Chapter 2
Basic Description of Fibre-Reinforced Soil

2.1 Introduction

Fibre reinforcement in soils can be observed in nature. In our day-to-day life, you may notice that the roots of vegetation (natural fibres) stabilize the near-surface soil that has low shear strength, mainly because of low effective stress, on both level and sloping grounds. Figure 2.1 shows how the fibres of different sizes (smaller than 1 mm to larger than 70 mm) as the roots of a tree strengthen the foundation soil for its long-term stability. The presence of plant roots is a natural means of incorporating randomly distributed fibre inclusions within the soil mass. The root fibres improve the strength of soil and the stability of soil foundations and slopes. With learning from the root reinforcements, the fibre reinforcement concept has also become significant in engineering construction practice. In fact, the soil strengthening/stabilizing/reinforcing effects of the natural fibres as the roots of vegetation may be replicated artificially by including different types of natural and synthetic fibres or as fibres from waste materials such as used plastic materials and old tyres (which pose challenging environmental and disposal problems) within the soil mass. In construction works, fibres are generally mixed randomly with soil, resulting in *randomly distributed fibre-reinforced soil* (RDFRS), which is often simply called the *fibre-reinforced soil* (FRS), as explained in Sect. 1.4 of Chap. 1. In some cases, materials like cement, lime, fly ash or bituminous products are also added to the soil along with fibres for achieving additional improvement in the engineering properties of soil. Note that fibres are a form of structural reinforcement, and their main role is working as a tension member to improve the strength characteristics of soil in addition to their roles in influencing other properties of soil (e.g. permeability, compressibility, etc.).

This chapter presents the basic description of fibres and fibre-reinforced soils, focusing on types of fibres and their characteristics, and phase concept of fibre-reinforced soil mass. Brief details of the soil reinforced with continuous fibres and multioriented inclusions are also provided.

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Fig. 2.1 Foundation soil reinforced randomly with natural root fibres (visible in an excavated trench closer to the tree) supporting a tree

2.2 Fibres

A *fibre* is a unit of matter characterized by flexibility, fineness and a high ratio of length to thickness (or diameter) (Fig. 2.1). In this book, the fibre has been considered a general term that refers to all filaments, yarns, staples, bristles/hairs, buffings, chips, crumbs and other similar highly flexible entities. A filament is an untwisted individual fibre and can be crimped or uncrimped. A yarn refers to a bundle or series of filaments twisted to produce a single fibre in which the individual filaments cannot be separated. Crimping of filaments helps prevent filament separation when the yarn is made. A staple is a cut length of fibre, measured and expressed in millimetres.

The ratio of length L to thickness (or equivalent diameter) D of the fibre is called the *aspect ratio* a_r. Thus

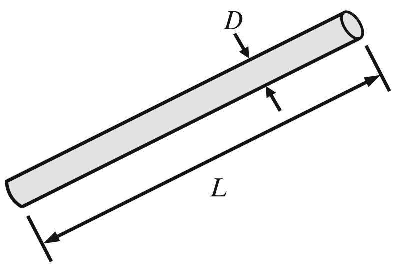
$$a_r = \frac{L}{D} \tag{2.1}$$

Fibres are obtained from natural, synthetic and waste (nonhazardous type) materials, and therefore, they may be categorized into the following three types:

- Natural fibres (Fig. 2.3)
- Synthetic fibres (Fig. 2.4)
- Waste fibres (Fig. 2.5)

In addition to coir and jute fibres, as shown in Fig. 2.3, there are several other natural fibres, such as wood chips, bamboo fibres, sisal fibres, palm leaves, grasses, banana fibres, corn stalks, oat and flax straws, manila fibres, cotton fibres, etc. They are available locally in different places worldwide, and can be used as the geofibres. Human and animal hairs are also available as natural fibres. Most natural fibres

Fig. 2.2 Geometrical dimensions of a typical fibre



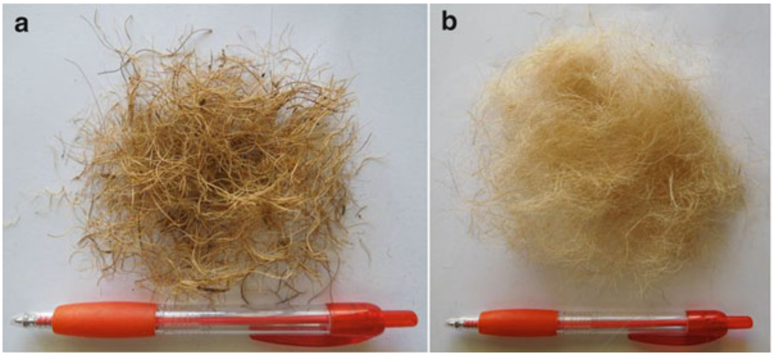


Fig. 2.3 Natural fibres: (**a**) coir fibres, (**b**) jute fibres

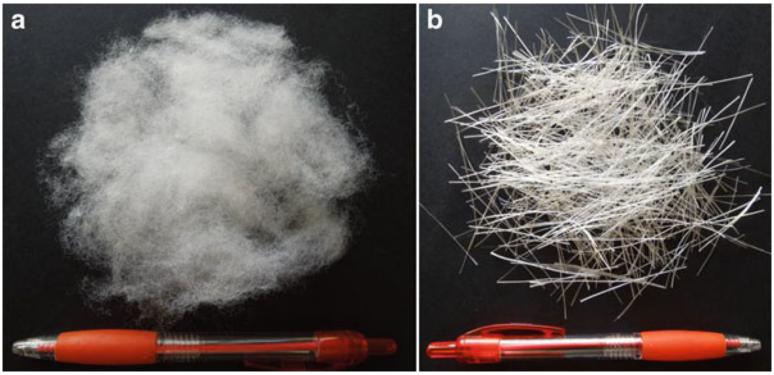


Fig. 2.4 Synthetic fibres: (**a**) polypropylene (PP) fibres, (**b**) glass fibres

Fig. 2.5 Waste fibres: (**a**) old/used tyre fibres, (**b**) waste/used plastic fibres

originate from plant and vegetation, animal and mineral sources. Bamboo grids and mats are also used as soil reinforcement to create systematically reinforced soils as the geosynthetic reinforcements are used.

Of most natural fibres, coir has the greatest tensile strength and retains this property even in wet conditions. It is a biodegradable organic fibre material containing 40% lignin and 54% cellulose (Rao and Balan 2000). The high content of lignin, which is a complex hydrocarbon polymer, makes the coir fibres degrading slowly, and so they are useful in different applications, as discussed in Chap. 5. The coir fibres may play their roles for a long period (1–2 years) when included within the soil mass, even in saline environment. Bamboo fibres are very strong in tension but have low modulus of elasticity and high water absorption. The best quality of bamboo fibres is that they are seldom eaten by pests or infected by pathogens. Certain fibres, such as sisal fibres, have very high initial tensile strength and are strong as the equivalent polyester fibres.

Table 2.1 provides the values of some specific properties of coir, jute and bamboo fibres, determined by Biswas et al. (2013), using a mini-tensile/compression testing machine, but these values contradict the observations reported in the fibre-reinforced

Table 2.1 Physical/mechanical properties of some fibres

Fibre types	Tensile strength (MPa)	Young's modulus of elasticity (MPa)	Strain at failure (%)
Coir (brown)	165–222	3.79	41.0
Coir (white)	185–237	3.97	38.7
Jute	331–414	28.43	2.6
Bamboo	615–862	35.45	4.1

After Biswas et al. (2013)

soil literature. This demonstrates that for any project work, the tabulated values of fibres may not be the realistic values for their direct use in design of fibre-reinforced soil structures. The properties of fibres, therefore, should be determined by conducting the tests on the fibres being used in the project, as the fibres can vary significantly in their properties even for the fibres coming from the same natural plant.

Natural fibres have affordable cost, strength, environmentally friendly characteristics (e.g. contributing to greener Earth by reducing the greenhouse gas emissions in construction) and bulk availability, but they have some practical drawbacks such as reproducibility and biodegradability. In addition, the fibre geometry varies significantly, thus the design procedure with application of natural fibres may require a special attention. Except coir fibre, most natural fibres have a poor resistance to alkaline environment.

Natural fibres exhibit progressive loss of strength and other characteristics when included within the soil mass. The rate of loss of property varies with type of fibres. The problem of biodegradability of geonaturals can be overcome by suitable treatment methods, such as alkali and other chemical treatments, enzyme treatment, UV grafting with monomers, physical and chemical coatings using synthetic polymers or resins, antimicrobial finishing, etc., with some additional cost. Thus, the natural fibres can be used as an alternative low-cost reinforcing materials or admixtures for improving the engineering behaviour of weak soils or other similar materials in some field applications, such as construction of pavements for village and forest areas, or at least in the short-term applications, such as erosion control, where strength durability of fibres is not an issue. The use of natural fibres for erosion control is a sustainable and environmentally friendly application.

Figure 2.4 shows only two types of synthetic fibres (PP fibres and glass fibres), but there are several others, such as polyester (PET) fibres, polyethylene (PE) fibres, nylon/polyamide (PA) fibres, carbon fibres, steel/metal fibres, etc. There are several environmental factors that affect the durability of polymers. Ultraviolet component of solar radiation, heat and oxygen and humidity are the factors above the ground that may lead to degradation. Below the ground, the main factors affecting the durability of polymers are soil particle size and angularity, acidity/alkalinity, heavy metal ions, presence of oxygen, water content, organic content and temperature. The resistance of commonly used polymers to some environmental factors is

Table 2.2 A comparison of the resistance of some polymers

Influencing factors	Resistance of polymers			
	PP	PET	PE	PA
Ultraviolet light (unstabilized)	Medium	High	Low	Medium
Ultraviolet light (stabilized)	High	High	High	Medium
Alkalis	High	Low	High	High
Acids	High	Low	High	Low
Salts	High	High	High	High
Detergents	High	High	High	High
Heat, dry (up to 100 °C)	Medium	High	Low	Medium
Steam (up to 100 °C)	Low	Low	Low	Medium
Hydrolysis (reaction with water)	High	High	High	High
Micro-organisms	High	High	High	Medium
Creep	Low	High	Low	Medium

Adapted from John (1987) and Shukla (2002)

Table 2.3 Typical properties of polymers

Polymers	Specific gravity	Melting temperature (°C)	Tensile strength at 20 °C (MPa)	Modulus of elasticity (GPa)	Strain at break (%)
PP	0.90–0.91	160–165	400–600	1.3–1.8	10–40
PET	1.22–1.38	260	800–1200	12–18	8–15
PE	0.91–0.96	100–135	80–600	0.2–1.4	10–80
PVC	1.38–1.55	160	20–50	2.7–3	50–150
PA	1.05–1.15	220–250	700–900	3–4	15–30

After Shukla (2016)

compared in Table 2.2. The basic properties of these polymers are given in Table 2.3. It must be emphasized that the involved reactions are usually slow and can be retarded even more by the use of suitable additives. When the polymers are subjected to a higher temperature, they lose their weight. What remains above 500 °C is probably carbon black and ash (Fig. 2.6).

The PP fibres have been widely used in experimental investigations of fibre-reinforced soils. The primary attraction is that of low cost. It is easy to mix PP fibres with soil, and they have relatively a high melting point, which makes it possible to place the fibre-reinforced soil in the oven and conduct the water content determination tests. Also, the PP is a hydrophobic and chemically inert material which does not absorb or react with the soil moisture or leachate. The fibres are produced in fibrillated bundles. If the fibres are added to the soil during mixing cycle, the mixing action opens the bundles and separates them into multifilament fibres (Miller and Rifai 2004).

Synthetic fibres have the following two advantages over natural fibres (Krenchel 1973; Hoover et al. 1982):

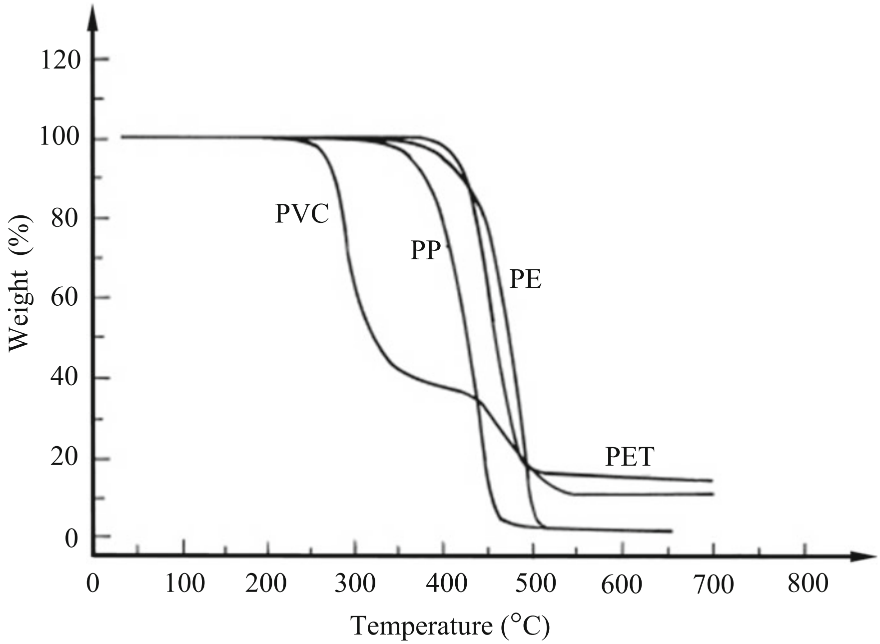


Fig. 2.6 Effect of temperature on some geosynthetic polymers (After Thomas and Verschoor 1988)

1. Synthetic fibres can be produced according to desired specifications. For example, geometry of fibres can be controlled and shape of fibres and surface conditions can be altered in order to enhance the frictional properties of fibres.
2. Most synthetic fibres do not biodegrade when subjected to variable environments of moisture, heat, cold or sunlight.

Old/used tyres and waste plastic materials are available in large quantities worldwide; they may be utilized in construction projects in various forms, especially in the granular form, chips or fibres; otherwise they may occupy a large volume of the landfills when disposed of. The type of the tyre chips and fibres depends primarily on the design of the shredder (i.e. machine for cutting). The average specific gravity of tyre chips/fibres typically ranges from 1.13 to 1.36 (average value of 1.22) depending on the metal content. The tyre chips/fibres without metal have a narrow range of specific gravity around 1.15. The unit weight of pure tyre chip fills typically ranges from 3 to 6 kN/m^3 (Edil and Bosscher 1994). Tyre buffings, also called the rubber fibres, are a by-product of the tyre retread process. They have an elongated fibrous shape with variable length of even dust size and high strength and extensibility, and so they can be used as soil reinforcement. Utilization of waste fibres, including some waste natural fibres (e.g. human and animal hairs) as soil reinforcement, can avoid the environmental and disposal problems. Additionally the use of waste fibre reinforcement helps in sustainable development of various infrastructures developed on weak and unsuitable soils.

In the area of fibre composites, fibres are also classified based on their length as (Agarwal and Lawrence 1980; Hoover et al. 1982) short fibres and continuous fibres. The fibres smaller than 76.2 mm (3 in.) are usually called the short fibres. The fibres longer than 76.2 mm (3 in.) when included in matrix material (e.g. soil) extend throughout the material mass, and so they are called the long/continuous fibres. The mechanics of stress transfer differs in composites reinforced with short and continuous fibres. For short fibre-reinforced composite, the applied stresses are first transferred to the matrix material, then to the fibres through the fibre ends and the surfaces of the fibres near the fibre ends. For continuous fibre-reinforced composite, the applied stresses are transferred to the fibres and matrix (soil) at the same time. Details of the soil mass reinforced with almost infinite length of fibres are briefly presented in Sect. 2.2. This book has mainly focused on presenting the fundamentals of soil reinforced with short, discrete, flexible fibres, as they have been studied and their applications have been reported, without strictly following the upper length limit for short fibres as classified in the area of fibre composites.

Basic properties of fibres used for reinforcing the soils in several laboratory and field studies of fibre-reinforced soils are given in Table 2.4.

The following points regarding fibres are worth mentioning:

1. A long continuous roll of a single filament, groups of filaments or yarns is called the tow.
2. Fibres can be either straight or crimped (texturized). Crimping is one of the texturing procedures for fibres.
3. In the fibre industry, the fibres are also described in terms of linear mass density (kg/m), which is generally expressed in denier (grams per 9 km of the fibre) or tex (grams per 1 km of the fibre). Thus, 1 denier = 1 g/9 km, 1 tex = 1 g/ km, and 1 tex = 9 denier.
4. Denier is an indirect measure of fibre diameter. For example, if 9 km of PET filaments weighs 120 g, it is classed as a 120-denier filament.
5. It is possible to convert denier to more conventional diametric measure by relating denier to specific gravity through the volumetric relation for a circular cylinder. As an example, a 75-denier filament would have a diameter corresponding to a fine-textured human hair, while a 2500-/250-denier yarn would correspond in size to a packing twine. A 2500/250 yarn of fibre denotes a fibre with a 2500 total denier measure but composed of 250 individual filaments, each of which is 10 denier (Hoover et al. 1982).
6. The fibre properties, such as tensile strength, tensile modulus, elongation/strain at break, tenacity, etc., are based on the denier of the fibre.
7. Tenacity is a measure of the tensile strength of a fibre expressed in terms of grams/denier. A 100-denier filament that breaks under a 250-g load is rated at 2.5 g/denier. Elongation at break refers to strain characteristic of the fibre, i.e. a measure of longitudinal deformation that occurs prior to rupture, and expressed as a percentage (Hoover et al. 1982).

Table 2.4 Properties of fibres

Characteristics of fibres	Kaniraj and Havanagi (2001)	Consoli et al. (2009)	Jha et al. (2015)	Park (2009)	Spritzer et al. (2015)	Lovisa et al. (2010)	Khattak and Alrashidi (2006)	Babu et al. (2008)	Spritzer et al. (2015)	Sarbaz et al. (2014)
Type	PET fibres	PP fibres	PE fibres	PVA fibres	Nylon fibres	Glass fibres	PC fibres	Coir fibres	Jute fibres	Date palm fibres
Specific gravity, G_f	1.3	0.91	0.99	1.3	1.15	1.7	1.5	1.07	1.47	0.92
Average length, L (mm)	20	24	12	12	6–18	10–15	3	15	7–9	295
Equivalent diameter, D (mm)	0.075	0.023	0.035	0.1	0.003–0.01	0.02	0.015	0.25	0.005–0.025	0.42
Tensile strength σ_f (MPa)	80–170	120	600	1078	300	300	500	102	331–414	123
Strain at break/failure (%)		80								5.10
Tensile modulus, E_f (GPa)	1.45–2.5	3					50	2		2.47

Note: PET polyester, PP polypropylene, PE polyethylene, *PVA* polyvinyl alcohol, *PC* processed cellulose (derived from processing of wood)

8. Steel fibres are prone to rust and acids. Glass fibres are expensive.
9. Natural fibres lose their strength when subjected to alternate wetting and drying environment. They are environmentally friendly construction materials.
10. What part of the plant the fibres come from, the age of the plant, and how the fibres are isolated are some of the factors which affect the performance of natural fibres in a natural fibre-reinforced soil (Rowell et al. 2000).

Example 2.1
Determine the aspect ratio of the PP fibres if their average length and diameter are 20 mm and 0.05 mm, respectively.

Solution
Given: $L = 20$ mm and $D = 0.05$ mm
From Eq. (2.1), the aspect ratio,

$$a_r = \frac{L}{D} = \frac{20}{0.05} = \mathbf{400}$$

2.3 Phases in a Fibre-Reinforced Soil Mass

Fibres can be considered similar to soil solid particles. Hence, like an unreinforced soil mass, the fibre-reinforced soil mass may be represented by a three-phase system as shown in Fig. 2.7, with fibre and soil solids represented separately. The concept of phase relationships, being adopted widely in soil mechanics (Shukla 2014) and geotechnical engineering (Shukla 2015) for unreinforced soils, can be utilized for developing the phase relationships for fibre-reinforced soils. Some phase relationships for the fibre-reinforced soils are defined below:

Void ratio of the soil mass only,

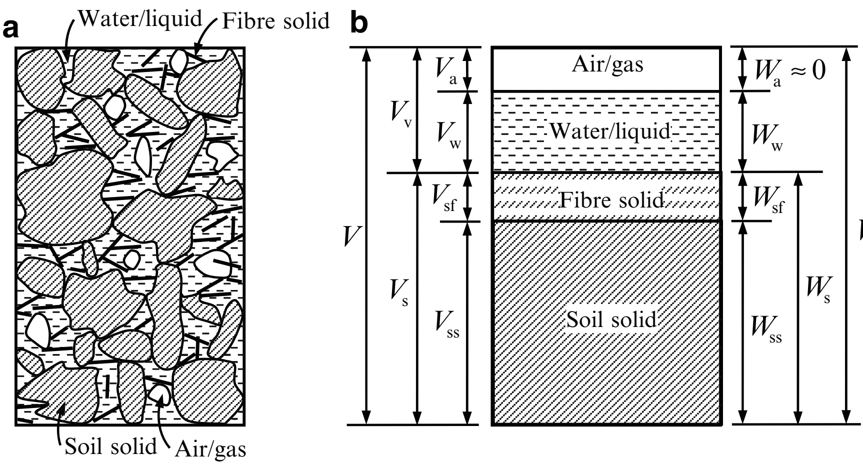


Fig. 2.7 An element of fibre-reinforced soil mass: (**a**) phases in the natural state, (**b**) phases separated for mathematical analysis

$$e_{\mathrm{s}} = \frac{V_{\mathrm{vs}}}{V_{\mathrm{ss}}} \tag{2.2}$$

Void ratio of the fibre mass only,

$$e_{\mathrm{f}} = \frac{V_{\mathrm{vf}}}{V_{\mathrm{sf}}} \tag{2.3}$$

Void ratio of the fibre-reinforced soil mass,

$$e_{\mathrm{R}} = \frac{V_{\mathrm{v}}}{V_{\mathrm{s}}} \tag{2.4}$$

Volume ratio of the fibre-soil solids,

$$V_{\mathrm{r}} = \frac{V_{\mathrm{sf}}}{V_{\mathrm{ss}}} \tag{2.5}$$

where V_{vs} is the volume of soil voids, V_{ss} is the volume of soil solids, V_{vf} is the volume of fibre voids, V_{sf} is the volume of fibre solids, $V_{\mathrm{v}}(=V_{\mathrm{vs}}+V_{\mathrm{vf}}=V_{\mathrm{a}}+V_{\mathrm{w}})$ is the volume of voids of fibre-reinforced soil and $V_{\mathrm{s}}(=V_{\mathrm{ss}}+V_{\mathrm{sf}})$ is the volume of solids of fibre-reinforced soil.

Note that in Fig. 2.7, the subscripts a, w, v and f refer to air, water, void and fibre, respectively. In symbols with dual subscripts, the subscript s when appears first refers to 'solid' but it refers to 'soil mass' when appears as the second subscript.

The following terms are often used to describe the behaviour of fibre-reinforced soils:

Fibre content (a.k.a concentration of fibres or weight ratio or weight fraction or gravimetric fibre content),

$$p_{\mathrm{f}} = \frac{W_{\mathrm{sf}}}{W_{\mathrm{ss}}} \tag{2.6}$$

Fibre area ratio,

$$A_{\mathrm{r}} = \frac{A_{\mathrm{f}}}{A} \tag{2.7}$$

Volumetric fibre content,

$$p_{\mathrm{vf}} = \frac{V_{\mathrm{sf}}}{V} \tag{2.8}$$

where W_{ss} is the weight of soil solids (i.e. dry weight of soil, W_{ds}), W_{sf} is the weight of fibre solids (i.e. dry weight of fibres, W_{df}), A_{f} is the total cross-sectional area of fibres in a plane (e.g. shear/failure plane) of area A within the reinforced soil mass and V is the total volume of the fibre-reinforced soil element.

The following points are worth mentioning:

1. In the denominator of Eq. (2.6), the weight of soil solids is used instead of the weight of fibre-reinforced soil solids for maintaining the consistency with soil mechanics practice as the water content is defined. This practice is often followed in stabilization of soil with admixtures such as cement, lime and fly ash. For example, the cement content p_c in cement-stabilized soil is defined as

$$p_c = \frac{W_{sc}}{W_{ss}} \tag{2.9}$$

where W_{sc} is the weight of cement solids (i.e. dry weight of cement, W_{dc}).
2. In the case of cement-stabilized fibre-reinforced soil, the fibre content may be defined as

$$p_f = \frac{W_{sf}}{W_{ss} + W_{sc}} \tag{2.10}$$

3. The values of p_f, p_{vf}, A_r and p_c are normally expressed as a percentage (%).
4. If the fibres are oriented perpendicular to the failure plane in any specific application, $A_r = p_{vf}$.
5. It is easier to measure p_f than p_{vf}. Hence, for practical purposes, such as preparation of test specimens of fibre-reinforced soil and its field applications, p_f is conveniently used. The use of p_{vf} is often done in modelling of fibre-reinforced soils based on theory of mixtures because the mechanical properties of the composite constituents (soil and fibres), especially when the unit weights of the constituents differ greatly, are governed significantly by the volumetric parameters, and they are not necessarily related to the unit weights (Michalowski and Zhao 1996).

From Eq. (2.8),

$$p_{vf} = \frac{V_{sf}}{V} = \frac{V - (V_{ss} + V_v)}{V} = 1 - \frac{V_{ss} + V_v}{V} = 1 - p_{vs} \tag{2.11}$$

where p_{vs} is the volumetric soil content in fibre-reinforced soil. Thus

$$p_{vs} = \frac{V_{ss} + V_v}{V} \tag{2.12}$$

and

$$p_{vs} + p_{vf} = 1 \tag{2.13}$$

The parameters p_{vs} and p_{vf} are also known as volumetric concentration factors for the soil matrix and fibres, respectively. These factors are used in the development of constitutive models for the fibre-reinforced soil (Ibraim et al. 2010). Note that in the definition of p_{vs}, the volume of voids V_v, excluding the part occupied by the fibres, is considered to be the part of the volume of soil matrix.

Using a mixture rule, the effective stress σ'_R within the fibre-reinforced soil can be divided into soil matrix and fibre matrix components as (Ibraim et al. 2010):

$$\sigma'_R = p_{vs}\sigma' + p_{vf}\sigma'_f \tag{2.14}$$

where σ' is the effective stress of the soil matrix and σ'_f is the effective stress of the fibre matrix. For an unreinforced soil, $p_{vf} = 0$, $p_{vs} = 1$ and $\sigma'_R = \sigma'$, which represents the effective stress for soil only in a conventional way as per the Terzaghi's effective stress concept.

One can develop useful phase interrelationships in view of their practical applications as we do in soil mechanics. Several researchers have considered the phase concept and used specific phase relationships and interrelationships while analysing the behaviour of fibre-reinforced soils as required in their investigations. For example, Maher and Gray (1990) considered fibres to be a part of solid fraction of fibre-reinforced soil with different specific gravity from that of soil solids in their study as considered in Fig. 2.7. Shukla et al. (2015) presented the following phase interrelationships:

$$e_R = \frac{e_s + V_r e_f}{1 + V_r} \tag{2.15}$$

$$V_r = p_f \frac{G}{G_f} \tag{2.16}$$

$$e_R = \frac{G_R \gamma_w}{\gamma_{dR}} - 1 \tag{2.17}$$

$$G_R = (1 + p_f)\left(\frac{1}{G} + \frac{p_f}{G_f}\right)^{-1} \tag{2.18}$$

where γ_w is the unit weight of water, G is the specific gravity of soil solids, G_f is the specific gravity of fibre solids, G_R is the specific gravity of fibre-reinforced soil solids and γ_{dR} is the dry unit weight of fibre-reinforced soil.

Referring to Fig. 2.7, the expression for γ_{dR} is given as

$$\gamma_{dR} = \frac{W_{sf} + W_{ss}}{V} = \frac{W_s}{V} \tag{2.19}$$

From Eqs. (2.6), (2.8) and (2.19),

$$p_{\mathrm{vf}} = \frac{p_{\mathrm{f}}\gamma_{\mathrm{dR}}}{(1+p_{\mathrm{f}})G_{\mathrm{f}}\gamma_{\mathrm{w}}} \tag{2.20}$$

or

$$p_{\mathrm{f}} = \frac{G_{\mathrm{f}}\gamma_{\mathrm{w}}p_{\mathrm{vf}}}{\gamma_{\mathrm{dR}} - G_{\mathrm{f}}\gamma_{\mathrm{w}}p_{\mathrm{vf}}} = \frac{1}{\frac{\gamma_{\mathrm{dR}}}{G_{\mathrm{f}}\gamma_{\mathrm{w}}p_{\mathrm{vf}}} - 1} \tag{2.21}$$

Using Eqs. (2.17) and (2.18), Eq. (2.20) becomes

$$p_{\mathrm{f}} = \frac{(1+e_{\mathrm{R}})G_{\mathrm{f}}p_{\mathrm{vf}}}{G[1-(1+e_{\mathrm{R}})p_{\mathrm{vf}}]} \tag{2.22}$$

Example 2.2
Derive the expressions given in Eq. (2.15) and (2.16).

Solution
Derivation of Equation (2.15):

$$e_{\mathrm{R}} = \frac{V_{\mathrm{v}}}{V_{\mathrm{s}}}$$

(using Eq. (2.4))

$$= \frac{V_{\mathrm{vs}} + V_{\mathrm{vf}}}{V_{\mathrm{ss}} + V_{sf}}$$

(Void volume occupied by air and/or water may be considered to be contributed by soil solids and fibre solids separately.)

$$= \frac{\frac{V_{\mathrm{vs}}}{V_{\mathrm{ss}}} + \frac{V_{\mathrm{sf}}}{V_{\mathrm{ss}}} \times \frac{V_{\mathrm{vf}}}{V_{\mathrm{sf}}}}{1 + \frac{V_{\mathrm{sf}}}{V_{\mathrm{ss}}}}$$

(dividing numerator and denominator by V_{ss})

$$= \frac{e_{\mathrm{s}} + V_{\mathrm{r}}e_{\mathrm{f}}}{1 + V_{\mathrm{r}}}$$

(using Eqs. (2.2), (2.3) and (2.5))

Derivation of Equation (2.16):

$$V_{\mathrm{r}} = \frac{V_{\mathrm{sf}}}{V_{\mathrm{ss}}}$$

(using Eq. (2.5))

$$= \frac{(W_{sf}/\gamma_w G_f)}{(W_{ss}/\gamma_w G)}$$

$$\left(\because G = \frac{W_{ss}/V_{ss}}{\gamma_w} \text{ and } G_f = \frac{W_{sf}/V_{sf}}{\gamma_w}\right)$$

$$= \frac{W_{sf} G}{W_{ss} G_f}$$

$$= p_f \frac{G}{G_f}$$

(using Eq. (2.6))

Example 2.3
If a clayey soil is reinforced with 1.25% of PET fibres, determine the specific gravity of the fibre-reinforced soil. Assume the specific gravity values for soil solids and fibre solids are 2.70 and 1.3, respectively.

Solution
Given: $p_f = 1.25\%$, $G = 2.70$, and $G_f = 1.3$
From Eq. (2.18), the specific gravity of fibre-reinforced soil is

$$G_R = (1 + p_f)\left(\frac{1}{G} + \frac{p_f}{G_f}\right)^{-1} = (1 + 0.0125)\left(\frac{1}{2.70} + \frac{0.0125}{1.3}\right)^{-1} = 2.66$$

Note that the phase relationships and interrelationships, as presented here, are fairly of general nature and can be utilized in several applications of fibre-reinforced soils in a way similar to that traditionally used in soil mechanics and geotechnical engineering for the analysis of unreinforced soils. Based on the laboratory experiments, Shukla et al. (2015) presented the variation of void ratio e_R of the fibre-reinforced sand with logarithm of $(100V_r + 1)$, as shown in Fig. 2.8, with the following empirical expression:

$$e_R = a\ln(100V_r + 1) + b \tag{2.23}$$

where $a = 0.0333$ is the slope of the linear relationship and represents the type of fibre used (i.e. virgin homopolymer polypropylene) and $b = 0.4913$ is the value of e_R at $V_r = 0$ and represents the type of sand used (i.e. poorly graded silica sand). For other types of fibre and/or sand, a and b can be obtained from the data obtained from a minimum of four compaction tests on the fibre-reinforced soil at hand from which the measured values of V_r and the corresponding e_R can be calculated and used to determine a and b, then the equation similar to Eq. (2.23) can be used for future prediction of the void ratio of the specific fibre-reinforced soil.

The coefficient of determination R^2 of the correlation in Eq. (2.23) is 0.9935. Note that R^2 is an index of the reliability of the relationship. A regression equation

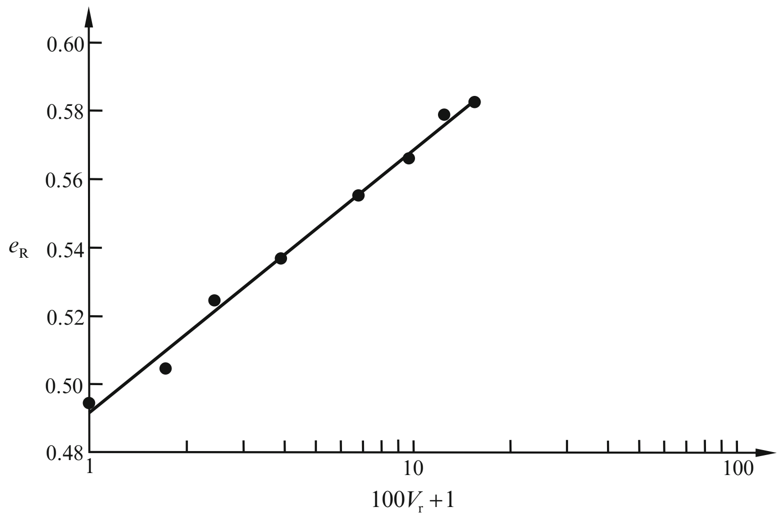


Fig. 2.8 Variation of void ratio e_R of the fibre-reinforced sand with logarithm of $(100\,V_r + 1)$ (Adapted from Shukla et al. 2015)

that lies close to all the observation points gives a higher value of R^2. The maximum value of R^2 is unity. A suitable numerical software package, such as MATLAB, is generally used for developing the statistical relationships between two or more variables. Such relationships are called the statistical or regression models. A few more regression models are presented in Chap. 4.

It is expected that the researchers may carry out experimental studies with several types of fibre and soil and also with cemented fibre-reinforced soils to compare their results with the phase relationships as presented here and also develop similar new expressions as required for their use by practicing engineers.

2.4 Soil Reinforced with Continuous Fibres and Multioriented Inclusions

The soil can be reinforced randomly with continuous fibres or multioriented (3-dimensional, 3D) inclusions. Some studies are available for such reinforced soils.

The sand reinforced with continuous synthetic (PET, PP, etc.) fibres/threads was originally conceived by Laboratoire Central des Ponts et Chaussees (LCPC) and registered as *Texsol* (Leflaive 1982). To obtain the soil reinforced with continuous fibres, a number of threads are pneumatically or hydraulically projected on sand in a movement at the extremity of a conveyor belt or at the vent of a pipe used to build a hydraulic fill at the construction site. A special machine was designed to produce up to 20 m^3/h of Texsol with the use of about 100 km/m^3 of thread, projected simultaneously from 50 bobbins at the speed of 10 m/s (Leflaive et al. 1983; Prisco and Nova 1993).

In the thread-reinforced soil, the sand particles and threads are closely connected because of friction between them, and hence the threads react in tension to any extensional deformation caused by loading, thus giving an artificial confinement to sand. As a consequence, both strength and stiffness of sand in the presence of threads increase (Prisco and Nova 1993). The fibre content typically varies between 0.1 and 0.2%. The triaxial compression tests on thread-reinforced sand shows that significant cohesions of the order of 200 kPa for 0.2% fibre content by weight of sand may result. The angle of internal friction of reinforced sand is, however, essentially the same as that of unreinforced sand. Note that the way in which such a material is put in place gives the reinforced soil an ordered structure, so that the measured cohesion and friction angle vary with the orientation of the bedding plane with respect to the principal axes of stress (Leflaive and Liausu 1986; Prisco and Nova 1993). Failure normally occurs at strains larger than those of unreinforced sand. Thus, the thread-reinforced soil is more ductile than sand and can be considered essentially as a cemented soil. To achieve the full strength of thread-reinforced soil, significant strains and consequently significant deformations may take place; this may not be a desirable characteristic for some applications, such as the use of thread-reinforced soil to support structural loads as a foundation bed. The design of structures constructed with thread-reinforced soils can be based on limit equilibrium methods when the strains/deformations are limited. Numerical and constitutive models have also been presented for the analysis of such reinforced soils (Villard and Jouve 1989; Prisco and Nova 1993).

In the past, thread-reinforced sandy soils have been used for constructing earth retaining walls, particularly on soft compressible soils, with facing slope angles as high as 75°, filter or drain resistant to erosion, embankments with steep slopes, foundation beds over compressible soils and explosion-resistant facilities in civil and military installations for storage of explosives and liquefied gas. Thread-reinforced soils are also used for slope stabilization works (Leflaive 1985; Khay et al. 1990; Ishizaki et al. 1992). The thread-reinforced soils provide a suitable environment for vegetation to grow on the reinforced soil structures, and they are also effective to resist dynamic loads.

The soil can be strengthened by inclusion of multioriented/3D geosynthetic elements (termed jacks) within or upon a compacted or naturally deposited granular soil (Lawton and Fox 1992; Lawton et al. 1993). These elements can be oriented randomly within a compacted soil mass by mixing them with soil prior to compaction; placed in layers on lifts of loose soil, compacted soil or naturally deposited soil layer; or placed in a layer on the surface of a naturally deposited soil or compacted fill and pressed into the soil by compaction. 3D elements can also be used as lightweight, highly porous artificial soil.

A large number of 3D elements of different sizes and shapes are available, and they can also be designed to meet specific requirements of the project. Lawton et al. (1993) used five types of 3D inclusions in their research. All 3D elements consisted of six stems extending radially from a central hub, with enlarged heads on four of the stems, but they differed in material and manufacturing process. Both layered and random oriented inclusions are effective in strengthening and/or stiffening the granular soil under certain conditions. Increases in deviator stress at failure as large as above 100% can be determined in triaxial tests. Additional details about behaviour of soils with 3D inclusions can be found in the works of Zhang et al. (2006) and Harikumar et al. (2016).

Chapter Summary

1. A *fibre* is a unit of matter characterized by flexibility, fineness and a high ratio of length to thickness (or diameter). In general, the fibre is a general term that refers to all filaments, yarns, staples, bristles/hairs, buffings, chips, crumbs and other similar highly flexible entities.
2. Fibres available for use in construction can be classified as natural fibres (e.g. coir fibres, jute fibres, etc.), synthetic fibres (e.g. polypropylene fibres, polyester fibres, etc.) and waste fibres (old/used tyre fibres, used plastic fibres, etc.).
3. The PP fibres have been widely used in experimental investigations of fibre-reinforced soils. The primary attraction is that of low cost.
4. In the fibre industry, the fibres are also described in terms of linear mass density (kg/m), which is generally expressed in denier (grams per 9 km of the fibre) or tex (grams per 1 km of the fibre).
5. An element of fibre-reinforced soil can be represented as a three-phase system consisting of solid, liquid and gas phases.
6. Fibre aspect ratio, fibre content, fibre area ratio and volumetric fibre content are commonly used parameters in the fibre-reinforced soil engineering.
7. There are several phase relationships and interrelationships for their use in analysis of fibre-reinforced soils.
8. The volume ratio of fibre-soil solid is uniquely related to the void ratio of the fibre-reinforced soil.
9. Texsol is a continuous thread-reinforced soil mass, generally created at the construction site, as a homogeneous construction material by mixing sand and threads in a highly specialized manner for construction of retaining walls and some other structures.
10. Soil can be improved by 3D inclusions of different shapes and sizes as per the requirement of the specific project.

Questions for Practice

(Select the most appropriate answer to the multiple-choice questions from Q 2.1 to Q 2.5.)

2.1 The specific gravity of glass fibres is
(a) 0.91
(b) 0.99
(c) 1.38
(d) 1.7

2.2 A 90-denier filament has a weight of
(a) 1 g/km
(b) 9 g/km
(c) 10 g/km
(d) 90 g/km

2.3 The ratio of length of a fibre to its average diameter is called
(a) Fibre content
(b) Fibre aspect ratio
(c) Fibre area ratio
(d) Volumetric fibre content

2.4 Which one of the following can be measured easily?
(a) Volumetric fibre content and aspect ratio
(b) Fibre content and volumetric fibre content
(c) Fibre content and aspect ratio
(d) Fibre content, volumetric fibre content and aspect ratio

2.5 In soil reinforced with continuous fibres, the fibre content typically varies between
(a) 0.1% and 0.2%
(b) 0.5% and 1%
(c) 1% and 2%
(d) 2% and 4%

2.6 Classify the available fibres on the basis of their sources.
2.7 What are the favourable and unfavourable characteristics of natural fibres?
2.8 Polypropylene (PP) fibres have been used widely for reinforcing soil in research works. Can you explain the reasons?
2.9 Compare the resistances of PP and PET fibres against the following: UV light, acids, alkalis and heat.
2.10 Compare the specific gravity values of different fibres.
2.11 Define the following: fibre content, aspect ratio and area ratio.
2.12 How is cement content in cement-stabilized soils defined? What are the two different ways of defining fibre content in cement-stabilized soils?
2.13 Develop a relationship between volumetric soil content and volumetric fibre content.
2.14 Write an expression for the effective stress within a fibre-reinforced soil mass.
2.15 Derive the following expressions in which the symbols have their usual meanings:

$$\text{(a)} \quad e_R = \frac{G_R \gamma_w}{\gamma_{dR}} - 1$$

$$\text{(b)} \quad G_R = (1 + p_f)\left(\frac{1}{G} + \frac{p_f}{G_f}\right)^{-1}$$

2.16 If a sandy soil is reinforced with 1% of PP fibres, determine the specific gravity of the fibre-reinforced soil. Assume the specific gravity values for soil solids and fibre solids are 2.65 and 0.91, respectively.

2.17 For a fibre-reinforced soil, the following details are available:

Fibre content, $p_f = 0.75\%$
Specific gravity of soil solids, $G = 2.66$
Specific gravity of fibre solids, $G_f = 0.99$
Determine the volume ratio of fibre-soil solids, V_r.

2.18 For a PP fibre-reinforced poorly graded sand, compacted at its maximum dry unit weight, the volume ratio of fibre-soil solids, $V_r = 5\%$. Estimate the void ratio of fibre-reinforced sand.

2.19 What is Texsol? List its different applications. Do you expect any difficulty in construction?

2.20 Collect the information about different multidirectional inclusions, which are available in your local area, for soil improvement purpose. How do these inclusions differ from short, discrete fibres?

Answers to Selected Questions

2.1 (d)
2.2 (c)
2.3 (b)
2.4 (c)
2.5 (a)
2.16 2.60
2.17 2%
2.18 0.545

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