the ebb and flow of the tide or just by wave motion.

14.9 Engineering properties of geotextiles

The physical and mechanical properties of soil are virtually unaffected by the environment over substantial periods. The natural fibre geotextiles could be used where the life of the fabrics is designed to be short. The definition of a short-term timescale varies from site to site and application to application. It depends ultimately on a number of factors, such as the size of the job, the construction period, the time of the year (weather), and so on. However, from the wealth of accumulated knowledge, a conservative design life expectancy of the geotextiles may be made for each given end-use. Applications exist where geotextiles are only required to perform for a few days after laying (drainage/filtration) or have to last up to a hundred years (reinforced earth abutments). The design life of natural fibre fabrics will be dictated by the type of fibre and the conditions to which they will be subjected. However, design lives of a few months to 4–5 years should be achieved for natural fibre geotextiles used in non-extreme situations, particularly since the need for the geotextile declines with the passage of time.

Natural materials such as timber have been used in the construction industry for a long time. However, the use of timber is limited because it is only used as a block,

that is, the individual components are not utilised. With natural fibres the stalks/stems can be stripped away to leave just the fibre which can be adapted to suit many different purposes in numerous forms and shapes with a wide range of properties. The key to developing geotextiles from natural fibres is the concept of designing by function, that is, to identify the functions and characteristics required to overcome a given problem and then manufacture the product accordingly. Provided the function can be satisfied technically and economically, these can compete with synthetic materials and in some situations they will have superior performance to their artificial counterparts.

14.10 Present state and uses of vegetable fibre geotextiles

The major use of vegetable fibre geotextiles is in the erosion control industry. Jute is readily biodegradable and ideally suited for the initial establishment of vegetation that in turn provides a natural erosion prevention facility. By the time natural vegetation has become well established the jute has started to rot/break down and disappear (6–12 months), without polluting the land.

Bangladesh, China, India and Thailand produce and sell jute geotextiles for erosion control. These are coarse mats, with open mesh woven structures made from 100% jute yarn produced on traditional jute machines. The jute geotextiles are laid on the surface of the slopes, where the weight and drapability of the mats encourage close contact with the soil. Between 1960 and 1980 a number of studies conducted by universities and highway departments demonstrated the effectiveness of jute geotextiles for surface erosion control.[21] Typical properties of a jute geotextiles[22] are:

- Pore size: 11 mm by 18 mm
- Open area ratio: 60–65%
- Water permeability: >500 litres $m^{-2} s^{-1}$ (100 mm head)
- Water absorption: 485%
- Breaking strength:
  warp 7.5 kN m^{-1}
  weft 5.2 kN m^{-1}

Some research has been directed towards reducing the degradation rate of jute, which can be made almost rot-proof by treating the fabric with a mixture of oxides and hydroxides of cobalt and manganese with copper pyroborate. Even after 21 days exposure in multiple-biological culture tanks, jute which had been subjected to this treatment had retained 96% of its original tensile strength. In soil incubation tests, the chemically treated jute had a 13-fold increase in lifetime over untreated jute.[23] Tests have been conducted on phenol formaldehyde-treated polypropylene–jute blended fabrics buried in soil to assess their susceptibility to microbial attack compared to untreated samples. It was concluded that the treated jute could withstand microbial attack more effectively than the untreated jute.[24] However, treated jute loses some of its 'environmental friendliness'.

There has been no substantial research on the engineering properties of vegetable fibres for soil strengthening or on the development of new and novel geotextile structures made from vegetable fibres for exploiting the beneficial properties of the fibre, fabric and ground for short-term or temporary applications.

14.11 Performance of natural fibre geotextiles for soil strengthening

An area which may offer the most new and upcoming potential for the use of vegetable fibres as geotextiles is to strengthen soils, as demonstrated by Sarsby *et al.*[25] in 1992. Hence, the remainder of this chapter is devoted to the use of vegetable fibres for this specific application.

Factors affecting the suitability of vegetable fibres for reinforcing geotextiles can be identified as: durability, tensile properties, creep behaviour, manufacturing feasibility and soil/geotextile interaction. To be accepted these materials must satisfy/fulfil all of the above criteria to some degree. The aim of this section is not to 'design' for a specific limited application, but to determine whether acceptable balances of properties may be established. To achieve this, comparisons are made between different vegetable fibre yarns for long-term stability, that is, for biodegradation and creep. Also, nine different vegetable fibre geotextiles are compared with two synthetic products in terms of fabric stress–strain and shearing interactive properties.

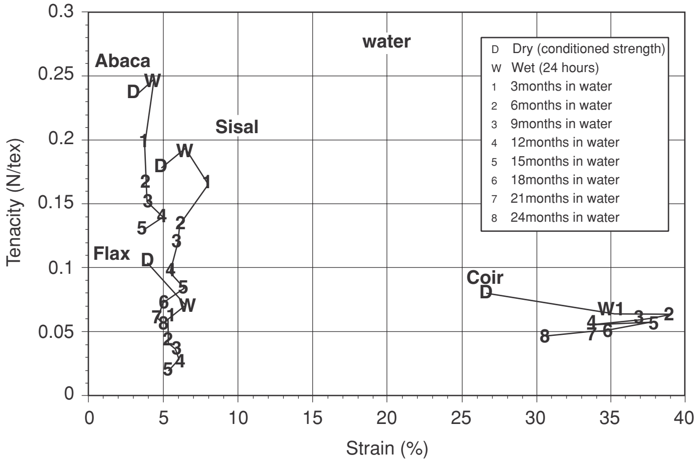
14.11.1 Long-term stability of natural fibre geotextiles

A geotextile should show the ability to maintain the requisite properties over the selected design life. One of the reasons for using vegetable fibre geotextiles is that they biodegrade when they have served their working life, but they must be sufficiently durable in different and aggressive ground conditions to last the prescribed duration. Only purely environmental deterioration will be considered, no damage to the geotextile caused by installation will be taken into account. The effects of biodegradation and creep will be considered for four vegetable fibre yarns which are particularly suitable for soil reinforcement: flax, abaca, sisal and coir.

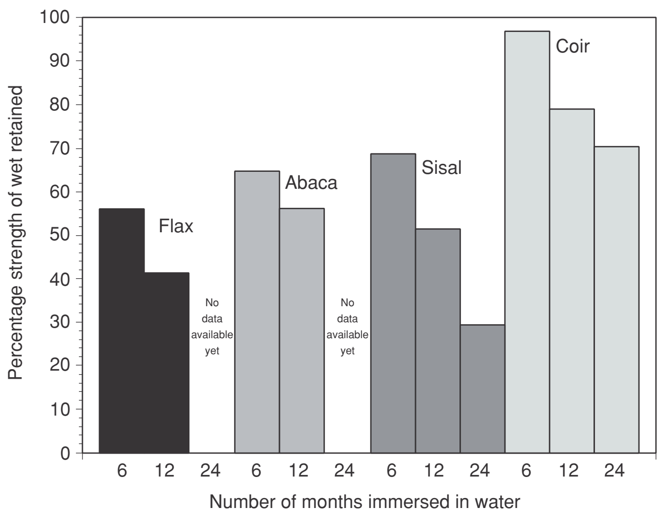
14.11.1.1 Durability/biodegradation rates

There are numerous factors which combine together to influence the rate of deterioration of vegetable fibres. However, to demonstrate simply the differences in the rates of deterioration, the change in strength and elongation of the four vegetable fibre yarns (fully immersed in water) is shown in Fig. 14.15.

The values shown are the average of five samples, tested after every three months. The samples were removed from the water and tested immediately, in other words the wet strength is given. This was chosen as representing the conditions most likely to be found in the ground. The original conditioned tex values were used at each testing stage to determine the yarns' tenacity. The initial strength of abaca and sisal (both leaf fibres) yarns increases by approximately 4% and 9%, respectively, when wet. However, with flax and coir (bast and seed/fruit fibres, respectively) there is a reduction in strength by 31% and 18%, respectively. This is in contrast to the earlier reference to the strength properties of flax increasing when wet. The reduction in strength could be accounted for by the yarn structure, rather than the fibre properties themselves. For the flax, abaca and sisal yarns there is a steady reduction in tenacity with time, with slight variations in strain. In contrast, the variations in the strength of coir yarn are minor, the difference between the groups of readings probably resulting from variations in the natural product itself. Figure 14.16 shows the



14.15 Effect of the deterioration process on the stress–strain properties of vegetable fibre yarns.

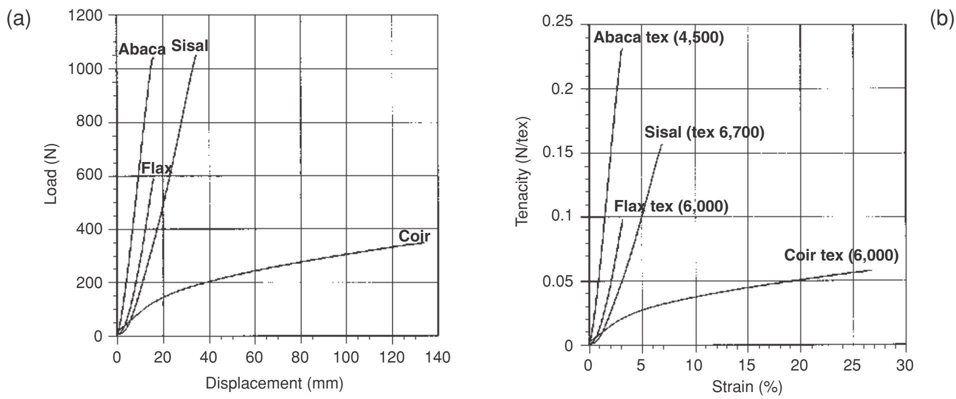


14.16 Percentage strength retained for vegetable fibre yarns in water for 6, 12 and 24 months.

percentage of the 24 hours wet strength retained for 6, 12 and 24 months. It can be seen that coir has retained by far the highest amount of strength. This was also true for coir and jute ropes which were immersed in pulverised fuel ash (PFA) for 10 and 36 months[25] – the reduction in strength for the coir was 38% and 47%, respectively whereas for jute it was 75% and 100%.

14.11.1.2 Creep

Creep and stress relaxation of geotextiles are prime factors in serviceability failure over the fabric's design life. Creep is a time-dependant increase in strain under



14.17 (a) Load–displacement and (b) stress–strain properties of the four vegetable fibre yarns.

constant load (e.g. reinforced walls), whereas stress relaxation is the reduction in tensile stress with time when subjected to constant strain (e.g. basal embankment reinforcement).

The main variables influencing creep for vegetable fibres geotextiles could be related to:

1 The fibre cell structure (e.g. abaca contains spiral molecules which are in a parallel configuration to each other, producing low extension).
2 Yarn type (e.g. between adjacent flax fibres cohesion is present, however with sisal no cohesion is present, the fibres are held together by twist only).
3 Fabric structure forms (e.g. crimp in woven structures).

Laboratory tests have been carried out in which the variables were load and time, with temperature and relative humidity being kept constant at 20 °C and 65%, respectively. Uniform loads of 40%, 20% and 10% of the maximum load (representing factors of safety of 2.5, 5 and 10) were applied to the four different vegetable fibre yarns and a gauge length of 500 mm was monitored.

Figure 14.17 illustrates typical short term load/extension curves at constant strain for flax, abaca, sisal and coir yarns, with the values of total strain and creep strain given in Table 14.13. Total strain includes the initial strain the sample undergoes when the load is applied plus the creep strain (this latter is the increase in change in length due to the passage of time, after the initial elongation).

14.12 Geotextile structure forms

Table 14.14 indicates the eleven different types of geotextile structure and fibre type together with their standard properties.

The creation of reinforcing geotextiles made from vegetable fibres introduces new manufacturing restraints, compared with the use of synthetic fibres and structures on existing textile machines. Numbers 1 to 5 of these structures have been designed, developed and produced in the Textile Centre at Bolton Institute from novel structure runs with selected natural fibres, namely flax, sisal and coir, to enable

Table 14.13 Total strain and creep strain of vegetable fibre yarns

Type of yarn	Max. load (kN)	Max. strain (%)	40% load (kN)	Strain at 40% load	20% load (kN)	Strain at 20% load	10% load (kN)	Strain at 10% load
Sisal	1.05	6.90	0.42	3.50	0.21	2.30	0.11	1.50
Abaca	1.04	3.19	0.42	1.40	0.21	0.80	0.10	0.50
Coir	0.35	26.71	0.14	3.70	0.07	1.50	0.04	0.70
Flax	0.68	4.02	0.27	2.30	0.14	1.50	0.07	0.90

Total strain for 10 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.6	2.7	1.5
Abaca	1.8	1.3	0.6
Coir	5.1	2.0	1.7
Flax	2.4	1.5	0.9

Creep strain for 10 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.1	0.4	0.0
Abaca	0.4	0.5	0.1
Coir	1.4	0.5	1.0
Flax	0.1	0.0	0.0

Total strain for 100 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.6	2.8	1.6
Abaca	1.9	1.4	0.7
Coir	6.0	2.3	1.8
Flax	2.6	1.5	1.0

Creep strain for 100 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.1	0.5	0.1
Abaca	0.5	0.6	0.2
Coir	2.3	0.8	1.1
Flax	0.3	0.0	0.1

Total strain for 1000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	4.8	3.0	1.8
Abaca	2.0	1.4	0.7
Coir	6.9	2.7	2.0
Flax	2.8	1.5	1.1

Creep strain for 1000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.3	0.7	0.3
Abaca	0.6	0.6	0.2
Coir	3.2	1.2	1.3
Flax	0.5	0.0	0.2

Total strain for 10 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	5.0	3.2	2.0
Abaca	2.1	1.5	0.8
Coir	7.9	3.1	2.1
Flax	2.9	1.6	1.2

Creep strain for 10 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	1.5	0.9	0.5
Abaca	0.7	0.7	0.3
Coir	4.2	1.6	1.4
Flax	0.6	0.1	0.3

Total strain for 100 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	5.2	3.3	2.1
Abaca	2.2	1.5	0.8
Coir	8.8	3.4	2.3
Flax	3.1	1.7	1.2

Creep strain for 100 000 min

Type of yarn	% of Max. load		
	40	20	10
Sisal	–	1.0	0.6
Abaca	–	0.7	0.3
Coir	5.1	1.9	1.6
Flax	–	0.2	0.3

Table 14.14 Standard properties of vegetable fibres and commercially available geotextiles

	Average of 5 fabric samples for all test results shown	Disp. at max. load (mm)	Load at max. (kN)	% Strain at max. load	Stress at max. load (MPa) ($N\,mm^{-2}$)	Load/Width at max. load ($kN\,m^{-1}$)	Modulus ($kN\,m^{-1}$)	Toughness (MPa) ($N\,mm^{-2}$)	Mass ($g\,m^{-2}$)	Thickness (mm) weight 100 g
1	Knitted flax sisal inlay (strength direction)	16.35	10.33	8.18	38.98	206.60	4657.64	3.85	1753.23	5.3
	Knitted flax sisal inlay (*x*-strength direction)	80.04	1.03	40.02	3.74	20.57	93.02	0.50		
2	Knitted grid flax sisal (strength direction)	14.88	7.88	7.44	32.63	143.58	2647.04	3.88	1613.81	4.4
	Knitted grid flax sisal (*x*-strength direction)	97.76	1.09	48.88	4.35	19.15	84.26	0.47		
3	Plain weave sisal warp flax weft (warp direction)	19.28	8.99	9.64	49.94	179.80	2604.24	4.34	1289.95	3.6
	Plain weave sisal warp flax weft (weft direction)	58.07	0.22	29.04	1.22	4.40	50.65	0.06		
4	Plain weave sisal warp coir weft (warp direction)	32.68	5.65	16.34	14.86	113.00	683.24	1.59	1895.48	7.6
	Plain weave sisal warp coir weft (weft direction)	51.70	1.32	25.85	3.48	26.42	256.73	0.73		
5	6 × 1 woven weft rib sisal warp coir weft (warp direction)	16.69	8.53	8.35	14.10	170.60	2947.56	0.96	3051.75	12.1
	6 × 1 woven weft rib sisal warp coir weft (weft direction)	68.16	5.58	34.08	9.23	111.70	710.27	2.87		
6	Plain weave coir geotextile (warp direction)	56.23	0.99	28.12	2.47	19.74	114.56	0.50	1110.99	8.0
	Plain weave coir geotextile (weft direction)	44.01	0.89	22.00	2.23	17.86	142.40	0.41		
7	Knotted coir geotextile (long direction)	105.90	0.92	52.95	5.93	18.38	56.11	1.87	605.37	3.1
	Knotted coir geotextile (width direction)	389.60	0.33	194.80	2.12	6.56	12.80	0.90		
8	Nonwoven hemp (machine direction)	112.70	0.11	56.37	0.48	2.15	2.48	0.16	683.16	4.5
	Nonwoven hemp (*x*-machine direction)	85.47	0.17	42.74	0.76	3.43	4.14	0.22		
9	Nonwoven coir latex (machine direction)	12.26	0.20	6.13	0.74	4.07	107.58	0.07	1018.24	5.5
	Nonwoven coir latex (*x*-machine direction)	11.18	0.15	5.59	0.54	2.95	72.05	0.05		
10	Plain weave synthetic polyester (warp direction)	16.35	2.07	8.17	51.62	41.30	768.72	2.94	432.09	0.8
	Plain weave synthetic polyester (weft direction)	19.62	2.30	9.81	57.50	46.00	669.36	3.52		
11	Synthetic warp knitted polyester (warp direction)	55.78	2.32	27.89	27.31	46.42	446.42	4.18	430.13	1.7
	Synthetic warp knitted polyester (weft direction)	102.87	0.11	51.43	1.31	2.23	70.64	0.26		

the creation of the most suitable compositions of fabrics. They have been created with the fundamental properties required to form geotextiles to reinforce soil, in that they have been designed to provide:

1 The highest possible strength in one direction, combined with ease of handling and laying on site
2 Soil particle interlock with the fabric to such an extent that the soil/fabric interface exhibits greater shearing resistance than the surrounding soil, i.e. the soil/fabric coefficient of interaction (α) is greater than one
3 A degree of protection to the high strength yarns during installation
4 A tensile strength in the range of 100–200 $kN\,m^{-1}$.
5 Ease of manufacture on conventional textile machines.

Numbers 1 and 2 are the most novel structures developed, being of weft knitting origin. The knitted structure is formed from a flax yarn (tex ≈ 400) encapsulating high strength sisal yarns (tex ≈ 6700). Knitted flax and inlay sisal yarns can be substituted by other natural fibres yarns.

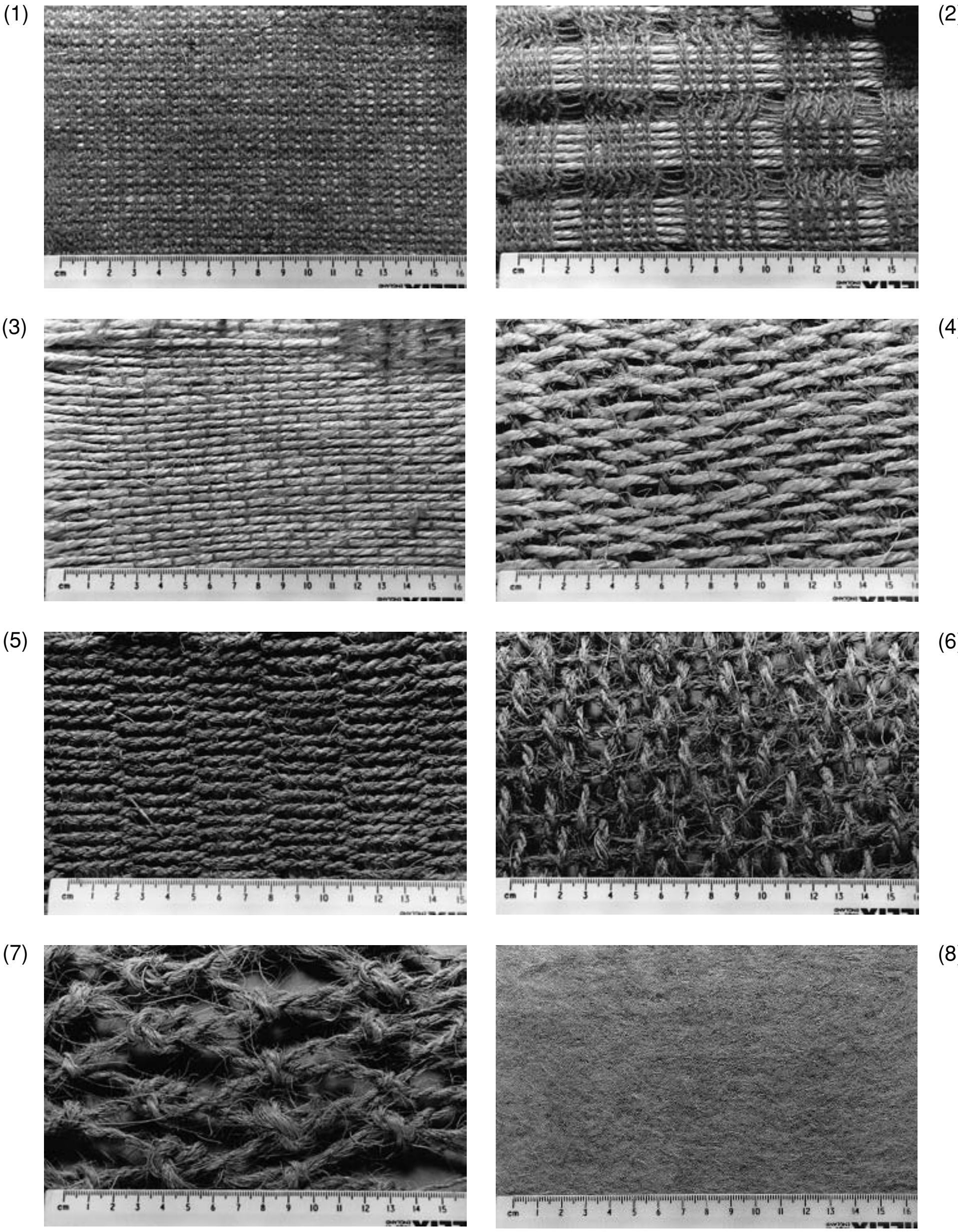
The knitted flax/sisal inlay number 1 (Fig. 14.18) has as many straight inlay yarns as possible in one direction which gives the geotextile its high strength, without introducing crimp into these yarns. Thus a fabric is produced which has low extensibility compared with conventional woven structures. The knitted loops hold the inlay yarn in a parallel configuration during transportation and laying on site; under site conditions it would be impractical to lay numerous individual sisal yarns straight onto the ground. The knitted loops also provide some protection for the sisal inlay yarns during installation/backfilling. The most advantageous use of the knitted loops in this structure is that they form exactly the same surface on both sides of the fabric and the sand is in contact not only with the knitted loops but with the inlay yarns as well. Thus the shear stress from the sand is transmitted directly to both the inlay yarns and the knitted skeleton.

With the grid flax/sisal geotextile number 2 (Fig. 14.18), at predetermined intervals needles were omitted and the sisal inlay yarn left out, to produce large apertures in the geotextile. This is similar in form to the Tensar Geogrid (commercial polymer grids designed for soil reinforcement), which allows large gravel particles to penetrate into the structure thereby 'locking' the gravel in this zone and forcing it to shear against the gravel above and below the geotextile, rather than just relying on the surface characteristics.

Structures 3 to 5 employed traditional woven patterns, but exploited combinations of different types of yarn and thickness to produce advantageous fabric properties for reinforcing geotextiles.

The plain weave sisal warp/flax weft geotextile number 3 (Fig. 14.18) allows the maximum possible number of the high strength sisal yarns to be laid in one direction, whilst the flax weft yarns hold the sisal yarns together during transportation and laying on site. By only using very thin weft yarns compared to the warp yarns no crimp is introduced in these warp yarns. This structure is not as stable as the knitted structures and the flax weft yarns offer no protection for the sisal warp yarns during installation.

The plain weave sisal warp/coir weft geotextile number 4 (Fig. 14.18) provides the sisal strength yarn in one direction whilst using the coir weft yarn to form ridges in the structures caused by its coarseness, thus creating abutments which the soil has to shear around. By using a thick weft yarn, crimp is introduced into the warp

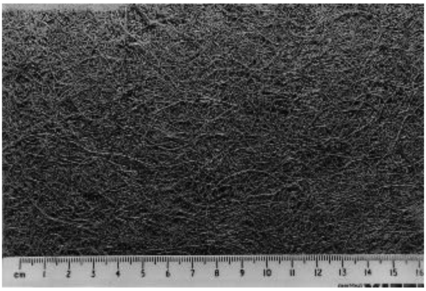


14.18 Photographs of different fabric structures used for tensile and shear interactive tests. (1) Knitted flax/sisal inlay, (2) knitted grid flax/sisal, (3) plain weave sisal warp/flax weft, (4) plain weave sisal warp/coir weft, (5) 6×1 woven weft rib sisal warp/coir weft, (6) plain weave coir warp/coir weft, (7) knotted coir grid, (8) nonwoven hemp, (9) nonwoven coir latex, (10) plain weave synthetic polyester, (11) synthetic warp-knitted polyester.

yarn and this in turn creates a more extensible geotextile, as well as providing no protection for the sisal strength yarns.

The woven 6×1 weft rib geotextile number 5 (Fig. 14.18) was designed to provide the ultimate protection for the high strength sisal yarns but without introducing any

(9)



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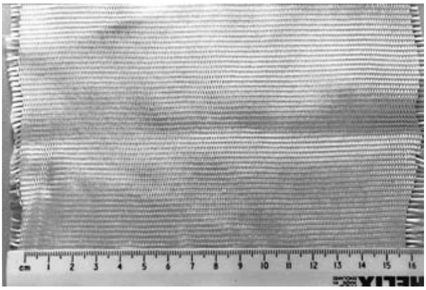

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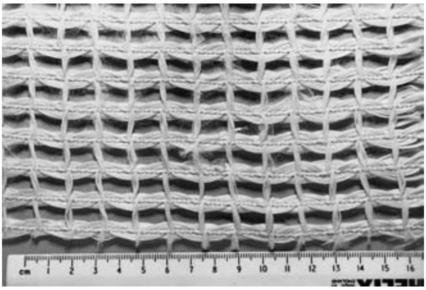


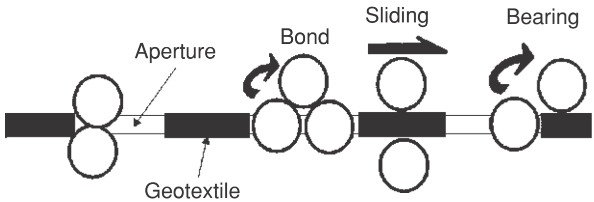
14.18 *Continued.*

crimp. However, this structure has comparatively lower productivity because of the high weft cover factor and thus it is more costly.

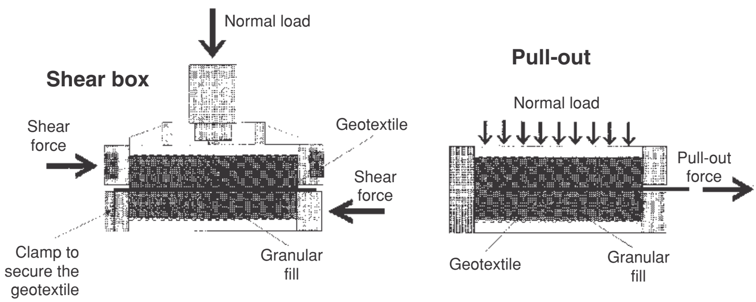
Numbers 6 to 11 are all commercially available geotextile products, with 6 to 9 being of a natural fibre origin. The coir knotted geotextile (Fig. 14.18) was chosen to study the effect of larger particle interlock with the fabric and large abutments formed by the knots. This geotextile was obtained from India (Aspinwall & Co. Ltd.) where the knots are produced by hand. The nonwoven samples 8 and 9 (Fig. 14.18) were obtained from Thulica AB, Sweden, for a comparison with the knitted and woven natural fibre structures. However, geotextiles 10 and 11 are of a synthetic origin from the midrange of synthetic products commercially available. These were used for a direct comparison with the natural fibre geotextiles using exactly the same tests and procedures. Both of these synthetic geotextiles were made of polyester, number 10 was a plain weave structure and number 11 was a warp-knitted grid (Fig. 14.18).

14.13 Frictional resistance of geotextiles

The frictional shearing resistance at the interface between the soil and the geotextile is of paramount importance since it enables the geotextile to resist pull-out failure and allows tensile forces to be carried by the soil/geotextile composite. The resistance offered by the fabric structure can be attributed to the surface roughness characteristics of the geotextile (soil sliding) and the ability of the soil to penetrate the fabric, that is, the aperture size of the geotextile in relation to the particle size of the soil, which affects bond and bearing resistance (Fig. 14.19). Bond resistance is created when soil particles interlock with the geotextile and permit these 'locked'



14.19 Forms of shearing resistance; sliding, bond and bearing.



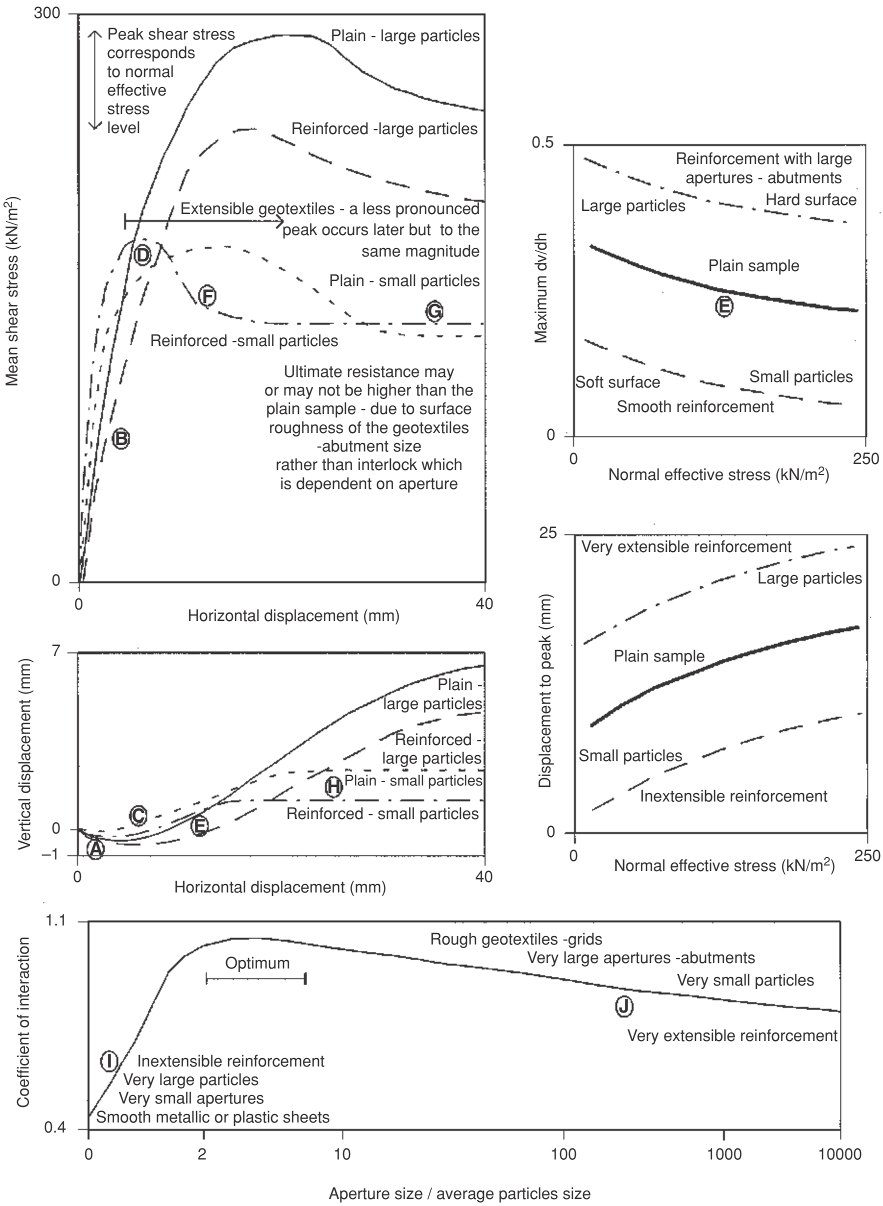
14.20 Laboratory tests to determine the frictional resistance of a geotextile.

particles in the apertures to shear against ambient soil in close vicinity above and below the geotextile surface, whereas bearing resistance, which can only really be assessed by pull-out tests, is the effect of soil having to shear around abutments in the geotextiles, or at the end of the apertures, in the direction of shear. This mode of resistance is very similar to that encountered in reinforced anchors and is determined by relating the pull-out force to the sum of projected area of the transverse members in the geotextile.

The efficiency of geotextiles in developing shearing resistance at the soil–fabric interface is indicated by the coefficient of interaction (α) defined as the ratio of the friction coefficient between soil and fabric ($\tan\delta$) and the friction coefficient for soil sliding on soil ($\tan\phi$). There are two conventional laboratory tests to determine the frictional resistance of a geotextile; the direct shear box and the pull-out test (Fig. 14.20). The main distinction between these tests is that in the direct shear box test, the soil is strained against the fabric, whereas in the pull-out test, strain is applied to the fabric thereby mobilising different degrees of shearing resistance along the fabric corresponding to a relative position of the fabric from the applied load and the extensibility of the fabric.

14.13.1 Performance of vegetable fibre geotextiles during shear

The stress–strain response and volumetric behaviour for all the geotextiles in both sand and gravel are typical of a densely packed granular dilating medium. Figure 14.21 illustrates typical curves that should be expected, relating the physical properties of the geotextiles to that of the fill. Initial volumetric compression (A) would occur to a higher degree than in plain soil as a result of the soil bedding in the geotextile. At relatively small strains, the stress level would increase rapidly more-or-



14.21 Typical shearing interactive curves, relating the physical properties of the geotextiles to that of the fill. Values indicated on these proposed charts are only shown as an estimate of the range of typical values which may lie within, for dense sand and gravel fills.

less linearly with strain (B). The stress increase will be at a higher rate than in plain soil if the geotextile limits the movement between adjacent soil particles caused by soil interlocking with the fabric. Volumetric expansion will develop at the same time, that is the soil will be dilating (C). At maximum shearing resistance the stress–strain response should produce a well-defined peak in the shear stress (D), more pro-

nounced than in plain soil, because of the 'locked' nature of the soil particles. This should correspond to the rate of maximum volume change (E), which is likely to be greater in reinforced samples than in plain soil, particularly if introduction of the geotextile produces 'abutments' around which the soil has to shear. At this stage all the available shearing resistance, under the given vertical pressure, has been mobilised and the shear stress at the soil–fabric interface is equal to the shear strength. This stage is followed by a reduction in shearing resistance, as particle interlocking is 'released', (F) towards the final state (G), where constant volume is maintained (H). Thus a thin rupture zone of the soil at critical density is produced. By increasing the particle size in the direct shear box the behaviour will be modified slightly, because the nature ratio of the soil–fabric contact will be reduced. The opportunity for movement between ambient soil particles will be reduced as will the soil–fabric interlock as the size of the apertures in the geotextile approach the diameter of the particles (I). With very small particles or large apertures the converse will apply (J), in that the ratio of particles to aperture size will be large and thus will permit additional freedom of movement between sand grains in the shearing zone. Furthermore, the use of larger particles will produce a less rapid stress/strain response, i.e. considerably more horizontal shear displacement is needed, more effort is therefore required, to enable a gravel particle to ride over another gravel particle than it would for corresponding sand particles. Therefore no constant volume shearing zones will be expected in a sample with large particles. The extensibility of the fabric is of paramount importance for producing different degrees of soil strain. The geotextile is required to strain sufficiently to permit maximum soil strength to be mobilised, but not to the extent that serviceability failure occurs.

14.13.2 Coefficient of interaction

Values of the shearing angle and coefficient of interaction, α, of the geotextiles sheared in sand and gravel are shown, together with a summary of their stress–strain values, in Table 14.15. The results for the nonwoven samples were not as favourable as the other geotextiles, for tensile strength and shearing interactive properties, indicating that these structures are not as suitable for soil reinforcement. Some of the α values are more than 1 for the sand, indicating that by introducing the geotextile in the sand it actually strengthens the ambient sand. This could possibly be due to the surface texture of some of these geotextiles, because the sand grains can interlock with the fabric and reduce movement. This scenario can be described as if sand were sheared against sandpaper producing a higher frictional resistance than shearing sand against sand. As a result of sand shearing against sand, the sand grains above and below the failure plane are free to move, but with the sandpaper the sand grains grains are unable to move. In a practical situation if α is more than 1, the failure surface would just be pushed up away from the geotextile into the region of sand against sand. The fabric structure can be further assessed by applying a flow rule analysis to the soil/fabric interface data, as demonstrated by Pritchard,[26] to enable an assessment of whether a higher shearing resistance was developed from the surface roughness characteristics of the geotextile (smoothness of the fabric) or as a result of interlock, that is, from a higher dilational component (the effect from the apertures and abutments in the fabric).

able 14.15 Shearing interactive values of vegetable fibre geotextiles compared to two synthetic geotextiles

	Geotextiles	($kN\,m^{-1}$)	% Strain at max.	θ′max Sand	∝ for θ′max	θ′r Sand	∝ for θ′r	θ′max Gravel	∝ for θ′max
	Fill vs Fill			40.5°	1.00	33.1°	1.00	54.7°	1.00
1	Knitted flax sisal inlay	207	8	40.9°	1.01	33.0°	1.00	50.5°	0.86
2	Knitted grid flax sisal	144	7	38.8°	0.94	32.5°	0.98	50.9°	0.87
3	Plain weave sisal warp flax weft	180	10	40.0°	0.98	32.4°	0.97	49.8°	0.84
4	Plain weave sisal warp coir weft	113	16	42.1°	1.06	33.1°	1.00	53.4°	0.95
5	6 × 1 Woven weft rib sisal coir	170	8	42.0°	1.05	33.2°	1.00	50.9°	0.87
6	Plain weave coir geotextile	20	28	41.9°	1.05	33.1°	1.00	51.2°	0.88
7	Knotted coir geotextile	18	53	43.5°	1.11	36.7°	1.21	51.8°	0.90
8	Nonwoven hemp	2	56	39.3°	0.96	34.8°	1.07	44.6°	0.70
9	Nonwoven coir latex	4	6	34.7°	0.81	–	–	36.4°	0.52
0	Plain weave synthetic (polyester)	41	8	40.4°	1.00	31.9°	0.95	46.6°	0.75
1	Warp knitted grid synthetic (polyester)	46	28	38.4°	0.93	31.8°	0.95	51.3°	0.88

ests conditions are: 300 × 300 mm shear box. Fill; Leighton Buzzard sand and limestone gravel (average particle diameter 0.8 mm and 6 mm, respectively). Nominal ormal stress; 200, 150, 100 and 50 $kN\,m^{-2}$. Nominal unit weight of 96% and 94% of the maximum nominal dry unit weight for the sand and gravel, respectively. Accu-cy of ±0.01 $Mg\,m^{-3}$ from the mean dry density in subsequent shear box tests. Leading side of the bottom half of the shear box had the geotextile clamped to it.
max = maximum shear angle.

14.14 Conclusions

Vegetable fibre geotextiles offer environmentally friendly, sustainable, cost effective, geotechnical solutions to many ground engineering problems, in both developed and less developed countries. The main area where they have been employed is in the erosion control industry, but new and novel structures are being produced which exploit advantageous fabric/ground interaction properties. One of the main areas, with the largest potential for development, is to use these natural products temporarily to strengthen the ground, during and just after construction, until the soil consolidates and becomes stronger. These reinforcing geotextiles then biodegrade leaving no alien residue in the ground.

From the extensive research conducted on vegetable fibres, the six most promising fibres for geotextiles are flax, hemp, jute (bast), sisal, abaca (leaf) and coir (seed/fruit). These can be refined down to the four most suitable fibres, flax, abaca, sisal and coir, when taking into account the relevant properties required for soil reinforcement.

It has been shown that coir yarns are far more durable than any of the other vegetable fibre yarns when tested in water. Also, the coir rope exhibited excellent durability qualities compared to that of the jute rope when subjected to a hostile environment of PFA. However, the coir yarn exhibited significantly higher creep rates than flax, abaca and sisal at increased load levels.

Vegetable fibre geotextiles have been found to have superior properties to the mid-range reinforcing synthetic geotextiles for soil reinforcement, when considering tensile strength (between 100–200 $kN\,m^{-1}$) and frictional resistance (α approximately 1). The high degree of frictional resistance of the vegetable fibre geotextiles probably develops from both the coarseness of the natural yarns and the novel structure forms.

Finally it must be pointed out that the success of synthetic geotextiles is due to excess manufacturing capacity and the large amount of research and development that has been carried out in relation to their production, properties and application and not simply because they are superior to fabrics made from natural fibres.

14.15 Relevant British Standards

BS 2576: 1986 Determination of breaking strength and elongation (strip method) of woven fabrics.
BS 6906: Part 1: 1987 Determination of the tensile properties using a wide width strip.
BS 6906: Part 2: 1987 Determination of the apparent pore size distribution by dry sieving.
BS 6906: Part 3: 1987 Determination of the water flow normal to the plane of the geotextile under a constant head.
BS 6906: Part 4: 1987 Determination of the puncture resistance (CBR (California bearing ratio) puncture test).
BS 6906: Part 5: 1987 Determination of creep.
BS 6906: Part 6: 1987 Determination of resistance to perforation (cone drop test).
BS 6906: Part 7: 1987 Determination of in-plane flow.
BS 6906: Part 8: 1987 Determination of geotextile frictional behaviour by direct shear.

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