Geosynthetic Engineering

Contents

Reinforced Soil Engineering – Basic Concepts

1. INTRODUCTION

Reinforced soil is a composite construction material formed by combining soil and reinforcement. This material possesses high compressive and tensile strength similar, in principle, to the reinforced cement concrete. It can be obtained by either incorporating continuous reinforcement inclusions (for example, strip, bar, sheet, mat or net) within a soil mass in a definite pattern or mixing discrete fibres randomly with a soil fill before placement. The term ‘reinforced soil’ generally refers to the former one, although it may more be appropriately called ‘systematically reinforced soil’, whereas latter one is called ‘randomly distributed/oriented fibre-reinforced soil’ or simply ‘fibre-reinforced soil’ (Shukla et al., 2009). Although the reinforced soil has been in practice in crude form since the ancient times, it is being used more frequently in the civil engineering applications since the development of the modern form of soil reinforcement in 1966 by Henry Vidal, a French architect and engineer.

In most of the current civil engineering applications, the reinforcement generally consists of geosynthetic sheets or strips of galvanized steel, arranged horizontally or in the directions in which the soil is subject to the undesirable tensile strains. Compared to the geosynthetic sheets, metal strips are assumed to be relatively inextensible at the stress levels experienced in civil engineering applications. In the early days, the metal strips were used as reinforcement, and the composite material so obtained was termed ‘Reinforced Earth’ by Henry Vidal (1966, 1969) who first presented the concept of improving the strength of a soil mass by inclusion of reinforcements within it. The soil should preferably be cohesionless, characterized by high frictional properties, in order to prevent the slip between the soil and the reinforcement. The surface texture of the reinforcement should also be as rough as possible for similar reasons.

The apparently simple mechanism of reinforced soil and the economy in cost and time have made it an instant success in geotechnical and highway engineering applications for temporary as well as permanent structures. Reinforcing soil-like materials such as coal ashes and other waste materials by continuous inclusions is also an economical means of improving their mechanical properties. One of the common applications of soil reinforcement is a reinforced soil retaining wall (Fig. 1), which is an alternative to a conventional heavy concrete/brick masonry/stone masonry retaining wall (Fig. 2). Reinforcement improves the mechanical properties of a soil mass as a result of its inclusion. In fact, any reinforcement, inextensible or extensible, has the main task of resisting the applied tensile stresses or preventing inadmissible deformations in geotechnical structures such as retaining walls, soil slopes, bridge abutments, foundation rafts, etc. In this process, the reinforcement acts as a tensile member (see Fig. 3) coupled to the soil/fill material by friction, adhesion, interlocking or confinement, and thus improves the stability of the soil mass.

The concept of reinforcing soil with fibres, especially natural ones, originated in the ancient times. Applications of reinforced soils using clayey soils and natural fibres can be seen even today in some countries including India for making containers, ovens, toys, etc. However, randomly distributed fibre-reinforced soils have recently attracted increasing attention in geotechnical engineering. In comparison with systematically reinforced soils, randomly distributed fibre-reinforced soils exhibit some advantages. Preparation of randomly distributed fibre-reinforced soils mimics soil stabilization by admixtures. Discrete fibres are simply added and mixed with soil, much like cement, lime, or other additives. Randomly distributed fibres offer strength isotropy and limit potential planes of weakness that can develop parallel to the oriented reinforcement as included in systematically reinforced soil.

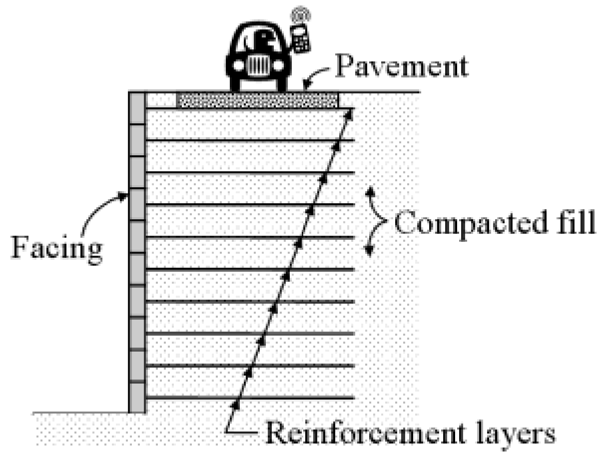


Fig. 1. Reinforced soil retaining wall

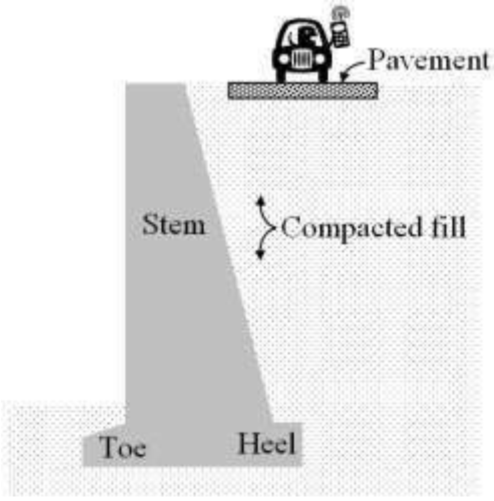


Fig. 2. Conventional concrete/brick masonry/ stone masonry wall

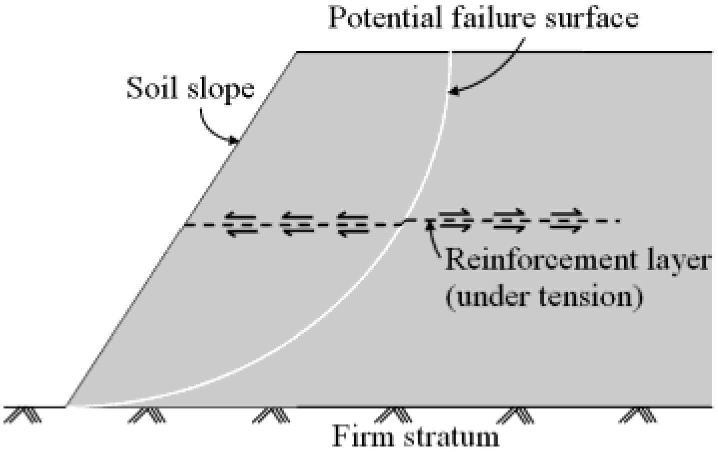


Fig. 3. Basic reinforcement mechanism

2. SYSTEMATICALLY REINFORCED SOIL

Systematically reinforced soil is a soil reinforced with geosynthetic (woven geotextile/ geogrid/ geocomposite) sheets or strips of galvanized steel in desired directions, and is currently widely used in civil engineering practice. It is mainly because such a reinforced soil possesses many novel characteristics, which render it eminently suitable for construction of geotechnical structures. The reinforcement can easily be handled, stored and installed. The soil that constitutes most of its bulk may be locally available and can be placed in position in limited time in an economical way by modern hauling and compaction equipment. The flexible nature of reinforced soil mass enables it to withstand vibrations caused by earthquakes and large differential settlements without significant distress. Systematically reinforced soil thus permits construction of geotechnical structures over poor and difficult sub-soil conditions.

The principle of reinforced soil is analogous to that of reinforced cement concrete; however, their basic reinforcing mechanisms differ significantly. If the reinforced soil is assumed as a homogeneous but anisotropic material, the Mohr-Coulomb failure criterion can be applied to explain the basic mechanism of reinforced soil. Consider a simplified situation shown in Figs. 4(a) and (b) where two cylindrical specimens of a cohesionless soil are subjected to the same triaxial loading. The first specimen is not reinforced, and the second is reinforced with horizontal reinforcement layers. Figure 4(c) shows a magnified view of the reinforced soil element PQRS as indicated in Fig. 4(b). Assume that that the Mohr-Coulomb failure criterion has been attained in the unreinforced specimen. For this case, the stress state in the soil can be represented, in the normal stress (σ) and shear stress (τ) space, by a Mohr circle 'a' as shown in Fig. 4(d), which is tangent to the Mohr-Coulomb failure envelope l_U for unreinforced soil. If the reinforced soil specimen is subjected to the same stress state, then due to friction and/or adhesion bonding between both constituents, the lateral deformation/strain of the specimen will be reduced. This lateral deformation of the composite material will be greater than the lateral deformation of the reinforcement but smaller than the lateral deformation of the soil that might occur in the absence of friction and/or adhesion bonding between both the constituents. This means that in case of perfect friction and/or adhesion bonding between reinforcement and soil, the reinforcement will be extended resulting in a mobilized tensile force *T*, and the soil will be compressed by additional compressive lateral stress as reinforcement restraint σ_R (= $\Delta\sigma_3$), introduced into it in the direction of the reinforcement as shown in Fig. 4(c). The stress state in soil represented by the Mohr circle 'b' in Fig. 4(d) is no more tangent to the failure envelope l_U, and the reinforced specimen is able to sustain greater stresses than those in the case of unreinforced soil.

Consider that the reinforced soil specimen shown in Fig. 4(b) is expanding horizontally due to decrease in applied horizontal stress σ_3 with constant vertical stress σ_1 and assume that failure occurs by rupture of the reinforcement, that is, the lateral restraint σ_R is limited to a maximum value σ_{RCmax} depending on the strength of the reinforcement. This state of stress is represented by the Mohr circle 'c' in Figure 4(d). The strength increase can be characterized by a constant cohesion intercept c_R as an apparent cohesion. It means the reinforced earth can be considered as a cohesive material with anisotropic cohesion, introduced due to reinforcement, being a function of strength and density of reinforcement (Schlosser and Vidal, 1969). Results of both the triaxial tests and the direct shear tests on sand specimens reinforced with tensile inclusions have also shown that the apparent cohesion of the reinforced soil material is a function of the orientation of the inclusions with respect to the direction of the maximum extension in the soil (Long et al., 1972; Schlosser and Long, 1974; Jewell, 1980; Gray and Refeai, 1986, Shukla et al. 2009). Thus, the strength envelope for reinforced cohesionless soil for reinforcement rupture condition can be interpreted in terms of Mohr-Coulomb failure envelope l_{RC} for the homogeneous cohesive soil as shown in Fig. 4(d).

For Mohr circle 'a', the principal stresses σ_1 and σ_3 are related to each other as:

$$\sigma_1 = \sigma_3 \tan^2(45^0 + \phi/2) \tag{1}$$

where ϕ is the angle of shearing resistance (or the friction angle) of the unreinforced soil.

For Mohr circle 'c', representing the stress state of a reinforced soil at failure, the principal stresses σ_1 and σ_3 are related to each other as:

$$\sigma_1 = \sigma_{3\min} \tan^2(45^0 + \phi/2) + 2c_R \tan(45^0 + \phi/2) \tag{2}$$

Since $\sigma_{3\min} = \sigma_3 - \sigma_{RC\max}$ as seen in Fig. 3(d), Eq. (2) becomes:

$$\sigma_1 = (\sigma_3 - \sigma_{RC\max}) \tan^2(45^0 + \phi/2) + 2c_R \tan(45^0 + \phi/2) \tag{3}$$

Eqs. (1) and (3) lead to:

$$c_R = \frac{\sigma_{RC\max}\tan(45^0 + \phi/2)}{2} = \frac{\sigma_{RC\max}\sqrt{K_p}}{2} = \frac{\sigma_{RC\max}}{2\sqrt{K_a}}$$

(4)

where

$$K_a = \tan^2(45^0 - \phi/2)$$

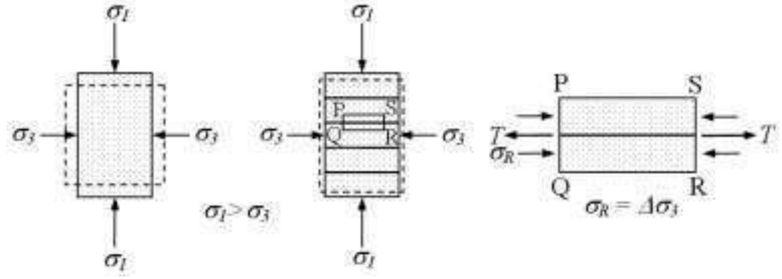
(5)

and

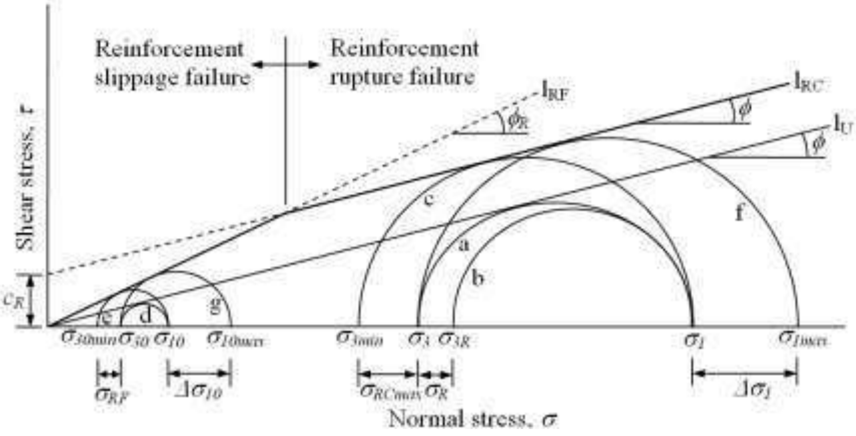
$$K_p = \tan^2(45^0 + \phi/2)$$

(6)

are the Rankine's coefficients of active and passive lateral earth pressures, respectively.



(a) (b) (c)



(d)

Fig. 4. Basic mechanism of reinforced soil in triaxial loading: (a) unreinforced cylindrical cohesionless soil specimen; (b) reinforced cylindrical cohesionless soil specimen; (c) magnified view of a reinforced soil element PQRS as indicated in (b); (d) Mohr circles for reinforced and unreinforced cases [*Note*: σ_1 is the major principal stress and σ_3 is the minor principal stress.]

Thus, it is found that the anisotropic cohesion is produced in the direction of reinforcement, and this concept is based on the beahaviour of laboratory tests (shear tests) on reinforced soil samples. It has, however, not been possible to define this cohesion in a way as to enable its use in the design of reinforced earth structures.

Now, consider that the reinforced soil specimen shown in Fig. 4(b) is expanding horizontally due to decrease in applied horizontal stress $\sigma_3 = \sigma_{30}$ with constant vertical stress $\sigma_1 = \sigma_{10}$ as represented by the Mohr circle 'd', and assume that failure occurs by slippage between the reinforcement and soil, that is, lateral restraint σ_R is limited to σ_{RF}, which is proportional to σ_{10}, that is,

$$\sigma_{RF} = \sigma_{10}F$$

(7)

where F is a friction factor that depends on the cohesionless soil – reinforcement interface characteristics. This concept is based on the Yang's experimental results (Yang, 1972) as presented by Hausmann and Vagneron (1977). The failure state of stress is represented by the Mohr circle 'e' in Fig. 4(d). The strength increase can be characterized by an increased friction angle ϕ_R. Thus, the strength envelope for reinforced cohesionless soil for reinforcement slippage condition can be interpreted in terms of the Mohr-Coulomb failure envelope l_{RF} for the homogeneous cohesionless soil as shown in Fig. 4(d).

For Mohr circle 'd', the principal stresses σ_{10} and σ_{30} are related by:

$$\sigma_{10} = \sigma_{30} \tan^2(45^0 + \phi / 2)$$

(8)

Substituting Eq. (5) into Eq. (8) yields:

$$\sigma_{10} = \frac{\sigma_{30}}{K_a}$$

(9)

For Mohr circle 'e', the principal stresses σ_{10} and σ_{30} are related by:

$$o_{10} = \sigma_{30\min} \tan^2(45^0 + \phi_R / 2)$$

(10)

Since $\sigma_{30\min} = \sigma_{30} - \sigma_{RF}$ as seen in Fig. 4(d), Eq. (10) becomes:

$$o_{10} = (\sigma_{30} - \sigma_{RF}) \tan^2(45^0 + \phi_R / 2)$$

(11)

Substituting Eq. (7) into Eq. (11) yields:

$$o_{10} = (\sigma_{30} - \sigma_{10} F) \tan^2(45^0 + \phi_R / 2)$$

(12)

From Eqs. (8) and (12),

$$1 = (K_a - F)\left(\frac{1 + \sin\phi_R}{1 - \sin\phi^R}\right)$$

or

$$\sin\phi_R = \frac{1 + F - K_a}{1 - F + K_a}$$

(13)

Now, consider that the reinforced soil specimen shown in Fig. 4(b) is expanding horizontally due to increase in applied σ_1 with constant σ_3 and assume that failure occurs by rupture of the reinforcement or reinforcement slippage. These failure states of stress are represented by the Mohr circles 'f' or 'g' in Fig. 4(d) respectively. It can be noted that the reinforcement increases the compressive strength of the soil by $\Delta\sigma_1$ or $\Delta\sigma_{10}$ depending on the type of failure mode of the reinforced soil.

The behaviour of the soil reinforced with extensible reinforcements, such as geosynthetics, does not fall entirely within the concepts as described above. The difference, between the influences of inextensible and extensible reinforcements, is significant in terms of the load-settlement behaviour of the reinforced soil system as shown in Fig. 5 (McGown et al., 1978). The soil reinforced with extensible reinforcement, termed *ply-soil* by McGown and Andrawes (1977), has greater extensibility and smaller losses of post peak strength compared to soil alone or soil reinforced with inextensible reinforcement, termed *reinforced earth* by Vidal (1966, 1969). In spite of some differences in the behaviour of ply soil and reinforced earth, a similarity between them exists in that both inhibit the development of internal and boundary deformations of the soil mass by developing tensile stresses in the reinforcement. In other words, both the ply soil and the reinforced earth are tensile strain inclusion systems.

Fluet (1988) subdivided the reinforcement, based on its function, into the following two categories:

1. A tensile member, which supports a planar load, as shown in Fig. 6(a).
2. A tensioned member, which supports not only a planar load but also a normal load, as shown in Fig. 6(b).

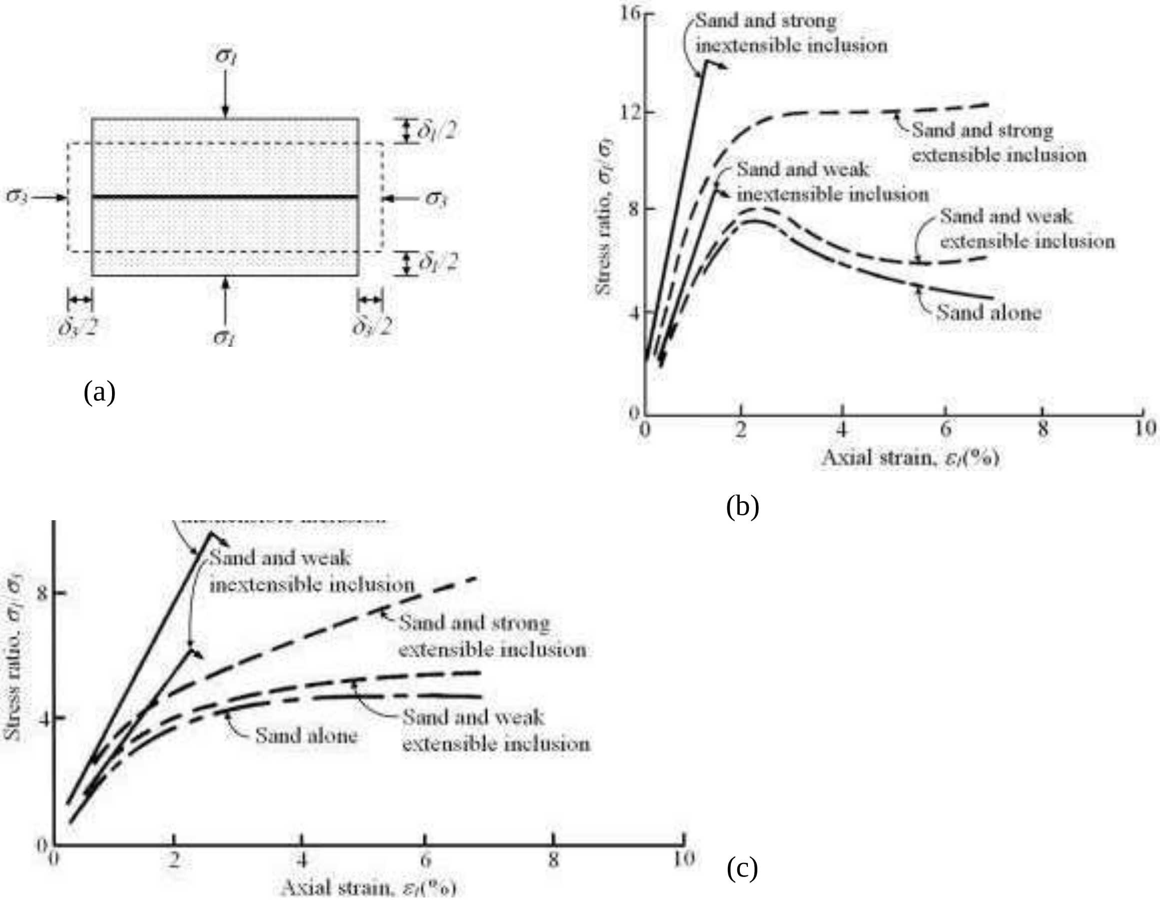
Jewell (1996) and Koerner (2005) consider not two but three mechanisms for soil reinforcement, because when the geosynthetic works as a tensile member it might be due to two different mechanisms: shear and anchorage. Therefore, the three reinforcing mechanisms, concerned simply with the types of load that are supported by the geosynthetic, are the following:

1. *Shear*, also called *sliding*: The geosynthetic supports a planar load due to slide of the soil over it.
2. *Anchorage*, also called *pullout*: The geosynthetic supports a planar load due to its pullout from the soil.
3. *Membrane*: The geosynthetic supports both a planar and a normal load when placed on a deformable soil.

Shukla (2002, 2004, 2012) and Shukla and Yin (2006) describe reinforcing mechanisms that take into account the reinforcement action of the geosynthetic, in other words, how the geosynthetic reinforcement takes the stresses from the soil and which type of stresses are taken by it. This concept can be observed broadly in terms of the following roles of geosynthetics:

1. A geosynthetic layer reduces the outward horizontal stresses (shear stresses) transmitted from the overlying soil/fill to the top of the underlying foundation soil. This action of geosynthetics is known as *shear stress reduction effect*. This effect results in a general-shear, rather than a local-shear failure (Fig. 7(a)), thereby causing an increase in the load-bearing capacity of the foundation. Through the shear interaction mechanism the geosynthetic can therefore improve the performance of the system with very little or no rutting. In fact, the change in the failure mode as a result of reduction in shear stress is the primary benefit of the geosynthetic layer at small deformations.
2. A geosynthetic layer redistributes the applied surface load by providing restraint of the granular fill if embedded in it, or by providing restraint of the granular fill and the soft foundation soil, if placed at their interface, resulting in reduction of applied normal stress on the underlying foundation soil (Fig. 7(b)). This is referred to as *slab effect* or *confinement*

effect of geosynthetics. The friction mobilized between the soil and the geosynthetic layer plays an important role in confining the soil.



(a)

(b)

(c)

Fig. 5. Postulated behaviour of a unit cell in plane strain conditions with and without inclusions: (a) unit cell; (b) dense sand with inclusions; (c) loose sand with inclusions (adapted from McGown *et al*., 1978; Shukla and Yin, 2006)

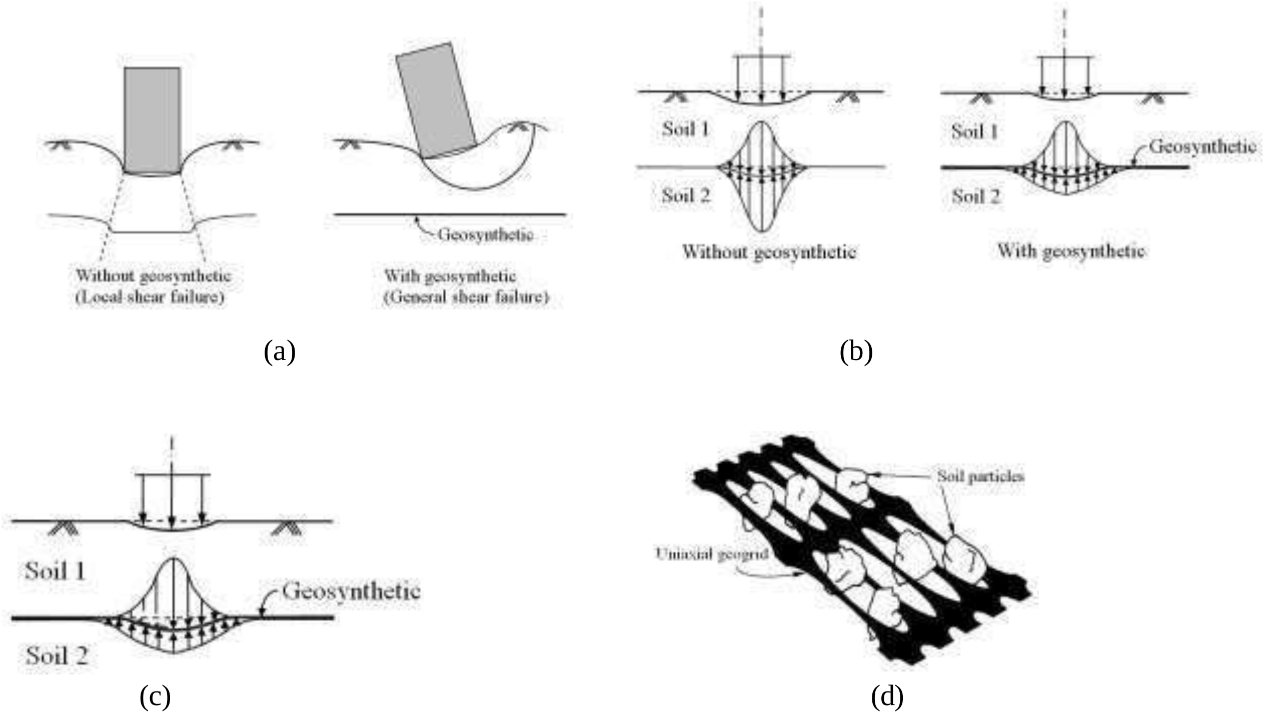
(a) (b)

Fig. 6. Reinforcement function: (a) tensile member; (b) tensioned member (adapted from Fluet, 1988; Shukla and Yin, 2006)

3. The deformed geosynthetic, sustaining normal and shear stresses, has a membrane force with a vertical component that resists applied loads, i.e. the deformed geosynthetic provides a vertical support to the overlying soil mass subject to loading. This action of geosynthetics is popularly known as its *membrane effect* (Fig. 7(c)). Depending upon the type of stresses - normal stress and shear stress, sustained by the geosynthetic during their action, the

membrane support may be classified as ‘normal stress membrane support’, and ‘interfacial shear stress membrane support’, respectively (Espinoza and Bray, 1995). Edges of the geosynthetic layer are required to be anchored in order to develop the membrane support contribution resulting from normal stresses, whereas membrane support contribution resulting from mobilized interfacial membrane shear stresses does not require any anchorage. The membrane effect of geosynthetics causes an increase in the load-bearing capacity of the foundation soil below the loaded area with a downward loading on its surface to either side of the loaded area, thus reducing its heave potential. It is to be noted that both the woven geotextile and the geogrid can be effective in membrane action in case of high-deformation systems.

4. The use of geogrids has another benefit owing to the interlocking of the soil through the apertures (openings between the longitudinal and transverse ribs, generally greater than 6.35 mm of the grid known as *interlocking effect* (Fig. 7(d)). The transfer of stress from the soil to the geogrid reinforcement is made through bearing (passive resistance) at the soil to the grid cross-bar interface. It is important to underline that because of the small surface area and large apertures of geogrids, the interaction are due mainly to interlocking rather than to friction. However, an exception occurs when the soil particles are small. In this situation the interlocking effect is negligible because no passive strength is developed against the geogrid.



(a) (b)

(c) (d)

Fig. 7. Roles of a geosynthetic reinforcement: (a) causing change of failure mode (shear stress reduction effect); (b) redistribution of the applied surface load (confinement effect); (c) providing vertical support (membrane effect) (adapted from Bourdeau *et al*., 1982 & Espinoza, 1994); (d) providing passive resistance through interlocking of the soil particles (interlocking effect) (Shukla, 2002, 2012; Shukla and Yin, 2006)

3. RANDOMLY DISTRIBUTED FIBRE-REINFORCED SOIL

Concept of the randomly distributed fibre-reinforced soil has been reported in the literature in the past few decades. A large number of experimental studies have been carried out to observe the characteristics of fibre-reinforced soils (see Shukla et al., 2009, 2010 for more details). It has now been established that the strength and deformation behaviour of the fibre-reinforced soils is governed by the soil characteristics (e.g., gradation and particle size and shape) and the fibre properties (weight ratio, aspect ratio, and modulus). In spite of this fact, a limited number of basic models (Waldron 1977; Gray and Ohashi, 1983; Mahar and Gray, 1990; Shewbridge and Sitar, 1990; Ranjan et al., 1996) have been suggested to explain the mechanism of fibre reinforcements in soils. It is probably because the modeling of the states of stress and strain in fibre-reinforced soil during deformation and failure is complex and difficult.

Based on the observations made in triaxial tests and statistical analysis of randomly distributed fibre-reinforced soils, Mahar and Gray (1990) has reported that the failure surfaces in triaxial compression tests are planer and oriented in the same manner as predicted by the Mohr-Coulomb theory. This finding suggests an isotropic reinforcing action with no development of preferred planes of weakness or strength. The principal stress envelops have been found to be either curved-linear or bilinear, with the transition or break occurring at a confining stress, called the critical confining stress, σ_{3crit} (Fig. 8).

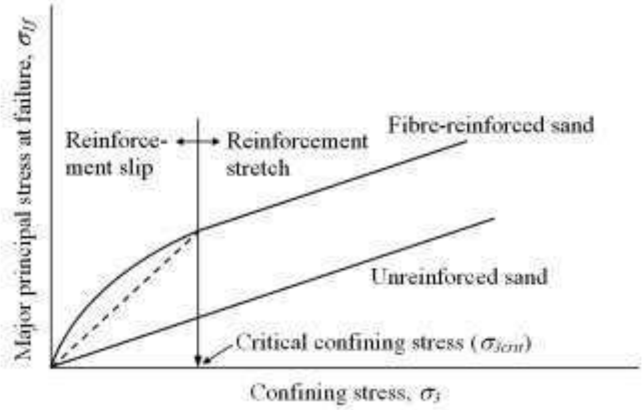


Fig. 8. Effect of the fibre inclusion in sand on its principal stress envelope obtained from triaxial compression tests (adapted from Maher and Gray, 1990; Shukla et al., 2009)

Recently Shukla et al. (2010) proposed a simple analytical model (Fig. 9) for predicting the shear strength behaviour of fiber-reinforced granular soils under high confining stresses, where it can be assumed that pullout of fibers does not take place. The model incorporates several significant parameters describing the characteristics of the granular soil and the fibers, such as: fiber content, aspect ratio, modulus of elasticity of fibers, specific gravity of fiber material, soil-fiber friction, initial orientation with respect to shear plane, normal confining stress, specific gravity of soil particles, angle of shearing resistance of soil, and void ratio of soil.

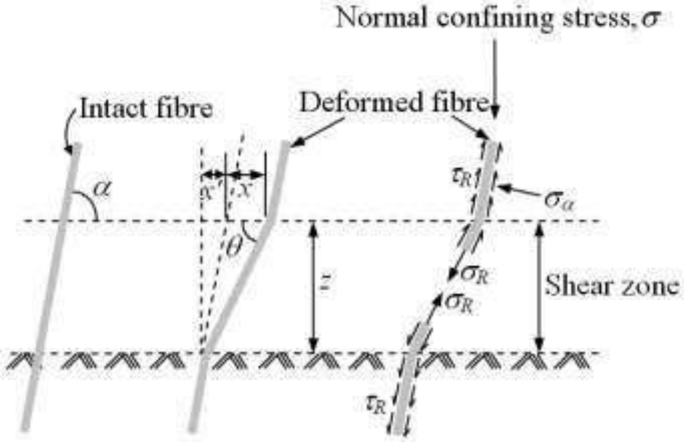


Fig. 9. Model for flexible, elastic reinforcement extending across the shear zone of thickness *z* (after Shukla et al., 2010)

The analytical expression developed by Shukla et al. (2010) for the ratio of shear strength of reinforced soil to that of unreinforced soil, called shear stress reduction ratio (SSR), is given below:

$$SSR = 1+2\left[\frac{\frac{W_R}{W_S}\left\{\frac{G_S}{G_R(1+e)}\right\}}{1+\frac{W_R}{W_S}\left\{\frac{G_S}{G_R(1+e)}\right\}}\right]\left[\frac{\sin\alpha+\left[1+2\left(\frac{\sigma}{E_R}\right)\left\{\frac{1-\sin\phi\sin(\phi-2\alpha)}{\cos^2\phi}\right\}\left(\frac{L}{D}\right)\tan\delta\sin\alpha\right]\tan\phi}{\sqrt{\cos^2\alpha+4\left(\frac{\sigma}{E_R}\right)\left\{\frac{1-\sin\phi\sin(\phi-2\alpha)}{\cos^2\phi}\right\}\left[1+\left(\frac{\sigma}{E_R}\right)\left\{\frac{1-\sin\phi\sin(\phi-2\alpha)}{\cos^2\phi}\right\}\left(\frac{L}{D}\right)\tan\delta\sin\alpha\right]\left(\frac{L}{D}\right)\tan\delta\sin\alpha}}\right]\left[\frac{1-\sin\phi\sin(\phi-2\alpha)}{\cos^2\phi}\right]\left(\frac{L}{D}\right)\tan\delta\sin\alpha \tag{14}$$

where σ is the total normal confining stress applied on the shear plane; ϕ is the angle of shearing resistance (or the angle of internal friction) of the granular soil; α is the initial orientation angle of the fiber with respect to shear surface; L and D are the length and the diameter of the fiber, respectively; δ is the fiber-soil friction angle; G_R is the specific gravity of fibers; G_S is specific gravity of soil particles; e is the void ratio of soil; W_R is the weight of the fibers; W_S is the weight of the soil; and E_R is the Young's modulus of elasticity of fiber in extension.

Eq. (14) shows that inclusion of fibers in the granular soil induces cohesion, may be called apparent cohesion, as well as increase in normal stress on the shear failure plane, which are proportional to the fiber content and aspect ratio, implying that increase in shear strength is also proportional to the fiber content and aspect ratio. The parametric study shows that the increase in shear strength of the granular soil due to presence of fibers is significantly contributed by the apparent cohesion, and the contribution to the shear strength from the increase in normal stress is limited.

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Geosynthetic Engineering – Basic Concepts

1. INTRODUCTION

In the past four decades, geosynthetics have been used successfully worldwide in several areas of civil engineering, and are now a well-accepted construction material. The utilization of geosynthetics offers excellent technical, economic, environment-friendly and/or energy-efficient alternatives to the conventional solutions for many civil engineering problems, and thus allows sustainable development of infrastructural projects.

Geosynthetics is a generic term for all synthetic materials used with soil, rock and/or any other civil-engineering-related material as an integral part of a man-made project, structure or system. It includes a broad range of synthetic products; the most common ones are (Shukla, 2002, 2012; Shukla and Yin, 2006):

- geotextiles
- geogrids
- geonets
- geomembranes
- geofoam
- geocomposites.

These products are almost exclusively polymeric, and they are available nowadays in numerous varieties in the market, under different trade names/designations for their use mainly in geotechnical, environmental, hydraulic and transportation engineering applications.

Geotextiles are permeable, polymeric textile products in the form of flexible sheets. Currently available geotextiles are classified into the following categories based on the manufacturing process:

- *woven geotextiles* – they are made from yarns (made of one or several fibres) by conventional weaving process with regular textile structure
- *nonwoven geotextiles* – they are made from directionally or randomly oriented fibres into a loose web by bonding with partial melting, needle punching or chemical binding agents (glue, rubber, latex, cellulose derivative, etc.)
- *knitted geotextiles* – they are produced by interlooping one or more yarns together
- *stitch-bonded geotextiles* – they are formed by the stitching together of fibres or yarns.

Geogrid is a polymeric, mesh-like planar product formed by intersecting elements, called ribs, joined at the junctions. The ribs can be linked by extrusion, bonding or interlacing, and the resulting geogrids are called *extruded geogrid*, *bonded geogrid* and *woven geogrid*, respectively. Extruded geogrids are classified into the following two categories based on the direction of stretching during their manufacture:

- *uniaxial geogrids* – they are made by longitudinal stretching of regularly punched polymer sheets and, therefore, possess a much higher tensile strength in the longitudinal direction than in the transverse direction
- *biaxial geogrids* – they are made by both longitudinal and ttransverse stretchings

of regularly punched polymer sheets and, therefore, possess equal tensile strength in both the longitudinal and the transverse directions.

The key feature of geogrids is that the openings between the longitudinal and transverse ribs, called apertures, are large enough to create interlocking with the surrounding soil particles. The ribs of geogrids are often quite stiff compared to the fibres of geotextiles. Also, the junction strength is important in the case of geogrids because, through these junctions, loads are transmitted from one rib to the other rib when geogrid layers are installed within the soil in field applications. *Geonets* are planar, polymeric product consisting of a regular dense network of integrally connected parallel sets of ribs overlying similar sets at various angles. At first glance, geonets appear similar to geogrids; however, they are different from each other, not mainly in the material or their configuration, but in their functions.

Geomembrane is a continuous membrane type barrier/liner composed of materials of low permeability to control fluid migration. The materials may be asphaltic or polymeric or a combination thereof. The term *barrier* applies when the geomembrane is used inside an earth mass. The term *liner* is usually reserved for the cases where the geomembrane is used as an interface or a surface revetment.

Geofoam is a lightweight product in slab or block form with a high void content, and has applications primarily as lightweight fills, thermal insulators and drainage channels. It is manufactured by the application of the polymer in semi-liquid form through the use of a foaming agent.

The term *geocomposites* is applied to products that are manufactured in laminated or composite form from two or more geosynthetic materials (geotextiles, geogrids, geonets, geomembranes, etc.) that, in combination, perform specific functions more effectively than when used separately. There can be several combinations, such as geotextile-geonet, geotextile-geogrid, geotextile-geomembrane, geonet-geomembrane, geomembrane-clay, and geomembrane-geonet-geomembrane, which are used in different civil engineering applications.

There are many other terms for products used in the field of geosynthetic manufacture and applications. Some of them are mentioned below.

- *Geomat* – a three-dimensional, permeable, polymeric structure made of coarse and rigid filaments bonded at their junctions, used to reinforce roots of vegetation such as grass and small plants and extend the erosion control limits of vegetation for permanent installation.
- *Geomesh* – a geosynthetic or geonatural generally with a planar woven structure having large pore sizes, which vary from several millimetres to several centimetres for use in mainly erosion control works.
- *Geocell* – a three-dimensional, permeable, polymeric honeycomb or web structure assembled from geogrids and special bodkins couplings in triangular or square cells on construction site or produced in the factory using strips of needle-punched polyester or solid high density polyethylene (HDPE).
- *Geopipe* – a plastic pipe (smooth or corrugated with or without perforations) placed beneath the ground surface and subsequently backfilled.
- *Geotube* – a factory assembled geosynthetic product, made from high strength woven geotextile/fabric in tube form and hydraulically filled with sand or fines at the shoreline protection/dewatering projects.
- *Geonatural* – a product manufactured from natural fibres (jute, coir, cotton, wool, etc.) having a short life span when used with soil, rock and/or other civil engineering related materials.
- *Electrokinetic geosynthetic (EKG)* - a mesh made from a metal wire stringer coated

in a conductive polymer; it resembles a reinforcing geomesh and is available in the form of sheets, strips or tubes.

The polymers generally used as raw materials for geosynthetics are polyester (PET), polypropylene (PP), polyethylene (PE) (very low density polyethylene (VLDPE), medium density polyethylene (MDPE), and high density polyethylene (HDPE)), chlorinated polyethylene (CPE), chlorosulfonated polyethylene (CSPE), polyamid (PA), polyvinyl chloride (PVC), expanded polystyrene (EPS), extruded polystyrene (XPS), etc.

Geosynthetics were introduced to the Indian engineers by the Central Board of Irrigation and Power (CBIP), New Delhi in 1985 by organizing the first National Workshop on Geomembranes and Geotextiles.

2. BASIC FUNCTIONS AND SELECTION

Geosynthetics have numerous application areas in civil engineering. They always perform at least one of the following major functions when used in conjunction with soil, rock and/or any other civil-engineering-related material (Shukla, 2002, 2012; Shukla and Yin, 2006):

- separation
- reinforcement
- filtration
- drainage (or fluid transmission)
- fluid barrier.

If a geosynthetic prevents intermixing of adjacent soil layers with different properties during construction and the projected service period of the geosynthetic-reinforced soil structure, it is said to have a *separation* function. Fig. 1 shows that the geosynthetic layer prevents the intermixing of soft soil with granular fill, thereby maintaining the structural integrity of the granular fill.

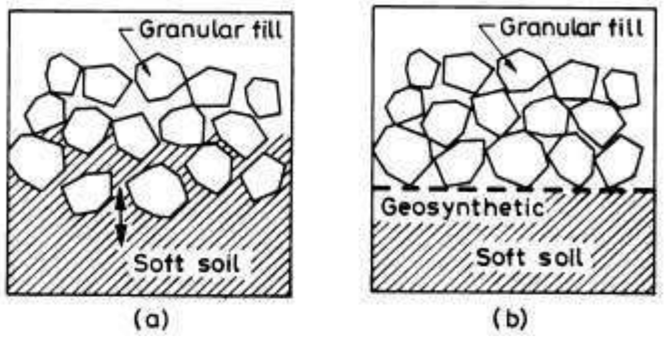


Fig. 1. Separation function: (a) granular fill – soft soil system without a geosynthetic separator; (b) granular fill – soft soil system with a geosynthetic separator (after Shukla and Yin, 2006; Shukla, 2012)

A geosynthetic shows its *reinforcement* function by increasing the strength of a soil mass as a result of its inclusion, thus it maintains the stability of the soil mass. In this process, the geosynthetic layer carries tensile loads (Fig. 2).

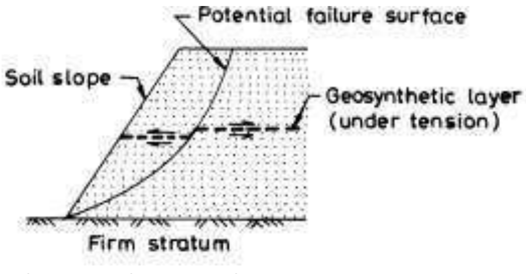


Fig. 2. Reinforcement function (after Shukla and Yin, 2006; Shukla, 2012)

Out of the reinforcement and the separation functions, selection of the major function is governed by the ratio of the applied stress on the soft soil to its shear strength (Fig. 3).

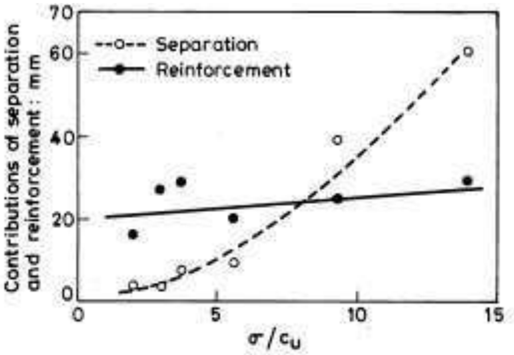


Fig. 3. Relationship between the separation and the reinforcement functions (after Nishida and Nishigata, 1994; Shukla, 2002, 2012; Shukla and Yin, 2006)

A geosynthetic may function as a *filter* that allows for adequate flow of fluids across its plane while preventing the migration of soil particles along with fluid flow during the projected service period of application under consideration (Fig. 4).

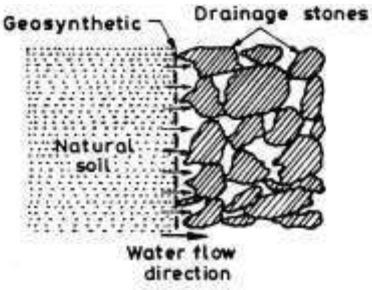


Fig. 4. Filtration function (after Shukla and Yin, 2006)

If a geosynthetic allows for adequate flow of fluids within its plane from surrounding soil mass to various outlets during the projected service period of application under consideration, it is said to have a *drainage* or *fluid transmission* function. Fig. 5 shows that a geosynthetic layer adjacent to the retaining wall collects water from the backfill and conveys it to the weep hole made in the retaining wall.

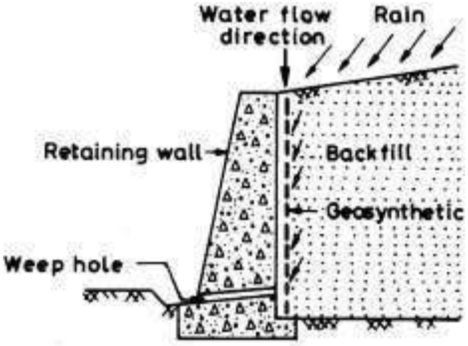


Fig. 5. Drainage function (Shukla and Yin, 2006; Shukla, 2012)

A geosynthetic may also act like an almost impermeable membrane as far as the flow of fluids is concerned, this function is called *fluid barrier*. Fig. 6 shows that the geosynthetic layer, kept at the base of a pond, prevents the infiltration of liquid waste into the natural soil.

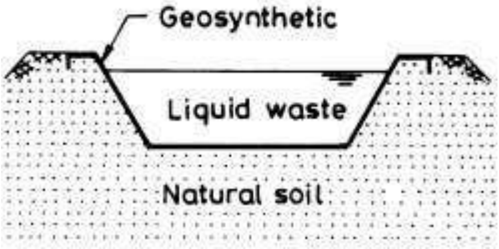


Fig. 6. Fluid barrier function (Shukla and Yin, 2006; Shukla, 2012)

In addition to the basic functions described above, in some specific field applications, a geosynthetic may also perform one or more than one of the following functions, which are basically dependant on the basic functions.

- *Protection* – where a geosynthetic is used as a localized stress reduction layer to prevent damage to a given surface or layer (e.g. geomembrane layer), it is said to perform the protection function.
- *Cushioning* – where a geosynthetic is used to control and eventually to damp dynamic mechanical actions, it is said to perform cushioning function. This function has to be emphasized particularly for the applications in canal revetments, in shore protections, and in geosynthetic strip layers as seismic base isolation of earth structures.
- *Absorption* – it is the process of fluid being assimilated or incorporated into a geotextile. This function may be considered for two specific environmental aspects: water absorption in erosion control applications, and the recovery of floating oil from surface waters following ecological disasters.
- *Interlayer* – it is a function performed by a geosynthetic to improve shear resistance between two layers of geosynthetic products and/or earth materials.
- *Containment* – with this function, a geosynthetic encapsulates or contain a civil engineering related material such as soil, rock or fresh concrete to a specific geometry and prevents its loss.
- *Insulation* – a geosynthetic provides insulation when it is used to reduce the passage of electricity, heat or sound.
- *Screening* – a geosynthetic provides screening when it is placed across the path of a flowing fluid carrying fine particles in suspension to retain some or all particles while allowing the fluid to pass through.

When installed, a geosynthetic may perform more than one of the listed functions simultaneously, but generally one of them will result in the lower factor of safety, thus it becomes the primary function. The use of a geosynthetic in a specific application needs classification of its functions as primary or secondary. The function concept is generally used in the design with the formulation of a factor of safety, *FS*, in the traditional manner as:

$$FS = \frac{\text{value of allowable (or test) property}}{\text{value of required (or design) property} \tag{1}$$

Factors of safety must be greater than 1; the actual magnitude depends upon the implication of failure, which is always site specific. The value of allowable property is obtained from a stimulated *performance test* (or an *index test* modified by site-specific reduction factors), whereas the required property is obtained from an appropriate design model. The entire process, generally called 'design by function' is widespread in its use.

The selection of a geosynthetic for a particular application is governed by several other factors, such as specification, durability, availability, cost, etc.

3. PROPERTIES AND TEST METHODS

Geosynthetics, being polymer-based products, are viscoelastic, which means that, under working conditions, their performance is dependent on the ambient temperature, the level of stress, the duration of the applied stress, the rate at which the stress is applied, etc. The properties of geosynthetics should therefore be used to keep these factors in view.

3.1. Physical Properties

The physical properties of geosynthetics that are of prime interest are *specific gravity*, *mass per unit area*, *thickness* and *stiffness*. The physical properties are more dependent on temperature and humidity than those of soils and rocks. In order to achieve consistent results in the laboratory, good environmental control during the testing is therefore important.

It is to be noted that the specific gravity of some of the polymers is less than 1.0, which is a drawback when working with geosynthetics underwater, that is, some of them may float. Table 1 provides the specific gravity of polymeric materials with their other properties.

The *mass per unit area* of a geosynthetic is usually given in units of gram per square metre (g/m^2). It can be a good indicator of cost and several other properties such as tensile strength, tear strength, puncture strength, etc. It is also necessary for quality control and thus it is the most useful basic property of geosynthetics. For commonly used geosynthetics, it varies in order of magnitude from typically 100 g/m^2 to 1000 g/m^2.

Table 1. Typical properties of polymers used for the manufacture of geosynthetics (after Shukla and Yin, 2006; Shukla, 2012)

Polymers	Specific gravity	Melting temperature (^{0}C)	Tensile strength at 20 ^{0}C (MN/m^2)	Modulus of elasticity (MN/m^2)	Strain at break (%)
PP	0.90 – 0.91	165	400-600	2000-5000	10-40
PET	1.22 - 1.38	260	800-1200	12000-18000	8-15
PE	0.91-0.96	130	80-600	200-6000	10-80
PVC	1.3 – 1.5	160	20-50	10-100	50-150
PA	1.05-1.15	220-250	700-900	3000-4000	15-30

The *thickness* of geosynthetics, particularly of geotextiles, is measured as the distance between the upper and the lower surfaces of the material at a specified normal pressure (generally 2.0 kPa). The thickness of commonly used geosynthetics ranges from 10 to 300 mils. Most geomembranes used today are 20 mils (0.50 mm).

The *stiffness* or *flexibility* of a geosynthetic is related to its bending under its own weight and indicates the feasibility of providing a suitable working surface for installation. It can be measured by its capacity to form a cantilever beam without exceeding a certain amount of downward bending under its own weight. It should be noted that the workability of a geosynthetic (ability of the geosynthetic to support personnel in an uncovered state and construction equipments during initial stages of cover fill placement) also depends on other factors, such as water absorption and buoyancy. When placing a geotextile or geogrid on extremely soft soils, a high stiffness is desirable.

Properties such as aperture size and shape, rib dimensions, etc., can be measured directly and are relatively easily determined.

3.2. Mechanical Properties

Mechanical properties are important in those applications where a geosynthetic is required to perform a structural role, or where it is required to survive installation damage and localized stresses.

Compressibility of a geosynthetic is measured by the decrease in its thickness at varying applied normal pressures. This mechanical property is very important for nonwoven geotextiles because they are often used to convey liquid within the plane of their structure.

Due to specific geometry and irregular cross-sectional area, the *tensile strength* of geosynthetics cannot be expressed conveniently in terms of stress. It is, therefore, defined as the peak load that can be applied per unit width. Tensile strength is generally determined by a wide-width strip tensile test on a 200 mm wide strip, because by approximating plane strain conditions, this test more closely simulates the deformation experienced by a geosynthetic embedded in soil (Fig. 7). The test provides parameters such as peak strength, elongation and tensile modulus. The measured strength and the rupture strain are a function of many test variables, including sample geometry, gripping method, strain rate, temperature, initial preload, conditioning, and the amount of any normal confinement applied to the geosynthetic. To minimize the effects of these factors, the test sample should have a width-to-gauge length ratio (aspect ratio) of at least 2 and the test should be carried out at a standard temperature.

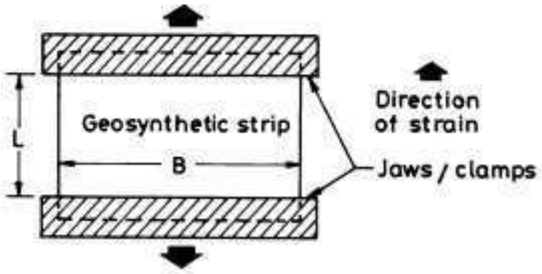
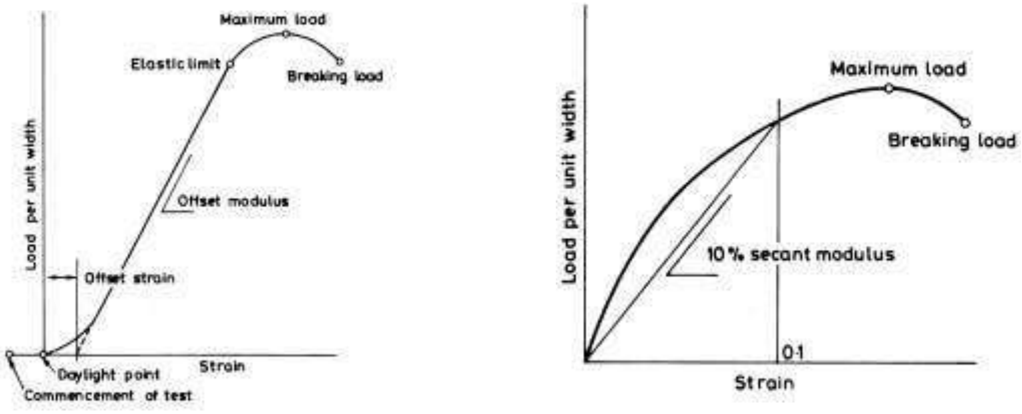


Fig. 7. Wide-width strip tensile test (*note* B = 200 mm, L = 100 mm) (after Shukla and Yin, 2006; Shukla, 2012)

Previously it was pointed out that the strength of woven geotextiles is governed by the weaving structure. It has been found that the strength of a woven geotextile is higher at 45° to the warp and weft directions, but is lower parallel to the warp/weft, whereas nonwoven geotextiles tend to have a lower but more uniform strength in all directions. One should obtain the minimum strength of the geosynthetic product and ensure that this stress is never exceeded in practical applications. The *tensile modulus* is the slope of the geosynthetic stress-strain or load-strain curve, as determined from wide width tensile test procedures. This is equivalent to the Young's modulus for other construction materials, i.e. concrete, steel, timber, structural plastic, etc. It depicts the deformation required to develop a given stress (load) in the material. Fig. 8 shows typical load-strain curves for geotextiles and interpretation methods of tensile modulus (Myles and Carswell, 1986).

For geotextiles that do not have a linear range, the modulus is typically defined as the *secant modulus* at 5 or 10% strain. The designer and specifier must have a clear understanding of the interpretation of these moduli. It is noted that woven geotextiles display generally the lowest extensibility and highest strengths of all the geotextiles. Geogrids have relatively high dimensional stability, high tensile strength and high tensile modulus at low strain levels. They develop reinforcing strength even at strain equal to 2%. The high tensile modulus results from prestressing during manufacture, which also creates integrally formed structures without weak points either in ribs or junctions.



(a) (b)

Fig. 8. Load – strain curves for geotextiles exhibiting: (a) linear behaviour; and (b) non-linear behaviour (after Myles and Carswell, 1986; Shukla and Yin, 2006; Shukla, 2012))

It is worthwhile mentioning index and performance tests. *Index tests* are carried out under standardized conditions used to compare the basic properties of geosynthetic products (e.g. wide-width tensile strength, creep under load, friction properties, etc.). They are generally used in quality control and quality assurance. They are also used to monitor changes that may occur after a geosynthetic has had some sort of exposure. Index tests generally do not reflect design features or applications. *Performance tests*, on the other hand, are carried out by placing the geosynthetic in contact with a soil/fill under standardized conditions in the laboratory, to provide better simulation of site conditions than index testing. Performance testing, if possible, should also be carried out at full scale at the site. It is to be noted that geosynthetics vary randomly in thickness and weight in any given sample roll due to normal manufacturing techniques. Tests must be conducted on representative samples collected as per the guidelines of available standards, which ensure that all areas of the sample roll and a full variation of the product are represented within each sample group.

When two pieces of similar or dissimilar geosynthetics (or related material) are attached to each other, this is known as a 'joint', and when a geosynthetic is physically linked to, or cast into, another, this is known as a 'connection'. When no physical attachment is involved between two geosynthetics or a geosynthetic and another material, this is known as an 'overlap'.

Where geosynthetic widths or lengths, greater than those supplied on one roll, are required, jointing becomes necessary and the same may be effected by one of the jointing methods, such as *overlapping*, *sewing*, *stapling*, *gluing*, etc. Different joints, currently in use, may be classified into prefabricated joints and joints made during field applications. In the vast majority of cases, the geosynthetic width or length is extended simply by overlapping, which is usually found to be the easiest field method.

An important criterion for assessing joint performance is load transmission between the two pieces of the geosynthetics. In some applications, it may be essential that the load transfer capability is equal to that of the parent material. For other situations, a more important criterion may be the magnitude of the deformation of the joint under load. *Seam strength* is the load-transfer capability from one geosynthetic roll to another when ends of both the rolls are joined together by any method. The efficiency (E) of a seam joint, between geosynthetic sheets, is generally defined as the percentage of the ultimate tensile strength of the geosynthetic, which the joint can bear before rupture. It is therefore expressed as:

$$E = \left(\frac{T_{\text{seam}}}{T_{\text{geosyntheitc}}} \times 100 \right) \%$$

(2)

where T_{seam} is the wide-width seam strength, and $T_{\text{geosynthetic}}$ is the wide-width (unseamed) geosynthetic strength.

There are some mechanical properties of geosynthetics, which are related to geosynthetic survivability and separation function. Such tests are known as *integrity tests* and are as follows.

- *Fatigue strength* – ability of geosynthetics to withstand repetitive loading before undergoing failure.
- *Burst strength* – ability of geosynthetics to withstand loading when no further deformation is possible.
- *Tear strength* – ability of geosynthetics to withstand tearing stresses often generated during their installation.
- *Impact strength* – ability of geosynthetics to withstand stresses generated by falling objects, such as rock pieces, tools and other construction items.
- *Puncture strength* – ability of geosynthetics to withstand stresses generated by penetrating objects, such as pieces of rock or wood, under quasi-static condition.

3.3. Hydraulic Properties

Hydraulic testing of geosynthetics is completely based on new and original concepts, methods, devices, interpretation and databases, unlike the physical and mechanical testing. The reason behind this is that the traditional textile tests rarely have hydraulic applications. *Porosity*, *permittivity* and *transmissivity* are the most important hydraulic properties of geosynthetics, especially of geotextiles, geonets and some drainage composites, which are explained below.

Geosynthetic porosity is related to the ability to allow liquid to flow through it and is defined as the ratio of the void volume to the total volume. It may be indirectly calculated for geotextiles using the relationship given below (Koerner, 1990; Shukla 2012):

$$\eta = 1 - \frac{m}{\rho t}$$

(3)

where η is the porosity, m is the mass per unit area, ρ is the overall geotextile density, and t is the thickness of the geotextile.

Per cent open area (POA) of a geosynthetic is the ratio of the area of its openings to its total area and is expressed in per cent. The pores in a given geosynthetic, especially in a geotextile, are not of one size but are of a range of sizes. The pore-size distribution can be represented in much the same way as the particle size distribution for a soil. Various methods are available for evaluating the pore-size distribution of geotextiles.

In the *dry sieving test method*, glass beads of a known size are sieved in dry condition through a screen made of the geotextile (Fig. 9). Sieving is done by using beads of successively coarser size until 5% or less, by weight, pass through the geotextile.

In the case of most geogrids, the open areas of the grids are greater than 50% of the total area. In this respect, a geogrid may be looked at as a highly permeable polymeric structure.

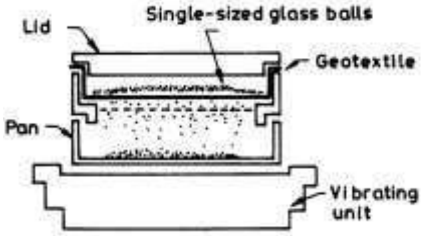


Fig. 9. Diagram showing details of dry sieving method (Shukla and Yin, 2006; Shukla, 2012)

Figure 10 shows pore-size distribution curves for typical woven and nonwoven geotextiles. The pore size at which 95% of the pores in the geotextile are finer, is originally termed the *equivalent opening size* (EOS) designated as O_{95}. If a geotextile has an O_{95} value of 300 mm, then 95% of geotextile pores are 300 mm or smaller. In other words, 95% of particles with a diameter of 300 mm are retained on the geotextile during sieving for a constant period of time. This notation is similar to that used for soil particle size distributions where, for instance, D_{10} is the sieve size through which 10%, by weight, of the soil passes. The *apparent opening size* (AOS) is equivalent to the EOS but is also quoted for other percentages retained, such as O_{50} or O_{90}. The EOS is used in many filter criteria established to prevent piping and erosion. It should be noted that the meaning of EOS and AOS values and their determination in the laboratory are still not uniform throughout the engineering profession and, hence, filter criteria developed in different countries may not be directly comparable.

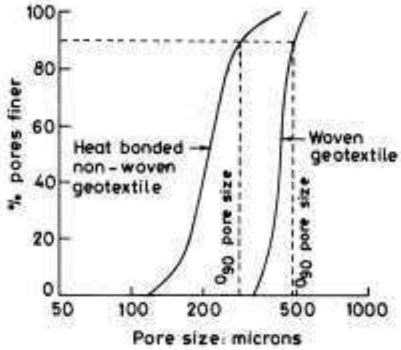


Fig. 10. Pore size distributions of typical geotextiles (after Ingold and Miller, 1988; Shukla and Yin, 2006; Shukla, 2012)

The permeability of a geosynthetic to water flow may be expressed by *Darcy's coefficient*, by *permittivity* (as defined below) or by a *volume flow rate*.

Permittivity of a geosynthetic (generally geotextile) is simply the coefficient of permeability for water flow normal to its plane (Fig. 11(a)) divided by its thickness. This property is the preferred measure of water flow capacity across the geosynthetic plane and quite useful in filter applications. Darcy's law, in terms of permittivity, can be expressed as:

$$Q_n = k_n \frac{\Delta h}{\Delta x}(LB) = \psi \Delta h A_n \qquad (4)$$

where Q_n is the cross-plane volumetric rate of flow (m^3/s), i.e. volumetric rate of flow for flow across the plane of the geosynthetic, k_n is the coefficient of cross-plane permeability (m/s), Δh is the head causing flow (m), Δx is the thickness of the strip of geosynthetic measured along the flow direction under a specified normal stress (m), L is the length of the strip of geosynthetic (m), B is the width of the strip of geosynthetic (m), $\psi = k_n/\Delta x$, which is the permittivity of the geosynthetic (s^{-1}), and $A_n = LB$, which is the area of cross-section of geosynthetic for cross- plane flow (m^2).

Transmissivity of a geosynthetic (thick nonwoven geotextile, geonet or geocomposite) is simply the product of the permeability for in-plane water flow (Fig. 11(b)) and its thickness. This property is the preferred measure of the in-plane water flow capacity of a geosynthetic and is widely used in drainage applications. Darcy's law in terms of transmissivity can be expressed as:

$$Q_p = k_p \frac{\Delta h}{L} A_p = k_p \frac{\Delta h}{L} (B\Delta x) = \theta iB$$

(5)

where Q_p is the in-plane volumetric rate of flow (m^3/s), i.e. volumetric rate of flow for flow within the plane of the geosynthetic, k_p is the coefficient of in-plane permeability, $\theta = k_p\Delta x$, which is the transmissivity of the geosynthetic (m^2/s), $i = \Delta h/L$, which is the hydraulic gradient, and $A_p = B\Delta x$ which is the area of cross-section of geosynthetic for in- plane flow (m^2). To exhibit a large transmissivity, a geotextile must be thick and/or have a large permeability in its plane.

(a) (b)

Fig. 11. Flow of water through a geotextile strip: (a) normal flow; and (b) in-plane flow (after Shukla and Yin, 2006; Shukla, 2012)

Eqs. (4) and (5) indicate that once permittivity (ψ) and transmissivity (θ) are successfully determined, the flow rates Q_n and Q_p do not depend on thickness of the strip of geosynthetic, Δx, which is highly dependent on the applied pressures and therefore, it is difficult to measure the thickness accurately.

To achieve satisfactory filter performance by geosynthetics, especially geotextiles, the following functions are required during the design life of the application under consideration.

(a) Maintain adequate permeability to allow flow of water from the soil layer without significant flow impedance so as not to build up excess hydrostatic porewater pressure behind the geosynthetic (*permeability criterion*).
(b) Prevent significant wash out of soil particles, i.e. soil piping (*retention* or *soil-tightness criterion*).
(c) Avoid accumulation of soil particles within the geosynthetic structure, called fabric clogging, resulting in complete shut off of water flow (*clogging criterion*).

It may be noted that the permeability criterion places a lower limit on the pore size of a geotextile, whereas the retention criterion places an upper limit on the pore size of a geotextile. These two criteria are, to some extent, contradictory, because the permeability of a geosynthetic filter increases with its increasing pore size. However, in the majority of cases, it is possible to find a filter that meets both the permeability criterion and the retention criterion.

The criteria of geotextile filter, commonly used, are given in the following forms:

$k_n \geq \lambda k_s$ (Permeability criterion)
(6)

$O_i \leq \beta D_j$ (Retention criterion)
(7)

3.4. Endurance and Degradation Properties

The endurance and degradation properties (creep behaviour, abrasion resistance, long-term flow capability, durability – construction survivability and longevity, etc.) of geosynthetics are related to their behaviour during service conditions, including time.

If the test method for determining the geosynthetic properties is not completely field-simulated, the test values must be adjusted. For example, the laboratory-generated tensile strength is usually an ultimate value, which must be reduced before being used in design. This can be carried out using the following equation (Koerner, 1990):

$$T_{allow} = T_{ult}\left[\frac{1}{FS_{ID} \times FS_{CR} \times FS_{CD} \times FS_{BD}}\right] \qquad (8)$$

where T_{allow} is the allowable tensile strength to be used in equation (1.1) for final design purposes, T_{ult} is the ultimate tensile strength from the test, FS_{ID} is the factor of safety for installation damage (1.1 - 3.0 for geotextiles, 1.1 - 1.6 for geogrids), FS_{CR} is the factor of safety for creep (1.0- 4.0 for geotextiles, 1.5 - 3.5 for geogrids), FS_{CD} is the factor of safety for chemical degradation (1.0 - 2.0 for geotextiles,), and FS_{BD} is the factor of safety for biological degradation (1.0 – 1.3).

4. APPLICATION AREAS

Geosynthetics are versatile in use, adaptable to many field situations, and can be combined with several traditional and new building materials. They are utilized in a range of applications in many areas of civil engineering, especially geotechnical, transportation, hydraulic, and environmental engineering, in which geosynthetics are widely used for achieving technical benefits and/or economic advantages because of their favourable basic characteristics as listed below.

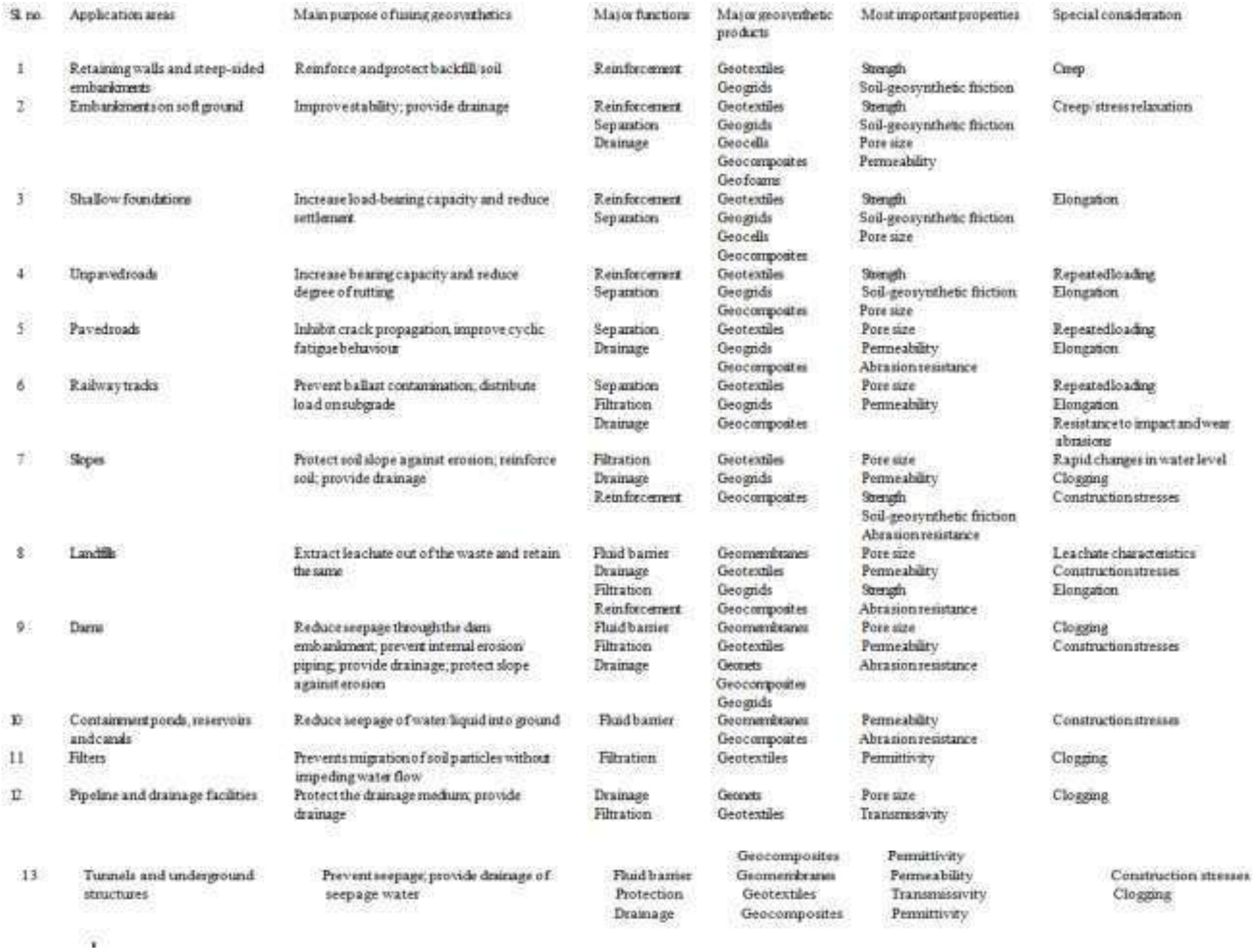
- non-corrosiveness
- highly inert to biological and chemical degradation
- long-term durability under soil cover
- high flexibility
- minimum volume
- lightness
- robustness (geosynthetics can withstand the stresses that may be induced during installation and throughout the life of the structure)
- factory-produced to have specific quality controlled standards and they do not exhibit the inherent variability of naturally occurring materials
- ease of storing and transportation
- simplicity of installation, even by unskilled personnel
- ease in control of execution
- rapid installation, even in adverse environmental conditions and thus speeding up the construction process

- useable, even with unsuitable soils
- replace soil/mineral construction materials – conserving scarce resources
- cause less wear and tear on equipment
- available in a wide range of products, in numerous configurations and weights, to perform a wide range of functions when placed in soils
- have capacity to solve even those problems which cannot be solved by traditional techniques
- make technically effective and economical solutions (the cost should be estimated to include the initial construction cost, continuing maintenance cost, cost related to production losses, in the case of roads as a result of their closure, etc.)
- provide environment-friendly and energy-efficient solutions, thus allow for sustainable development
- improved performance of structure
- provide good aesthetic look to structures.

The technical acceptance of geosynthetics has been achieved in a large number of application areas. Table 2 lists the major application areas for the geosynthetics.

Recently attempts have also been made to explore the possibility of using geosynthetics to improve the geotechnical structures constructed using waste materials such coal ashes (Gill et al. 2013a,b). The research outcomes based on laboratory model tests are very encouraging for their field applications.

Table 2. Major application areas for geosynthetics (after Shukla, 2012)



Sl. no.	Application areas	Main purpose of using geosynthetics	Major functions	Major geosynthetic products	Most important properties	Special consideration
1	Retaining walls and steep-sided embankments	Reinforce and protect backfill soil	Reinforcement	Geotextiles Geogrids	Strength Soil-geosynthetic friction	Creep
2	Embankments on soft ground	Improve stability; provide drainage	Reinforcement Separation Drainage	Geotextiles Geogrids Geocells Geocomposites Geofoams	Strength Soil-geosynthetic friction Pore size Permeability	Creep/stress relaxation
3	Shallow foundations	Increase load-bearing capacity and reduce settlement	Reinforcement Separation	Geotextiles Geogrids Geocells Geocomposites	Strength Soil-geosynthetic friction Pore size	Elongation
4	Unpaved roads	Increase bearing capacity and reduce degree of rutting	Reinforcement Separation	Geotextiles Geogrids Geocomposites	Strength Soil-geosynthetic friction Pore size	Repeated loading Elongation
5	Paved roads	Inhibit crack propagation, improve cyclic fatigue behaviour	Separation Drainage	Geotextiles Geogrids Geocomposites	Pore size Permeability Abrasion resistance	Repeated loading Elongation
6	Railway tracks	Prevent ballast contamination; distribute load on subgrade	Separation Filtration Drainage	Geotextiles Geogrids Geocomposites	Pore size Permeability	Repeated loading Elongation Resistance to impact and wear abrasions
7	Slopes	Protect soil slope against erosion; reinforce soil; provide drainage	Filtration Drainage Reinforcement	Geotextiles Geogrids Geocomposites	Pore size Permeability Strength Soil-geosynthetic friction Abrasion resistance	Rapid changes in water level Clogging Construction stresses
8	Landfills	Extract leachate out of the waste and retain the same	Fluid barrier Drainage Filtration Reinforcement	Geomembranes Geotextiles Geogrids Geocomposites	Pore size Permeability Strength Abrasion resistance	Leachate characteristics Construction stresses Elongation
9	Dams	Reduce seepage through the dam embankment; prevent internal erosion/piping; provide drainage; protect slope against erosion	Fluid barrier Filtration Drainage	Geomembranes Geotextiles Geonets Geocomposites Geogrids	Pore size Permeability Abrasion resistance	Clogging Construction stresses
10	Containment ponds, reservoirs and canals	Reduce seepage of water/liquid into ground	Fluid barrier	Geomembranes Geocomposites	Permeability Abrasion resistance	Construction stresses
11	Filters	Prevents migration of soil particles without impeding water flow	Filtration	Geotextiles	Permittivity	Clogging
12	Pipeline and drainage facilities	Protect the drainage medium; provide drainage	Drainage Filtration	Geonets Geotextiles	Pore size Transmissivity	Clogging
13	Tunnels and underground structures	Prevent seepage; provide drainage of seepage water	Fluid barrier Protection Drainage	Geocomposites Geomembranes Geotextiles Geocomposites	Permittivity Permeability Transmissivity Permittivity	Construction stresses Clogging

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