Chapter 5
Applications of Fibre-Reinforced Soil

5.1 Introduction

In the previous chapters, you studied about the basic characteristics of soils and fibres, engineering behaviour of fibre-reinforced soils with or without other admixtures/additives (lime, cement, fly ash, etc.) and reinforcing mechanisms and models. In most applications, the discrete fibres are simply added and mixed randomly with soil or other similar materials (coal ashes, mine tailings, etc.), in much the same way as lime, cement or other additives are used to stabilize and improve the soil. However, some difficulties occur at the construction site in getting a uniform mixture of soil and fibres. In the present-day construction practice, the use of fibres is one of the cost-effective and environmentally friendly ground improvement techniques. This chapter describes the possible field applications of fibre-reinforced soils, focusing on presenting specific application/construction guidelines.

5.2 Field Applications

Reinforcing the soil with discrete fibres is a ground improvement technique that has not yet been fully utilized worldwide as this technique can be adopted in the present-day engineering practice. This is probably because of unavailability of standards and codes of practice, especially in developing countries. In comparison with the systematically reinforced soils (i.e. soils with oriented reinforcements such as the geosynthetic-reinforced soils), the randomly distributed/oriented fibre-reinforced soils exhibit some advantages, as listed below:

1. Preparation of randomly distributed fibre-reinforced soils mimics the conventional/traditional soil stabilization techniques, which uses the admixtures, such as lime, cement, fly ash, etc. Hence, the field application or construction

S.K. Shukla, *Fundamentals of Fibre-Reinforced Soil Engineering*,
Developments in Geotechnical Engineering, DOI 10.1007/978-981-10-3063-5_5

procedure may be similar to that adopted for conventional soil stabilization techniques.

2. Addition of fibre reinforcement in soil causes a significant improvement in strength and stiffness, although a decrease in stiffness may take place as reported in some studies.
3. Fibre-reinforced soil exhibits greater toughness and ductility and smaller losses of post-peak strength as compared to soil alone.
4. Addition of fibres improves the permeability and compressibility/swelling characteristics of soils.
5. Inclusion of fibres improves the load-carrying capacity of soils.
6. Addition of fibres significantly decreases the liquefaction potential of coarse silts and fine sands.
7. Randomly distributed fibres with even orientations in all directions offer a better isotropy in strength or other properties and limit the potential planes of weakness that can develop parallel to the oriented reinforcement as included in a systematically reinforced soil.
8. Before the failure takes place, because of greater extensibility characteristics of fibre-reinforced soils, one can notice large strains/deformations in the fibre-reinforced soil structures, and hence, suitable corrective measures may be taken easily within the available time.
9. Fibre-reinforced soil can facilitate reinforcement of geoenvironmental barriers where continuous/systematic reinforcements may result in a preferential pathway for contaminant migrations.
10. Traditional planar reinforcements, such as geosynthetic reinforcements, when used in slopes and other such irregular sections, need anchorage and excavation into the slope, and there is a possibility of failures in addition to difficulty in placement. The use of fibre reinforcement in these applications provides a flexible solution.
11. Compared to the geosynthetic reinforcements, the fibre reinforcement can be used in a limited space, especially for the stabilization of failed soil slopes.
12. The use of fibre reinforcement can result in economical solutions because fibres have lower cost, and at some construction sites, they may be available freely as geonaturals or waste materials, such as old tyres and plastics.

In view of several advantages and favourable characteristics, the fibre-reinforced soils have a great potential for their applications in several areas, and they are now recognized as a viable ground improvement technique. The key applications are the following:

- *Geotechnical applications*: backfills behind the retaining structures; stabilization of soils beneath the footings and rafts; stabilization of failed soil slopes; construction of embankments using marginal soils, and over weak soils, such as organic soft soil deposits; lightweight fill materials; admixtures in fine sands and silts to increase the resistance to liquefaction; and strengthening the granular piles and trenches
- *Transportation applications*: pavement subgrades, subbases and bases, especially for low-volume roads; drainage layers for roads, runways, playgrounds, etc.; thermal insulator for limiting the frost penetration; and vibration damping layers beneath railway tracks

- *Hydraulic and geoenvironmental applications*: admixtures in soil to control the hydraulic conductivity; improving the soil resistance against water and wind erosion; stabilization of thin soil veneers, landfill liners and final covers; admixtures for mitigating the formation of shrinkage/desiccation cracks in compacted clays; controlling seepage and preventing the piping erosion in dams and other water-retaining structures (river levees, contour bunds, canal diversion works, check dams, etc.); leachate collection systems; and geotextile tube dewatering applications

In reinforcement applications, the fibres are generally most effective when oriented within the soil mass in the same direction as the tensile strains caused by the applied loads. Hence, for any particular loading condition, the properties of fibre-reinforced soil depend significantly on the orientation of fibres with respect to the loading direction.

In the laboratory testing and the field/practical applications, the distribution of fibres can usually be characterized by a preferred plane of fibre orientation (Michalowski and Cermak 2002; Diambra et al. 2007). The orientation of fibres depends on the following:

- Method of mixing of soil with fibres
- Specimen preparation method for tests
- Method of field placement

The laboratory test specimens are prepared in two stages, namely, mixing and compaction. Water, as required, is added to the dry soil, and then mixed together uniformly, followed by adding the fibres to the wet soil and mixing in order to have the even distribution of fibres. The test specimens in the desired test mould are prepared by one of the following techniques (Michalowski and Cermak 2002; Diambra et al. 2010; Ibraim et al. 2012):

- Tamping technique: the soil-fibre mix is compacted in specific number of layers by tamping with a rammer having a flat base.
- Vibration technique: the soil-fibre mix is densified by vibrating the test mould filled with the soil-fibre mix on a vibration table.

Tamping and vibration techniques for preparing the fibre-reinforced soil specimens in moist conditions lead to a preferred near-horizontal orientation of fibres. Both techniques leave at least 80% of the fibres oriented between ± 30° of horizontal, and 97% of fibres have an orientation that lies within ± 45° of the horizontal plane. These techniques generally produce a soil fabric/structure that resembles that of the rolled-compacted construction fills (Diambra et al. 2010; Ibraim et al. 2012). Hence, inclusion of fibres in soil in the field application may not result in isotropic properties of fibre-reinforced soil as generally considered, and hence the use of some simplified isotropic models, as discussed in Chap. 4, may not result in accurate predictions of the benefits attributed to fibres. For cases where the predominant load is perpendicular to the preferred plane of fibre orientation, the isotropic models, in general, under-predict the benefits from the fibres (Michalowski and Cermak 2002).

As there are several factors affecting the engineering characteristics of fibre-reinforced soil (see Sect. 3.2), the selection of fibres for any specific application may not be an easy task. In spite of the fact that a significant amount of research has been carried out worldwide, there is currently no scientific standard or code of practice on fibre-reinforced soils and their applications. Typically, the selection should consider the following (Hoover et al. 1982):

1. Survivability of the fibres within the soil mass with consideration of varying nature of the soil-water system in regard to alkalinity, chemical composition, temperature and environmental variations
2. Range of required mechanical properties of the fibres
3. Availability of fibres in length range required for the specific application
4. Potential inability to properly incorporate fibres into the soil to a random state of orientation
5. Procurement cost of fibres

5.3 Analysis and Design Concepts

In Chap. 3, you learnt that the engineering behaviour of fibre-reinforced soil is governed by a large number of factors/parameters. As described in Chap. 4, attempts have been made to idealize the behaviour of fibre-reinforced soil, and several models are now available to predict the specific engineering behaviour of fibre-reinforced soil. However, it is difficult to suggest sound and rational design methods for specific applications of fibre-reinforced soil as listed in the previous section. Section 5.4 discusses the experience gained in some specific applications and provides several application guidelines. Analysis and design concepts relating the basic characteristics of fibre-reinforced soils for some field applications are presented in this section. The actual design of the structure can be carried out in a conventional way, considering the fibre-reinforced soil as one of the materials used for the construction of a specific structure. For the final analysis and design of a structure being constructed with fibre-reinforced soil, if possible, a suitable field test should be carried out based on the detailed laboratory findings and observations of the behaviour of fibre-reinforced soil.

Design of fibre-reinforced soil structures can be carried out by adopting one of the following two approaches:

1. *Composite approach:* The fibre-reinforced soil structure is analysed in a traditional way, considering the engineering properties of fibre-reinforced soil as a homogeneous material. It is based on the fact that inclusion of fibres contributes to stability due to an increase in shear strength of the homogenized composite reinforced soil mass, although the reinforcing fibres actually work in tension and not in shear. The contribution of the fibres is typically quantified by an equivalent cohesion intercept and angle of internal friction angle of the soil. Several composite models, following different approaches (e.g. mechanical, statistical, energy based, etc.) have been proposed as they are presented in Chap. 4.

2. *Discrete approach:* The fibre-reinforced soil structure is analysed, considering the contributions of soil and fibres separately (Zornberg 2002). Under shearing caused by applied load, the fibre reinforcement contributes to the increase of shear resistance of soil by mobilizing the tensile stresses within the fibres. The analysis requires independent testing of soil and of fibres, but not of fibre-reinforced soil. The results obtained are more realistic. Additionally the fibres can be optimized in terms of their quality, content, aspect ratio, etc. for delivering the cost-effective designs. The fibre-induced distributed tension, σ_R, to be used in this design approach to account for the tensile contribution of the fibres in limit equilibrium analysis is taken as a minimum of σ_{RP} and σ_{Rt} as they are discussed in Chap. 4 for fibre pullout and fibre breakage cases, respectively.

In the current design practice, the fibre-reinforced soil structures are often designed by discrete approach as the most geosynthetic-reinforced soil structures are routinely designed based on working stress design method or limit state design method. Note that the fibres, being flexible, may not remain straight and they may get folded several times randomly within the specimen. It is difficult to consider this situation exactly while analyzing the behaviour of fibre-reinforced soils by discrete approach. Hence, some designers may prefer to design the fibre-reinforced soil by adopting the composite approach, especially when the fibres of relatively higher lengths are used.

In discrete approach, there is a need to properly consider the interfacial interaction of fibres with soil particles through adhesion and/or friction. Studies may be conducted to determine the ratio of adhesion to soil cohesion intercept and also for the ratio of angle of skin friction to angle of internal friction of soil as these factors are determined between soils and other construction materials (Potyondy 1961).

It is important to note that the long fibre-reinforced soils perform well when the application of loading direction and magnitude is known. When the load and its direction are not known, short, discrete, randomly distributed/oriented fibre-reinforced soil may be preferred. The basic principles of reinforcement design are the same for systematically reinforced soil and randomly distributed fibre-reinforced soils, except that suitable reduction factors should be applied in the case of randomly distributed fibre-reinforced soil. In the reinforced soil, only the reinforcements aligned normal to the applied stress, carry any stress. In randomly distributed fibre-reinforced soils, some fibres do not carry any stress at all, and this should be accounted for by *strength reduction factors*, more commonly termed the *efficiency factors* (Hoover et al. 1982).

Achieving a uniform distribution of fibres at the construction site is generally a difficult task. The poor distribution of fibres within the soil mass in the field application may not result in the design property as expected based on the laboratory tests that may have a uniform distribution of fibres in test specimens. If the distribution of fibres is not uniform, the laboratory property value should be adjusted suitably by applying a factor of safety. In the case of strength property, for considering the uncertainty induced by non-uniform fibre distribution, the design strength of fibre-reinforced soil should be reduced to a value lower than the laboratory strength.

Michalowski (2008) presented the limit analysis of anisotropic fibre-reinfroced soil, and considering the ellipsoidal distribution of fibres, defined a term as *distribution ratio* p_r varying practically between 0 and 1. If the fibre-reinforced soil behaves as an isotropic material, p_r equals 1. The kinematic approach of limit analysis was used to present the values of active earth pressure coefficient K_a and the bearing capacity factor N_γ as given in Tables 5.1 and 5.2, respectively. The total active earth pressure P_a against a rough vertical wall from the fibre-reinforced cohesionless soil backfill (Fig. 5.1) and load-bearing capacity (average stress)

Table 5.1 Active earth pressure coefficient $K_a$for a rough vertical wall with fibre-reinforced cohesionless soil backfill

ϕ (degrees)	δ (degrees)	$a_r p_{vf} \tan \phi_i$	p_r	K_a
30	15	0	–	0.301
		0.2	1.0	0.271
			0.5	0.260
			0.2	0.245
		0.4	1.0	0.242
			0.5	0.221
			0.2	0.193
		0.6	1.0	0.215
			0.5	0.184
			0.2	0.145
35	15	0	–	0.248
		0.2	1.0	0.218
			0.5	0.207
			0.2	0.192
		0.4	1.0	0.189
			0.5	0.168
			0.2	0.141
		0.6	1.0	0.162
			0.5	0.131
			0.2	0.094
40	15	0	–	0.201
		0.2	1.0	0.171
			0.5	0.160
			0.2	0.146
		0.4	1.0	0.142
			0.5	0.121
			0.2	0.096
		0.6	1.0	0.115
			0.5	0.085
			0.2	0.048

After Michalowski (2008)

Note: ϕ is the angle of internal friction of soil, δ is the soil-wall interface friction angle, ϕ_i is the fibre-soil interface friction angle, a_r is the aspect ratio of fibres. and p_{vf} is the volumetric fibre content

Table 5.2 Bearing capacity factor N_γ for fibre-reinforced cohesionless foundation soil

ϕ(degrees)	$a_r p_{vf} \tan \phi_i$	p_r	N_γ
30	0	–	21.394
	0.2	1.0	33.239
		0.5	35.775
		0.2	39.598
	0.4	1.0	53.301
		0.5	62.636
		0.2	79.380
35	0	–	48.681
	0.2	1.0	84.305
		0.5	92.280
		0.2	104.612
	0.4	1.0	155.559
		0.5	191.827
		0.2	263.931
40	0	–	118.826
	0.2	1.0	241.893
		0.5	272.732
		0.2	321.365
	0.4	1.0	561.436
		0.5	755.590
		0.2	1207.296

After Michalowski (2008)

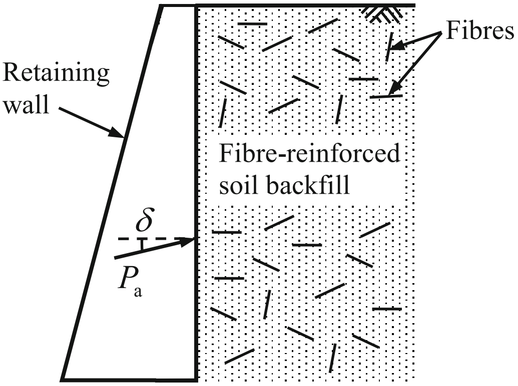

Fig. 5.1 A retaining wall with a vertical back face supporting a fibre-reinforced cohesionless soil backfill

q_a of a strip footing resting over fibre-reinforced cohesionless foundation soil (Fig. 5.2) can be determined using the following expressions along with the values of K_a and N_γ from Tables 5.1 and 5.2, respectively:

$$P_a = \frac{1}{2} K_a \gamma H^2 \tag{5.1}$$

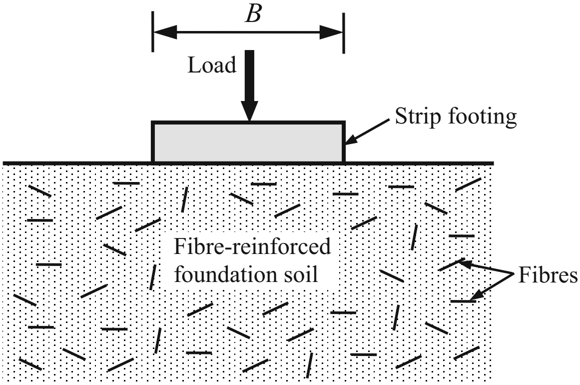

Fig. 5.2 A strip footing resting on a fibre-reinforced cohesionless foundation soil

where γ is the total unit weight of fibre-reinforced backfill and H is the height of the retaining wall.

$$q_a = \frac{1}{2}\gamma B N_\gamma \tag{5.2}$$

where γ the total unit weight of fibre-reinforced foundation soil and B is the width of the strip footing.

Note that P_a is inclined at an angle δ to the normal to the vertical back of the wall because the analysis has considered a rough vertical wall.

The following points are worth mentioning:

1. Addition of fibres to the soil backfill reduces the active earth pressure coefficient K_a and hence the total lateral earth pressure P_a on the wall.
2. The value of P_a decreases with an increase of the concentration of fibres in the backfill, but it is also affected by the distribution of fibre orientation. The near-horizontal-preferred orientations contribute significantly to the reduction of P_a.
3. As the internal friction of sand is increased with the addition of fibres, the bearing capacity factor N_γ also increases. The anisotropic distribution of fibre orientation contributes further to this increase; that is, the distribution of fibres with the horizontal preferred plane benefits the bearing capacity more than the isotropic distribution.

Example 5.1

For a fibre-reinforced sand backfill supported by an 8-m high retaining wall with a vertical back face, consider the following:

Angle of internal friction of sand, $\phi = 30^\circ$
Total unit weight of fibre-reinforced sand, $\gamma = 15.61$ kN/m^3
Fibre-reinforced soil-wall interface friction angle, $\delta = 15^\circ$

Fibre-soil interface friction angle, $\phi_i = 20^\circ$
Fibre aspect ratio, $a_\mathrm{r} = 75$
Volumetric fibre content, $p_\mathrm{vf} = 1\%$

Determine the total active earth pressure from the fibre-reinforced sand backfill on the retaining wall, assuming the fibre-reinforced sand behaves as an isotropic material.

Solution
As the fibre-reinforced sand behaves as an isotropic material, the distribution ratio,

$$p_\mathrm{r} = 1$$

Using the given values,

$$a_\mathrm{r} p_\mathrm{vf} \tan\phi_i = (75)(0.01)(\tan 20^\circ) = 0.273$$

From Table 5.1, the active earth pressure coefficient,

$$K_\mathrm{a} = 0.271 - \left(\frac{0.271 - 0.242}{0.4 - 0.2}\right)(0.273 - 0.2) = 0.260$$

From Eq. (5.1), the total active earth pressure from the fibre-reinforced sand backfill,

$$P_\mathrm{a} = \frac{1}{2} K_\mathrm{a} \gamma H^2 = \left(\frac{1}{2}\right)(0.260)(15.61)(8)^2 = \mathbf{129.9\ \ kN/m}$$

Example 5.2
For a fibre-reinforced foundation sand bed supported by a 1-m wide surface strip footing, consider the following:

Angle of internal friction of sand, $\phi = 30^\circ$
Total unit weight of fibre-reinforced sand, $\gamma = 15.61\ \ \mathrm{kN/m^3}$
Fibre-reinforced soil-wall interface friction angle, $\delta = 15^\circ$
Fibre-soil interface friction angle, $\phi_i = 20^\circ$
Fibre aspect ratio, $a_\mathrm{r} = 75$
Volumetric fibre content, $p_\mathrm{vf} = 1\%$

Determine load-bearing capacity of the surface strip footing resting over the fibre-reinforced sand bed, assuming the fibre-reinforced sand behaves as an isotropic material.

Solution

As the fibre-reinforced sand behaves as an isotropic material, the distribution ratio,

$$p_{\mathrm{r}} = 1$$

Using the given values,

$$a_{\mathrm{r}} p_{\mathrm{vf}} \tan \phi_i = (75)(0.01)(\tan 20^\circ) = 0.273$$

From Table 5.2, the bearing capacity factor,

$$N_\gamma = 33.239 + \left(\frac{53.301 - 33.239}{0.4 - 0.2}\right)(0.273 - 0.2) = 40.56$$

From Eq. (5.2), load-bearing capacity of the surface strip footing resting over the fibre-reinforced sand bed,

$$q_{\mathrm{a}} = \frac{1}{2}\gamma B N_\gamma = \left(\frac{1}{2}\right)(15.61)(1)(40.56) = \mathbf{316.6\ \ kPa}$$

The overall stability of a shallow foundation constructed over the weak foundation soil can be significantly improved by placing a compacted cement-stabilized fibre-reinforced soil layer of a suitable thickness (say 0.3*B*, where *B* being the width of the footing) over the weak foundation soil as shown in Fig. 5.3. The thickness may be decided based on the plate load test. The ultimate load-bearing capacity of this layered soil system can be estimated using the analytical methods proposed by Vesic (1975) and Mayerhof and Hanna (1978). The later considers a punching failure along the footing perimeter. Consoli et al. (2003) have reported that Vesic's method significantly overestimates the bearing capacity of the footing resting on the layered system, while Meyerhof and Hanna's method underestimates it. A research is required to develop an appropriate bearing capacity equation for determining the bearing capacity of footings resting on cement-stabilized fibre-reinforced soil layer over the weak foundation soil.

Note that for the field situation shown in Fig. 5.3, if required, a geosynthetic reinforcement layer (woven geotextile or geogrid layer) can be installed at the interface of the cement-stabilized fibre-reinforced soil layer and the weak foundation soil for having additional reinforcement benefits. At several construction sites, the fibre-reinforced foundation soil with or without geosynthetic reinforcement may be technically feasible for supporting the structural loads, and additionally they may have the following advantages:

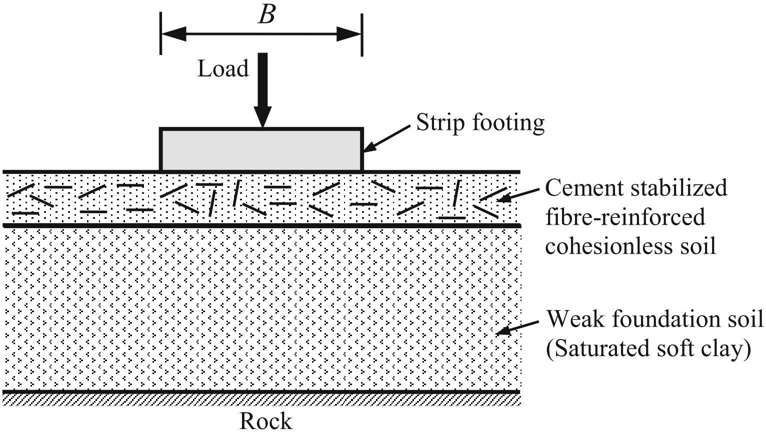

Fig. 5.3 A strip footing resting on a cement-stabilized fibre-reinforced cohesionless soil layer over a weak foundation soil stratum

1. The use of fibres from the waste materials, such as old/used tyres and used plastic materials, in large quantities, whose presence causes environmental problems and their safe disposal in engineered landfills costs significantly
2. Reduced foundation cost compared to the cost of deep foundations, such as piles that carry the loads and transfer them to the rock bed or firm stratum underlying the weak foundation soil

Young's modulus is often the dominant parameter for the design of shallow foundations. Although the fibre-reinforced soil is more compressible than unreinforced soil, it still complies with the stiffness requirements for several applications (50–120 MPa), namely, shallow foundations, subgrade, capping or subbase layers. This compliance means that the fibre-reinforced soil is a suitable material for construction of these structures. In fact, a reinforced soil exhibits a suitable bearing capacity and trafficking under the heavy construction machines. Driving passes of the motor scraper in the close proximity to the borders of fibre-reinforced embankment confirm the good quality of the reinforced soil as a construction material (Falorca et al. 2011).

Design of fibre-reinforced granular pavement layers requires evaluation of fibre-reinforced granular materials by the trafficability test, simulating the conditions of repetitive traffic loading and adverse environment. Details of the test and findings in terms of variation of average rut depths with number of load cycles are presented by Hoover et al. (1982) for some fibre-reinforced soils. The findings show that the inclusion of fibres improves the vertical load stability and prevents lateral shear and/or displacement for a greater number of load cycles when compared to the behaviour of unreinforced soil. Further improvement of stability, compressive characteristics, ductility and control of cracking through brittle failure can be obtained through addition of cement or lime, mainly due to improved soil-fibre interfacial bonding. The crimped PP fibres are found to be most effective in improving the engineering characteristics of soil. The scanning electron microscopy shows that the straight PP fibres exhibit severe surficial damage after compaction and testing, and the glass fibres appear undamaged.

Benefits of reinforcing the pavement layers (subgrade, subbase course and/or base course) with fibres (or other reinforcement types) are generally expressed in terms of an extension of service life of the pavement and/or a reduction in the thickness of pavement layer. An extension of service life of the pavement is typically expressed in terms of the *traffic benefit ratio* (*TBR*), which is defined as follows (Perkins and Edens 2002):

$$TBR = \frac{N_{\mathrm{R}}}{N_{\mathrm{U}}} \tag{5.3}$$

where N is the number of traffic loads/passes required for producing a pavement surface deformation (i.e. rutting) up to the allowable rut depth for the pavement and the symbols U and R denote unreinforced and reinforced pavement sections, respectively. Thus, the *TBR* basically indicates the additional traffic loads/passes that can be applied to the pavement with fibre-reinforced layer, with all other pavement materials and geometry being equal.

The benefit of reinforcing in reduction in the thickness of pavement layer (subbase course, base course and/or surface course) is typically expressed in terms of *layer reduction ratio* (*LRR*), which is defined as follows:

$$LRR = \frac{D_{\mathrm{U}} - D_{\mathrm{R}}}{D_{\mathrm{U}}} \tag{5.4}$$

where D_{U} and D_{R} are the pavement layer thickness of the unreinforced and fibre-reinforced pavement sections, respectively, for equivalent service life. If the layer is base course, the layer reduction ratio (*LRR*) may be better called *base course reduction ratio* (*BRR*) as considered by Perkins et al. (2002).

The pavement can also be designed for any intermediate thickness to reduce the thicknesses of the pavement layers and/or to gain additional benefits in terms of extension of the service life of the pavement. For example, by reinforcing the subgrade soils, the thickness of the subbase course can be reduced as required. If a reduction in the thickness of the subbase course is not required, then with fibre inclusions into subgrade soils, the benefits can be achieved in terms of *TBR*. Thus the actual advantage of fibre inclusions depends upon the option exercised by the pavement designer (Chandra et al. 2008).

For the design of a pavement structure, repeated dynamic load test may be conducted in a model test tank as Kumar and Singh (2008) presented their work using a steel tank of size 0.6 m × 0.6 m × 0.6 m and creating a pavement structure with subgrade, subbase and base courses. Wet Mix Macadam (WMM) was used as the base course. For the rural roads, the traffic load was considered the medium load (41 kN). The number of load cycles applied on the top of the base course was limited to 10,000 only. Table 5.3 shows the deformation of the top surface of the

Table 5.3 Rut depth in a model section after 10,000 cycles in each case

Combination of subbases	Rut depth (mm)	Percentage decrease in rut depth
Fly ash only	6.07	
Fly ash + 0.2% fibres	4.29	29
Fly ash + 0.3% fibres	3.25	46
Fly ash + 25% soil	4.44	27
Fly ash + 25% soil + 0.2% fibres	3.20	47

base course for different combinations of subbases of fly ash (silt of low compressibility, ML) and local soil (poorly graded fine sand, SP) with PP fibres. Note that the rut depth is an indicator of the life of the pavement. A reduction in the rut depth due to loading shows more expected life. Fly ash alone has 6.07-mm rut depth, but in the case of fly ash with 25% soil and 0.2% fibres, rut depth is nearly half of the rut depth in the case of fly ash only.

Jha et al. (2014) analysed the benefit of reinforcing the industrial waste materials (fly ash, stone dust and waste recycled product) with HDPE plastic waste strips in terms of *LRR* for their applications as the subbase course material in the construction of flexible pavements. Their analysis shows that with inclusion of plastic waste strips into industrial wastes, the thickness of subbase course can be reduced up to 50%, depending on the service life and site requirements. The reduced thickness of the pavement layers results in lower total cost of the pavement and lower construction time, thus consuming reduced quantities of natural soil and materials for construction and hence providing an environmentally friendly solutions in a sustainable manner.

Permeability is the most important design parameter for water-retaining structures. The effect of fibre inclusions in soil on its permeability has been presented in Sect. 3.6. In general, inclusion of fibres in soil decreases its coefficient of permeability (a.k.a. hydraulic conductivity), and hence this benefit can be used in reducing the seepage through the body of water-retaining soil structures. Babu and Vasudevan (2008) have explained the benefits of mixing coir fibres into red soil used for the construction of a temporary check dam over an impermeable bed (Fig. 5.4). The seepage analysis shows that an increase in fibre content decreases the discharge per unit length of the dam (Fig. 5.5). Thus the coir fibres are effective in controlling the seepage through the body of check dams, which are often constructed for the water conservation purposes in many countries.

Sheet pile walls have several applications in civil engineering as permanent and temporary structures. A sheet pile wall embedded in a soil is often used to retain water. Babu and Vasudevan (2008) have also explained the benefits of replacement of the soil deposit by coir fibre-reinforced soil on the downstream side of the sheet pile wall (Fig. 5.6). The analysis for soil piping shows that as the fibre content in soil increases, the factor of safety against the piping failure, as determined from Eq. (1.27), also increases (Fig. 5.7). The maximum exit hydraulic gradient may be calculated using the following relationship (Harr 1962):

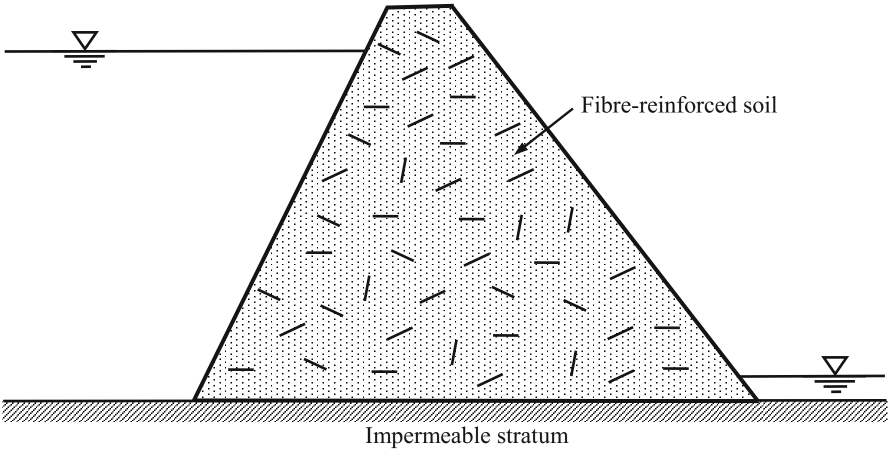

Fig. 5.4 A check dam constructed with coir fibre-reinforced red soil

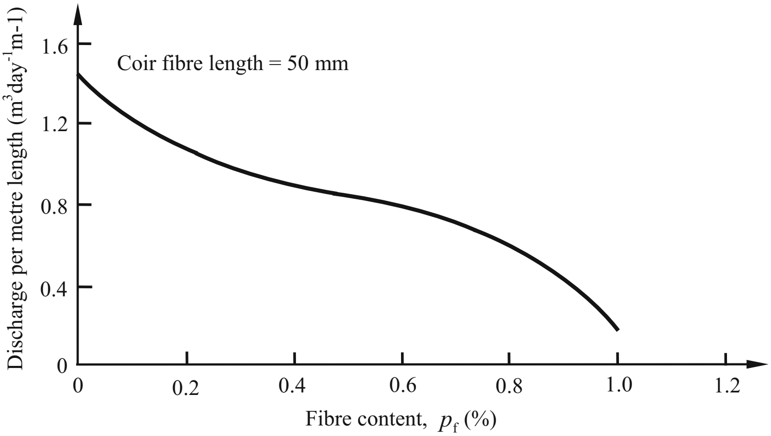

Fig. 5.5 A typical variation of discharge per unit length of the check dam, constructed with coir fibre-reinforced red soil over an impermeable stratum, with fibre content (Adapted from Babu and Vasudevan 2008)

Note: Base width of dam = 10 m; height of dam = 2 m; top width of dam = 2.48 m; side sloping angle = 28°; dry unit weight of soil = 14.3 kN/m^3; moulding water content = 17.8%; and free board = 0. 2 m

$$i_e = \frac{H}{3.14D} \tag{5.5}$$

where H is the total head lost in the flow and D is the depth of penetration of sheet pile wall. Equation (5.5) is based on the assumption that the impermeable layer is available at a shallow depth.

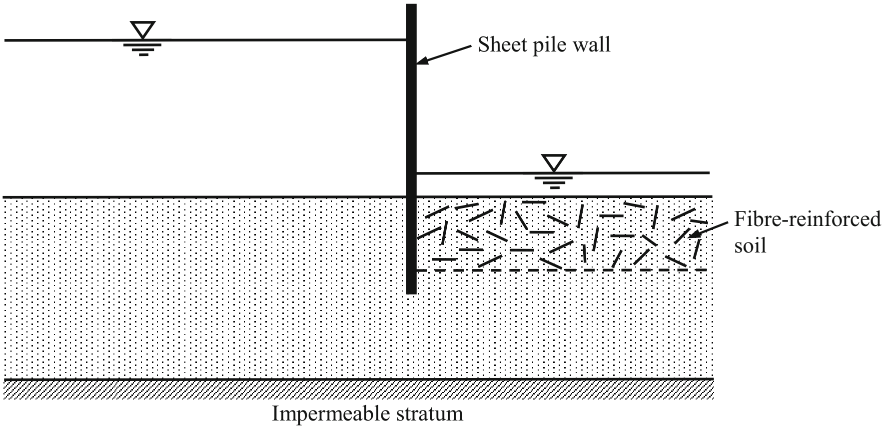

Fig. 5.6 A sheet pile wall with compacted coir fibre-reinforced soil on the downstream side

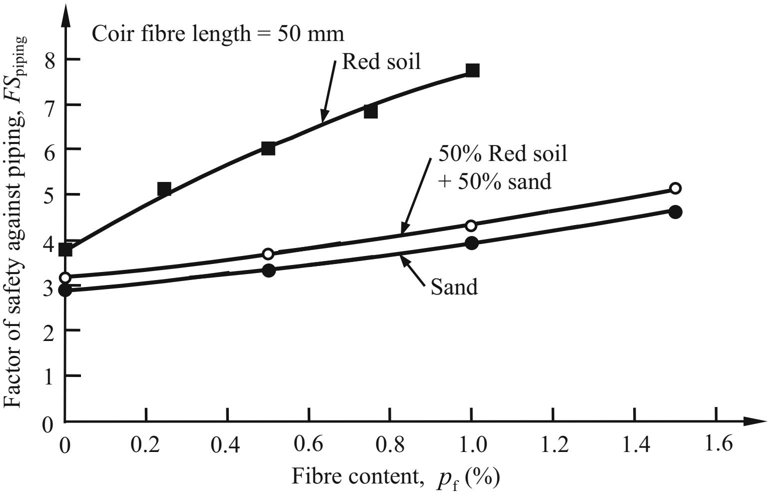

Fig. 5.7 Effect of fibre content on factor of safety against piping failure for the sheet pile with coir fibre-reinforced soil on the downstream side (Adapted from Babu and Vasudevan 2008)
Note: Embedded depth = 2 m; upstream water depth = 2.5 m; downstream water depth = 0.5 m

Desiccation cracking of soil is a problem encountered in many engineering disciplines, including geotechnical and geoenvironmental engineering. Desiccation of landfill clay liners is a major factor affecting landfill performance. Desiccation leads to the development of shrinkage cracks. The cracks provide pathways for moisture migration into the landfill cell and thus increases the generation of waste leachate and ultimately increases the potential for soil and groundwater contamination. For liner design applications, Miller and Rifai (2004) presented the concepts of crack evaluation. The following terms can be used to assess the liner crack potential:

1. Crack intensity ratio (CIR): It is defined as the ratio of cracked area (A_{C}) to the total surface area (A) of the soil, that is,

$$CIR = \frac{A_{\mathrm{C}}}{A} \tag{5.6}$$

   The value of CIR is normally expressed as a decimal.

2. Crack Reduction Factor (I_{CR}): It is defined as

$$I_{\mathrm{CR}} = \frac{CIR_{\mathrm{U}} - CIR_{\mathrm{R}}}{CIR_{\mathrm{U}}} \tag{5.7}$$

where CIR_{U} is the crack intensity ratio for unreinforced soil and CIR_{R} is the crack intensity ratio for fibre-reinforced soil. The value of (I_{CR}) is normally expressed as a percentage.

For landfill applications, Miller and Rifai (2004) studied the effect of PP fibre reinforcement (length varying from 0.5 to 2 in.) on desiccation cracking of medium plasticity soil (classified as CL with liquid limit = 40 and plasticity index = 17) compacted at 2% wet of the optimum water content as a function of fibre content and crack reduction. The relationship between crack reduction and fibre content (Fig. 5.8) shows that increasing the fibre content, from 0.2 to 0.8%, significantly increases the crack reduction, from 12.3 to 88.6%, respectively. The slope of the curve in Fig. 5.8 suggests that increasing the fibre content would have increased the crack reduction further. However, exceeding a fibre content of 0.8% is not practical due to difficulty in fibre-soil mixing to obtain uniform distribution of fibres within the soil. The cracks are observed wider and more intensive in the natural soil specimen than those shown in the fibre-reinforced soil specimen. The cracks in the latter are so small that they are barely visible.

The magnitude of hydraulic conductivity of clayey soil should be one of the primary characteristics used to judge its acceptability for containment structures (i.e. landfill covers and bottom liners). Therefore, it is critical that the effect of fibre inclusion on the hydraulic conductivity of the clayey soil should be evaluated as one of the design steps for covers and liners. Miller and Rifai (2004) conducted hydraulic conductivity test on a medium plasticity soil (classified as CL with liquid limit = 40 and plasticity index = 17) using modified compaction effort and 2% wet of optimum water content. The tests were performed using fibre contents of 0.0, 0.2, 1.0, 1.5 and 2.0%. The test results, as presented in Fig. 5.9, indicate that the hydraulic conductivity of the fibre-reinforced soil is dependent on the fibre content, generally increasing with fibre content increase. The slight decrease of hydraulic conductivity noted around 0.2% fibre content is within the limits of experimental error and should not be used to infer that minor fibre additions improve the

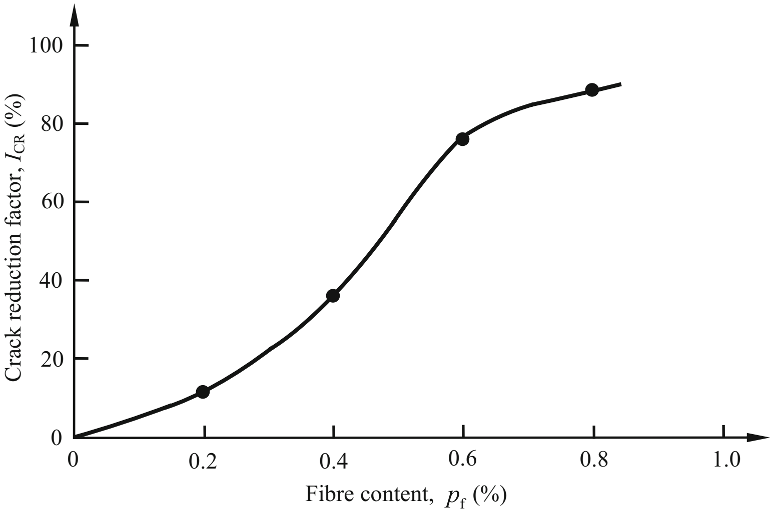

Fig. 5.8 Variation of crack reduction factor for a medium plasticity soil with fibre content (Adapted from Miller and Rifai 2004)

hydraulic conductivity. The increase in hydraulic conductivity is most significant for fibre contents exceeding 1%.

Note that the optimum fibre content that is necessary to achieve the maximum crack reduction, maximum dry unit weight and acceptable hydraulic conductivity within the range of mixing workability is found to be between 0.4 and 0.5% in the experimental study conducted by Miller and Rifai (2004).

5.4 Field Application Experience and Guidelines

Influences of the engineering properties of soil and reinforcement and the scale effects on the properties of the fibre-reinforced soils have not been investigated fully, and hence the actual behaviour of fibre-reinforced soil is not yet well known. The large-scale investigations for all possible applications of fibre-reinforced soil are limited in the literature, and hence they are the subject of further study. Thus, the use of randomly oriented discrete fibres for different applications, as described here, requires investigations at a large scale.

Park and Tan (2005) conducted full-scale tests on a retaining wall with PP fibre-reinforced soil backfill (with 0.2% fibre content), with and without geogrid reinforcement (tensile strength of 50 kN/m in machine direction and 20 kN/m in cross machine direction), in Korea Railway Research Institute, using a large soil box (22 m in length, 5 m in width and 3 m in depth), a loading frame and a reaction plate. The test was fully instrumented with earth pressure cells, displacement gauges, load cells and settlement plates. The numerical model of the wall with

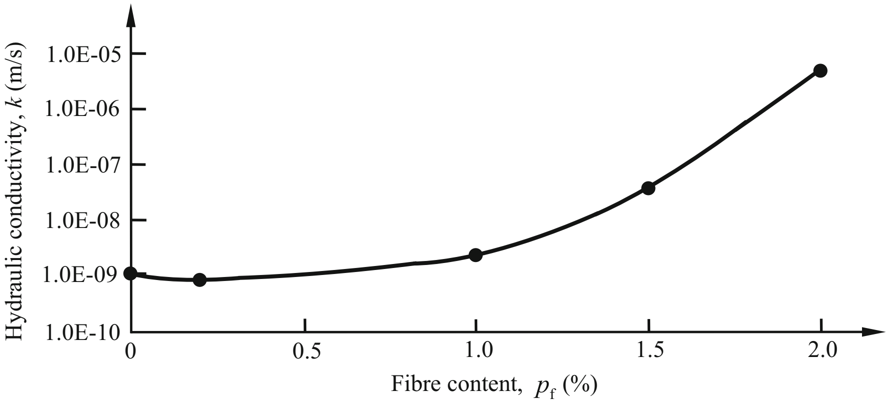

Fig. 5.9 Variation of hydraulic conductivity of medium plasticity soil with PP fibre content (Adapted from Miller and Rifai 2004)

reinforced backfill was also developed using a finite element programme (2D PLAXIS version 7.2). Some of the key observations are given below:

1. Distribution of vertical earth pressure is almost the same for all cases of unreinforced as well as reinforced soil system. When a load is applied on the backfill, the fibre-reinforced soil backfill shows slightly smaller vertical stress increase compared to unreinforced soil.
2. Immediately after construction, and upon loading, the fibre-reinforced soil backfill without geogrid appears to have the smallest horizontal pressure distribution.
3. Wall deflection is smaller if the fibres are included within the backfills. The presence of geogrid reinforcement reduces the wall deflection further to some extent, but very small reduction in deflection cannot justify the cost of using geogrid reinforcement along with fibres.

The fibre-reinforced compacted soil backfill is thus stronger and stiffer than unreinforced compacted soil backfill. Inclusion of geosynthetic reinforcement layers within the fibre-reinforced soil backfill can lead to an economical construction of very high retaining wall, even with a vertical face, especially in built-up areas.

At some sites, shallow foundations and pavements are often constructed along the ground supported by sheet pile walls or other retaining structures, as shown in Fig. 5.10. Nasr (2014) studied experimentally and numerically the potential benefits of reinforcing the poorly graded sand backfills at a relative density of 50% in the active zone behind a model steel sheet pile wall (750 mm long, 499 mm wide and 3.3 mm thick) by using PP fibres (12 mm long, 0.023 mm thick) and cement kiln dust (15.42% SiO_2, 3.92% Al_2O_3, 2.95% Fe_2O_3, 51.23% CaO, etc.). The test involved loading a rigid strip footing (499 mm long, 100 mm wide and 25 mm thick) resting on the sand backfill surface in the active zone adjacent to the sheet pile wall in a steel test tank (1.5 m long, 0.5 m wide and 0.9 m high). The sheet pile

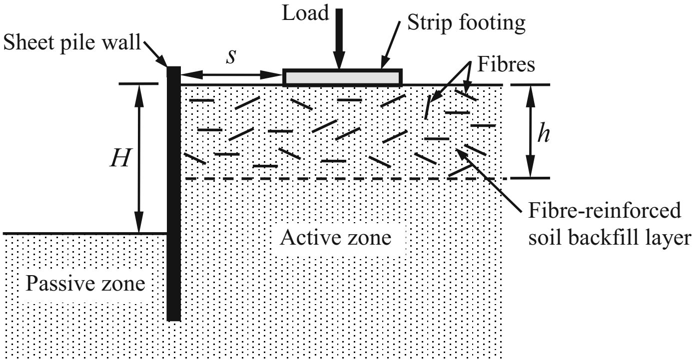

Fig. 5.10 Loaded active zone adjacent to a sheet pile wall (Adapted from Nasr 2014)

wall was embedded 500 mm in the sand bed. The results obtained from the study suggest the following:

1. Addition of PP fibres to the cemented sand increases the ductility as indicated by the increase in deformability index D_i. For lower fibre content ($\leq 0.5\%$), D_i is weakly influenced by the cement kiln dust content.
2. The presence of fibres in the cemented sand backfill behind the sheet pile wall decreases the lateral deflection of the wall significantly. For the cement kiln dust content (as per Eq. (2.9)) of 9%, the maximum lateral deflection decreases by about 51% at a fibre content (as per Eq. (2.10)) of 0.75%.
3. Ultimate bearing capacity of the strip footing resting on the fibre-reinforced cemented sand in the active zone increases with an increase in the thickness of reinforced sand layer. However, for higher fibre content ($\geq 0.75\%$), an increase in ultimate bearing capacity is not significant at a thickness h of fibre-reinforced cemented sand layer greater than $0.4H$($H=$ wall height; see Fig. 5.10).
4. Increasing the distance between the strip footing and the sheet pile wall leads to a significant increase in ultimate bearing capacity of the footing and a decrease in the maximum lateral deflection of the sheet pile wall. However, for higher fibre content ($\geq 0.75\%$), if the distance s between the strip footing and the sheet pile wall is more than $0.8H$, there is no appreciable increase (about 4.8%) in ultimate bearing capacity of the footing.

Sand and sandy gravels are generally not used in the top courses (high level of base course or surface course) of pavements although they are easily available at several construction sites because their properties do not meet the technical requirements of top courses. In order to utilize sand as a construction material on a larger scale in the top courses, sand can be reinforced with short fibres by mixing sand and fibres by the mix-in-plant process. Lindh and Eriksson (1990) provided the details of a pilot experiment performed in 1988 on two pavement test stretches, 20 m and 40 m, by incorporating a 100-mm layer of sand in the pavement mixed with short (48-mm) plastic fibres at 0.25 and 0.5% fibre contents, respectively. Sand, water and plastic fibres were mixed successfully in a concrete mixing plant of the drum

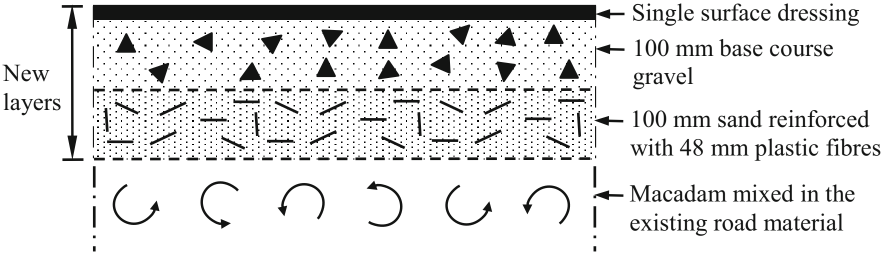

Fig. 5.11 Longitudinal test section of road pavement (lengths of 20 m and 40 m with the use of plastic fibre contents of 0.25% and 0.5%, respectively, in the sand layer) (Adapted from Lindh and Eriksson 1990)

mixer type. The 100-mm reinforced sand layer was applied directly on the old road surface. A 100-mm layer of base course gravel was applied on the sand layer, followed by a surface dressing (see Fig. 5.11). Prior to applying the fibre-reinforced sand, the grading curve of the material in the surface layer of the old road was improved by mixing in macadam. The spreading and rough levelling of the fibre-reinforced sand were performed with a grader. The normal shaping could not be performed on the reinforced sand as it became matted, and adhered to the shaper in lumps. The final shaping of the surface therefore had to be performed with hand tools. After compaction, the fibre-reinforced sand had considerably better stability than the layers of packed sand, and showed no rutting of the road surface during about the first 2 years' use by traffic; thus the test stretches performed well. With inclusion of fibres, the sand absorbs tensile strains and can therefore improve resistance to permanent deformation of sand layer when loaded.

Santoni and Webster (2001) described the laboratory and field tests conducted using a new fibre stabilization technique for sands. Laboratory unconfined compression tests using 51-mm long monofilament PP fibres to stabilize a poorly graded (SP) sand showed an optimum fibre content of 1% (by dry weight). The field test sections were constructed and traffic tested using simulated C-130 aircraft traffic with a 13,608 kg tyre load at 690 kPa tyre pressure and a 4536 kg military cargo truck loaded to a gross weight of 18,870 kg. The test results showed that the sand-fibre stabilization over a sand subgrade supported over 1000 passes of a C-130 tyre load with less than 51 mm of rutting. The top 102 mm of the sand-fibre layer was lightly stabilized with tree resin to provide a wearing surface. Based on limited truck traffic tests, 203-mm thick sand-fibre layer, surfaced with a spray application of tree resin, would support substantial amounts of military truck traffic.

Tingle et al. (2002) reported the details of two field test sections to evaluate the ability of fibre-stabilized sand beds to sustain military trucks. It is observed that the fibrillated fibres provide the best rut resistance, followed by the monofilament, the tape and then the Netlon mesh elements. The 0.8% fibre content recommended by Santoni et al. (2001) showed to provide adequate structural support for the test traffic. Slightly better performance was noted at a fibre content of 1%, but the slight increase in rut resistance did not justify the added cost of the additional fibres. The field tests demonstrated similar performance between 51-mm (2 in.) and 76-mm (3 in.) fibre lengths, but the 76 mm tended to hand up on the mixing equipment. Thus, 51-mm fibre length appears to be more appropriate for field use. In general, the design criteria for unsurfaced roads are based on the development of a 76-mm (3 in.) rut upon completion of the design traffic. The amount of rutting, 63–89 mm (2.3–3.5 in.), exhibited in the field tests indicates that the design thickness of 203 mm (8 in.) was appropriate for the design traffic, except for the case with the Netlon mesh fibres. The test sections demonstrated the need for a surfacing for fibre-stabilized layers to keep the tyre friction from pulling the fibres out of the sand. Road Oyl provided a good wearing course for the applied traffic. Cousins Pine Sap Emulsion and PennzSuppress D also provided adequate resistance to fibre pullout. The hexagonal mat surfacing provided an adequate wearing course, but no additional structural strength was provided by the mat since the sand had already been confined by the fibres. Note that the majority of the permanent deformation or rutting that occurred during the test period consisted of densification of the stabilized sand and supporting sand layers.

Based on the available experience and studies reported in the literature as well as the author's experience, some application guidelines are given below:

Care and Consideration

- There are a large number of factors and variables that affect the engineering behaviour of fibre-reinforced soils. The stress-strain properties of fibre-reinforced soils are functions of fibre content, aspect ratio and skin friction along with the soil and fibre index and strength characteristics and confining pressure. Thus, the design and construction of fibre-reinforced soil structures should properly consider all these variables.
- Because of the major influence of confining stress, the design parameters should be based on the triaxial compression tests, especially on the large-size specimens.
- The method of fibre-reinforced soil placement should be similar to the method used for preparing the fibre-reinforced soil specimens for the tests conducted to obtain the design parameters. This is essential to maintain the fibre orientations the same in both the tests and field applications.
- In general, fibres are most influential when orientated in the same direction as the tensile strains. Therefore, for any particular loading condition, the effectiveness of fibre inclusions depends on their orientation, which in turn depends on the sample mixing and formation procedure. However, an attempt should be made to make the reasonably uniform distribution of the fibres within the soil mass.
- The in situ mixing and compacting may cause preferred near-horizontal orientations; hence, the properties of fibre-reinforced soil are anisotropic to some extent.
- The consequence of an assumed isotropy as generally expected in the soil-fibre mixes may result in an overestimation or underestimation of reinforced soil design parameters, depending on the direction of practical importance.
- Since the limited settlement is generally the design criterion for actual foundations on soil, a comparison of the bearing pressure values at some selected

settlement levels for the reinforced and unreinforced cases should be made for the design purpose.

- Site-specific laboratory and field tests should be conducted to determine the design parameters/variables.
- As several contradictory observations/conclusions have been reported in different studies, they should be used carefully in analysis and design of fibre-reinforced structures.
- As the significant influence of fibre reinforcement on the ultimate strength of fibre-reinforced soil continues to be observed even at very large shear strains (horizontal displacements) in the laboratory study, there is no tendency to lose strength, and the fibre-reinforced soils would therefore be unlikely to suffer from brittle failure in field applications even in cases where the strains localize, as they do in a ring shear apparatus. Thus there is a great potential of PP and other similar fibres as the soil reinforcement (Heineck et al. 2005).
- The use of natural fibres such as coir and jute fibres may make possible constructions, such as embankments and bunds, rural road bases, etc., cost-effective and environmentally friendly, especially in applications for short duration of 2–3 years in order to have short-term stability. Of most natural fibres, coir has the greatest tearing strength and retains this property even in wet conditions.

Mixing, Placement and Compaction

- The simplest method of mixing fibre and soil in a rotating drum mixer does not result in a uniform mixture due to a large difference in specific gravities of fibre and soil. The drum mixing method usually results in the segregation or floating of fibres even when some water is added. In fact, because of the lightweight and low specific gravity of fibres (for some types it can be even less than unity) compared to soil particles, the fibres cannot be uniformly distributed in the mixture during drum rotation.
- The effective method of fibre inclusion can be spraying the fibres over each soil lift during field compaction, especially in pavement bases and subbases. The main advantages of fibre reinforcement in bases and subbases are increase in load-carrying capacity, reduction in rut depth, reduced cost, etc.
- One of the most satisfactory mixing techniques can be provided by blowing fibres into a rotary mixer chamber with a mulch spreader equipped with a flexible hose. Blade mixing provides a reasonable satisfactory random distribution of fibres (Hoover et al. 1982).
- Mixing is a critical factor in the case of discrete, randomly oriented fibre reinforcement. Blade- or paddle-type mixers do not work as they tend to drag and ball up the fibres. Vibratory mixers tend to float the fibres up. A special oscillatory or helical action mixer can be used to avoid these problems; but even this type of mixer has limitations on the maximum fibre content that can be uniformly and randomly distributed in the mix. The degree of randomness in the mixture may be determined by visual inspection (Gray and Al-Refeai 1986).
- Compared to hand mixing, the z-blade mixer produces suitable even mixes of clay and PP fibres within a reasonable time (Gelder and Fowmes 2016).

- Water content of the soil should be lower than the optimum water content corresponding to the level of compaction required to facilitate pulverization of the soil particles.
- In order to easily mix the fibres uniformly, the initial/natural water content of the cohesive soil may be increased to optimum mixing moisture content (OMMC) prior to the introduction of fibres if lime has to be added. By introducing quicklime, excess moisture is removed through the hydration (exothermic reaction) process, thus improving the workability of soil. If lime is not added, the mixture should be allowed for air drying at the site to get the moisture content reduced to the target value (Gelder and Fowmes 2016).
- For preparing a good-quality mixture of fibres and clayey soil, the water content of the soil may be kept near its plastic limit, which may fall on the wet side of the compaction curve (Falorca and Pinto 2011).
- For proper mixing of fibres with soil, water required to obtain the target water content should be added to soil prior to placing the fibres on the soil. This is done to keep the fibres from sticking together during mixing (Tingle et al. 2002).
- Higher fibre content, longer fibres and crimped fibres can make the mixing procedure more difficult.
- Compaction of soil fibres can be done in two stages: one pass of the motor scrapper followed by 4–6 passes of a roller.
- A vibratory rubber-tyred roller may be most suitable for the compaction of fibre-reinforced soils (Falorca et al. 2011).
- More compaction energy may be necessary to produce specimens with higher fibre contents at a given dry unit weight. Thus, the fibre-reinforced soil may provide an increased resistance to compaction, even in field compaction.
- In general, for the embankment construction, the soil-fibre mixture should be produced and placed in a single step only. It is not feasible to spread and level the mixture by maintaining the homogeneity, as some clods of fibres are produced and dragged by the motor scraper. The reinforced layers must therefore be ready for compaction immediately after placement, with no need for levelling procedures. For a better uniform distribution of fibres within the compacted soil mass, the soil and fibres may be spread in a sandwich pattern and then mixed with a rotary tiller, in the following steps (Falorca et al. 2011):
  - The predetermined quantity of fibres is spread uniformly by hand or other suitable means over the surface.
  - The necessary amount of soil is then spread over the fibres.
  - Finally, the rotary tiller is driven along the entire area of the section in a regular pattern at a slow speed, combined with high rotation, in order to have a satisfactorily homogeneous mixture.

These steps can be repeated until a 0.2-m thick layer is completed. The number of sub-layers needed to complete a 0.2-m thick layer is found to depend on the fibre characteristics. This procedure becomes impractical when the number of sub-layers is greater than six. For the highest fibre content and lowest fibre diameter, the maximum number of fibres needs to be mixed with the soil. This is the most difficult situation, which requires the highest number of sub-layers.

- A thin top soil layer of about 50-mm thickness should be placed over the entire surface area of the embankment to protect the synthetic fibres, such as PP fibres from UV degradation. The top soil layer also helps minimize fissures which may be caused by a recovering deformation of the reinforced soil (Falorca et al. 2011).
- In pavement base/subbase construction, the selected type and amount of fibres should be weighed and can be uniformly spread by hand across the surface of the moist base/subbase material. Four to six passes of a self-propelled rotary mixer should be initially used to mix the fibres with base/subbase material. Then the material should be piled and releveled, and four to six additional passes of the rotary mixer should be used to uniformly mix the fibres with the material. The fibre-reinforced material should then be dumped in place as required for compaction by rollers.
- If required, the individual fibres from the yarns can be separated by first, punching a few holes with a paper hole punch near the closed end of a large (say, 125 L) plastic bag. Next, a handful of yarn fibres are placed in the bag. The bag is hand-held closed around an air nozzle and inverted, and air is blown through the fibres. The air separates the fibres from the yarn effectively and promptly. The separated fibres form the fluffy bundles that resemble cotton candy (Santoni and Webster 2001).
- When tyre chips are used, construction activities may be eased by specifying tyre chips less than 75 mm (maximum dimension). For compaction of tyre fibre-reinforced soil, vibratory roller should not be specified. Compaction specifications should not be based on a final unit weight, but the optimum number of passes should be determined based on a test section in the field. Compressibility is the governing parameter in designing structural fills using tyre chips. To achieve minimum compressibility, a minimum soil cover thickness of 1 m over the tyre chips should be specified. The use of a geotextile to separate the cover soil from the porous tyre chip fill is recommended to prevent migration of the soil into the tyre chips pores. Sand-tyre chips mixtures exhibit higher moduli than clay-tyre chips mixtures at the same soil-tyre chips ratio (Edil and Bosscher 1994).

Durability

- Attempts are being made to increase the long-term durability of fibres in a cost-effective way, such as coating of fibres with phenol and bitumen, and probably in the future, several coating methods will be available. However, natural fibres can be used routinely in less critical applications (e.g. pavement bases/subbases) or short-term applications (e.g. erosion control).
- The surface of fibres may be made rough by cementing a layer of suitable materials, such as fine sand particles, to the fibres for achieving a full mobilization of soil angle of internal friction during shearing.

- Natural fibres may be protected from biodegradation by coating with suitable materials. Ahmad et al. (2010) coated oil palm empty fruit bunch (OPEFB) fibres with acrylonitrile butadiene styrene (ABS) thermoplastic for increasing the resistance to biodegradation. A layer of coating on a fibre also increases its diameter and the surface area, resulting in increased interface friction of fibre and soil as well as the fibre tensile strength. Hence, as an additional advantage, the inclusion of coated OPEFB fibres in silty sand increases its shear strength much more compared to uncoated fibres, as reported by Ahmad et al. based on the results obtained from consolidated drained and undrained triaxial compression tests. Sarbaz et al. (2014) used bitumen-coated palm fibres for reinforcing fine sand and studied the effect of bitumen coating on the *CBR* strength of sand.

Application Experience

- Stability of retaining walls under dynamic load conditions may require the use of more stable backfills. For increase in stability of walls by the reduction of lateral earth pressure, short fibres (say, 60-mm long PP fibres) may be included randomly in soil backfills (Park and Tan 2005). The beneficial effect can be more to some extent when short fibres are used in combination with geogrid reinforcement within the backfill.
- Inclusion of tyre chips (20 mm long, 10 mm wide and 10 mm thick; specific gravity = 1.08 and unit weight = 6.45 kN/m^3) up to 30% by weight in the poorly graded sand backfill behind the wall effectively works to reduce the wall displacements and lateral earth pressures against the wall by about 50–60%, thereby resulting in reduced dimensions of the wall (Reddy and Krishna 2015).
- Shallow foundations on fibre-reinforced cohesionless/granular soil deposits should be designed based on the findings of large-scale model footing tests or, if possible, by testing full-scale trial footings; otherwise, a simple test may be devised, for example, in the form of measuring the imprint dimensions or the penetration depth of a falling object (Wasti and Butun 1996).
- Even though the sand-cement layer provides a higher bearing capacity when compared to cement-stabilized fibre-reinforced sand layer, the latter, in terms of post-peak behaviour, leads to a more reliable solution and possibly to a reduction in the design safety factor, because the fibre inclusion reduces dramatically the brittle response of the foundation soil system (Consoli et al. 2003).
- The beneficial effects of fibre reinforcement in soil can be enhanced significantly by stabilizing the fibre-reinforced soil with cement in a suitable quantity, say using cement content of 5–10%.
- The footing or pavement load should be placed suitably away from the retaining structure to get maximum benefits from inclusion of fibres in terms of increase in the load-bearing capacity of the footing.
- The granular pile and trench, which are used for stabilizing the weak clayey foundation soil, can be strengthened by inclusion of fibres in place of reinforcing them by layers of geosynthetic reinforcement (Gray and Al-Refeai 1986).
- With increase in shear strength of soil with inclusion of fibres, a steeper slope may be constructed, resulting in saving of the land area, which may be utilized

suitably. The slope stability analysis of the fibre-reinforced slopes may be carried out using the discrete approach, which considers the fibre-induced distribution of tension parallel to the failure plane along with the soil shear resistance separately.

- Decrease in rut depth, which is an indicator of increase in the life of pavement, takes place as a result of inclusion of fibres in soil and other similar materials such as fly ash.
- Stabilization of sand with discrete fibres is a viable alternative to traditional stabilization techniques for low-volume road applications. Fibre stabilization requires less material (fibre additives) by dry weight than most traditional stabilization techniques. The construction and maintenance techniques have been shown to be practical and successful in terms of maintaining the serviceability of the road. However, the densification of fibre-stabilized materials under repeated traffic loadings may limit the applicability of this technology for use in situations in which settlements and deformations cannot be tolerated (Tingle et al. 2002).
- During trafficking by the heavy construction machinery, in terms of depth of ruts, the fibre-reinforced soil sections are observed to be more stable than the unreinforced sections.
- In case of rural roads, the subbase material should have a minimum soaked *CBR* of 15%. Fly ash reinforced with PP fibres with 0.2% fibre content has been found to have *CBR* of 16.6%; therefore, this is suitable for rural road subbases. Fibre content can be reduced to 0.1% if fly ash is mixed with 25% of poorly graded fine sand (SP) (Kumar and Singh 2008).
- Cement-stabilized soils are often used as pavement base courses, backfills behind retaining walls, embankments and foundation. As the cement content increases, the strength properties of soil improve significantly, but an increase in cement content causes a brittle or sudden failure without a plastic deformation. As the brittle/sudden failure is undesirable in engineering applications, for preventing the brittle failure, fibres may be added to cement-stabilized soil in a suitable quantity with a random distribution.
- Fibre inclusions with an optimum aspect ratio increase the *CBR* of the soil subgrade/subbase/base courses and hence may cause a substantial decrease in design thickness of the pavement layers, thus making the pavement project economical.
- Fibre inclusions mixed with soil subgrade also provide needed tensile strength under traffic loads.
- The fibre reinforcement of roadway soils should be associated with base or subbase courses having adequate surfacing (Hoover et al. 1982).
- Shredded waste tyres can be used as soil subgrade reinforcement, aggregate in leach beds for septic systems, additive to asphalt, substitute for leachate collection stone in landfills, daily cover materials in landfills, lightweight fills, edge drains, etc.
- The *CBR* values decrease significantly as the amount of tyre buffings (gradation between 1.0 mm and 12.5 mm) increases in the subbase gravel (crushed stone, classified as well-graded gravel, GW). Subbase gravel with 3% cement and 5%

tyre buffings give higher *CBR* values than gravel alone. The use of gravel, tyre buffings and cement can reduce the tyre disposal problems in pavement granular courses (Cabalar and Karabash 2015).

- In pavement applications, the stabilization of cohesionless materials, such as sand and gravel, with discrete fibres requires that some form of surfacing should be used as a wearing course to prevent the fibres from being pulled out of the sand/gravel during trafficking if used as the surface layer of the pavement structure, especially in unsurfaced (unpaved) pavements. Friction forces imparted on the surface of the pavement by the vehicle tyres tend to pull the individual fibres from the sand and gravel over time. As the fibres are withdrawn out of sand and gravel, the reinforcement of the stabilized layer is degraded (Tingle et al. 2002). Resin-modified emulsion, biodegradable emulsion composed of tree sap and water-emulsified resin base are some examples of spray-on materials available commercially under different trade names. Different types of ultraviolet ray-resistant plastic mat panels are also available in the market for use as surfacings.
- The cement-stabilized fibre-reinforced soil may be used to construct the top layers of an embankment if it has to support a pavement or any other structural load.
- The monofilament fibres show a great potential for use in rapid stabilization of sandy soils for pavement base/subbase applications. The field demonstration tests should be carried out to test fibre stabilization performance under actual road/air traffic landing. The field tests should also be conducted to test the durability and maintenance requirements for sand-fibre pavement layers (Santoni and Webster 2001).
- The laboratory investigations carried out by Santoni et al. (2001) indicate the optimum conditions for fibre reinforcement to include the following: a dirty sand with 1–4% silt; the use of 51-mm (2 in.) long fibrillated fibres at the smallest available denier; a fibre content of 0.8% by dry weight; fibres and soil mixed at ± 2% of optimum water content of the of the composite material.
- In general, the addition of cement significantly increases the strength of soil under both static and dynamic loads, contributes to the volume stability, and increases the resistance to liquefaction in fine sandy and coarse silty soils. The strength of cement-stabilized soil can further be increased significantly by addition of fibres.
- For reinforcing the black cotton soils with glass fibres, the maximum fibre content can be limited to 2% by weight to achieve the optimum benefits (Gosavi et al. 2004).
- Since a potential use of fibre-reinforced cohesive soil is in landfill liners and covers, it is important to assess the effect of specific fibre inclusion on hydraulic conductivity of soil.
- For achieving more tensile strength of fibre-reinforced clayey soil, with a given fibre content, shorter and better dispersed fibres should be used (Maher and Ho 1994).

- PP and glass fibre reinforcements can be used in kaolinite clay beams undergoing flexural load to limit the cracks and increase the toughness (Maher and Ho 1994).
- Fibres can be mixed into soil for making embankment dams and other water-retaining structures more resistant to piping erosion, provided the optimum fibre content is selected based on a suitable piping test. A high fibre content, say greater than 0.15% for PP and PET fibres, may be harmful and may actually reduce the piping resistance (Das and Viswanadham 2010).
- A cluster of fibres in one location within the soil, which may take place with high fibre content, can result in increased permeability, reduced piping resistance and reduced strength.
- Dredging of sediments and dewatering of the dredged sediment/slurry through the geotextile tubes is common engineering tasks in several countries. A variation in slurry particle sizes, particularly fine-grained particles, creates issues with soil loss and dewatering rates within the geotextile tubes. The dewatering rate and final filter cake properties have the most importance to dewatering applications. The faster the flocculated sediments settle and dewater, the quicker the next geotextile tube can be filled. The pressure filtration tests show that the dewatering time decreases significantly with inclusion of 0.5% of both nylon and jute fibres, but is not dependent on the fibre length. However, the increase in shear strength of filter cake is dependent on fibre length. Jute fibres do not show a high strength gain as the nylon fibres but increase the dewatering times by an average of 14–22% compared to filter cakes with nylon fibres. One possible explanation for variations in dewatering rates between nylon and jute fibres can be by the fact that jute fibres have a larger diameter and overall surface area, which allows for more soil-fibre interaction, thereby causing an increase in void volume through which water can pass easily and, therefore, expedite the dewatering rate (Spritzer et al. 2015).
- Fibre reinforcement would be an efficient method in limiting or even preventing the occurrence of the lateral movement of the sandy soils due to liquefaction as normally observed for unreinforced sands (Noorzad and Amini 2014).

Quality Control

- Regular visual inspections should be carried out to control the randomness and both the horizontal and vertical uniformity of the fibre distribution. The actual fibre content at different locations should be checked by suitable methods and compared with the design fibre content.
- While constructing the fibre-reinforced soil structure, the fibres should be introduced in each sub-layer by mixing the amount of fibres with soil as per the designed content.
- The compaction control through the dry unit weight measurement is of little interest for fibre-reinforced soils because fibres do not just have a significantly lower specific gravity than that of the soil particles; they are also a minor physical component of the composite material. It is better to measure the material stiffness for compaction control, which can be done by means of

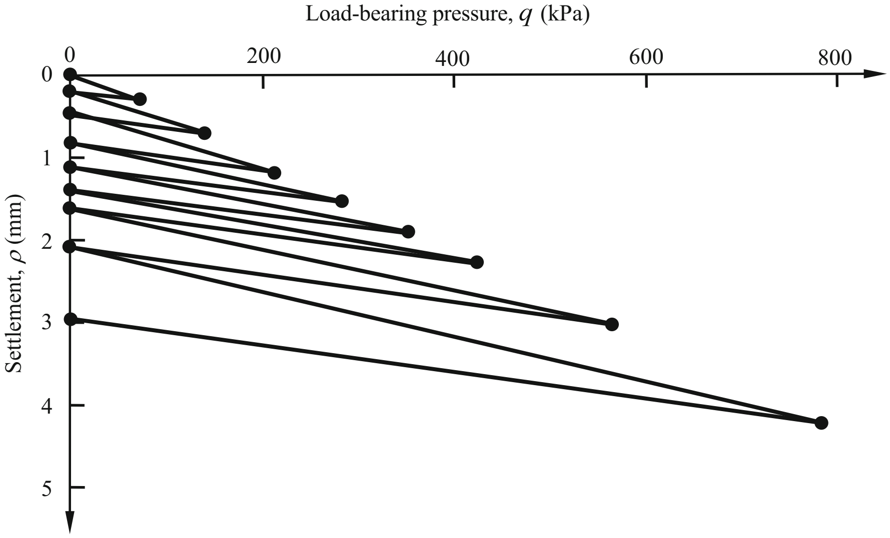

Fig. 5.12 Results of the plate load tests conducted on randomly distributed monofilament PP fibre-reinforced silty sand embankment (50 m long, 10 m wide and 0.6 m high), using a semi-rigid circular plate, 300 mm in diameter, under repeated loading and unloading (Adapted from Falorca et al. 2011)

compaction equipment integrating continuous control compaction (CCC) (Falorca et al. 2011).

- The quality control may be done by conducting the plate load tests, which allow direct characterization of the soil compressibility with the applied pressure, as seen in Fig. 5.12.
- The ratio of porosity n to the volumetric cement content p_{vc}, all expressed as a percentage of the total volume, can be useful in the field control of cement-stabilized fibre-reinforced soil. Based on the unconfined compressive strength tests on specimens submerged for 24 h and achieving an average degree of saturation of 87%, the following relationships have been suggested to estimate the unconfined compressive strength q_{u} (Consoli et al. 2010):

For cement-stabilized soil,

$$q_{\mathrm{u}}(\mathrm{kPa}) = 2.2 \times 10^{7}\left(\frac{n}{p_{vc}^{0.28}}\right)^{-3.08} \quad \left(R^{2} = 0.98\right) \tag{5.8}$$

For cement-stabilized fibre-reinforced soil,

$$q_{\mathrm{u}}(\mathrm{kPa}) = 1.0 \times 10^{7}\left(\frac{n}{p_{vc}^{0.28}}\right)^{-2.73} \quad \left(R^{2} = 0.95\right) \tag{5.9}$$

Equations (5.8) and (5.9) are relevant for specific materials (nonplastic silty sand, classified as SM, Portland cement of high early strength, monofilament PP fibres with fibre content ranging from 0 to 0.5%, cement content ranging from 0 to 8%) and test conditions, as considered by Consoli et al. (2010) in their experimental study. Similar relationships may be developed for other materials and site conditions for the specific field application. Attempts can also be made to present the generalized relationships. During the quality control, once a poor compaction is identified, it can be readily taken into account in the design, using these equations and adopting corrective measures accordingly, such as the reinforcement of the treated layer or the reduction in the load transmitted.

5.5 Scope of Research

As mentioned earlier, the actual behaviour of fibre-reinforced soils is not yet well known because the current understanding is largely based on small-scale laboratory investigations and very limited large-scale or field studies. Hence, further studies, especially involving field tests and performance evaluation of different applications, are essentially required to better understand the behaviour of fibre-reinforced soils so that the fibre-reinforcements can be routinely utilized based on a more rational analysis and design. In spite of some limitations, reinforcing the soils with discrete flexible fibres can be a cost-effective means of improving their performance in several applications. Additionally the use of fibres from the waste materials can reduce the disposal problem in an economically and environmentally beneficial way. Detailed investigations are expected in the future on several aspects of fibre-reinforced soils, including the following:

- Cost-effective mixing technique
- Optimum size and shape of fibres for different applications
- Durability of fibres in different physical and environmental site conditions
- Drainage and pore water pressure developments within the fibre-reinforced soil
- Effective stress concept for fibre-reinforced soil
- Creep behaviour of fibre-reinforced soil
- Freezing-thawing behaviour of fibre-reinforced soil
- Cyclic loading behaviour of fibre-reinforced soil
- Fibre-clay interface behaviour
- Generalized analysis and design methods for different specific applications of fibre-reinforced soil
- Cost-benefit analysis of different applications of fibre-reinforced soil

It is expected that applications of fibres in mining, agricultural and aquacultural engineering will also be reported significantly in the future, although the applications discussed here are equally applicable for similar projects in these areas.

Note that some wastes, such as the municipal solid wastes, may be physically similar to randomly distributed fibre-reinforced soils, and, therefore, the concepts of fibre-reinforced soil engineering, as presented in this book, are also equally applicable to such wastes to manage their disposal and utilization.

Chapter Summary

1. The technique of reinforcing soils with discrete fibres has several advantages, and hence this has become one of the cost-effective and environmentally friendly ground improvement techniques in the present-day construction practice.
2. There are a large number of applications of fibre-reinforced soils in civil and other related engineering areas. Major applications can be categorized as geotechnical applications, transportation applications, and hydraulic and geoenvironmental applications.
3. Much care is required to obtain a reasonably uniform distribution of fibres within the soil mass, especially when the fibre content is large. Mixing of fibres with soil can be carried out using an oscillatory- or helical-type mixer to avoid fibre segregation, dragging, balling and floating problems, which are associated with commonly used blade-type mixers.
4. Fibre-reinforced soil structures can be designed by composite or discrete approach. The composite approach considers the fibre-reinforced soil a homogeneous material, while the discrete approach uses the contributions of soil and fibres separately in the design.
5. Orientation of fibres must be considered properly in analysis and design of fibre-reinforced soil structures. For field applications, the fibre content and the aspect ratio should be selected based on experimental observations with specific soil and fibres under consideration as these two parameters significantly govern the behaviour of fibre-reinforced soil, and moreover, they can be controlled easily.
6. Addition of fibres to the soil backfill behind a retaining wall increases the stability of the wall with reduced lateral earth pressure and displacement of the wall.
7. Overall stability of a shallow foundation constructed over the weak foundation soil can be significantly improved by placing a compacted cement-stabilized fibre-reinforced soil layer of a suitable thickness (say $0.3B$, where B being the width of the footing) over the weak foundation soil.
8. Benefits of reinforcing the pavement layers with fibres are generally expressed in terms of an extension of service life of the pavement and/or a reduction in the thickness of pavement layer. Traffic benefit ratio (*TBR*) and layer reduction ratio (*LRR*) are two commonly used parameters for design of pavement layers.
9. Fibres can be used effectively in reducing the seepage through the body of water-retaining soil structures, increasing the soil-piping resistance and

controlling the desiccation cracks in compacted clay layers used in liner and cover applications.

10. Some application experience and guidelines are available for successful applications of fibre-reinforced soils. Further studies, especially involving field tests and performance evaluation, are expected to develop the confidence level for different applications.

Questions for Practice

(Select the most appropriate answer to the multiple-choice questions from Q 5.1 to Q 5.5.)

5.1 Tamping and vibration techniques for preparing the fibre-reinforced soil specimens in moist condition lead to

(a) Vertical orientation of fibres
(b) Near-vertical orientation of fibres
(c) Horizontal orientation of fibres
(d) Near-horizontal orientation of fibres

5.2 Fibre inclusion in the pavement base soil

(a) Increases the dry unit weight
(b) Decreases the unconfined compressive strength
(c) Increases the *CBR* value
(d) Both (a) and (c)

5.3 The most suitable roller for compacting fibre-reinforced soils is

(a) Smooth wheel roller
(b) Vibratory rubber-tyred roller
(c) Sheepsfoot roller
(d) Grid roller

5.4 For protecting the synthetic fibres from UV degradation, the entire surface area of fibre-reinforced soil embankment should be covered with a top soil layer having a thickness of about

(a) 50 mm
(b) 100 mm
(c) 150 mm
(d) 200 mm

5.5 The beneficial effects of fibre reinforcement in soil can be enhanced significantly by stabilizing the fibre-reinforced soil with cement in a suitable quantity, say using cement content of

(a) 0.5–1%
(b) 1–5%
(c) 5–10%
(d) 10–20%

5.6 What are the advantages exhibited by the fibre-reinforced soils?

5.7 In the laboratory, prepare a mixture of sand and fibres by any suitable means in dry and wet conditions, and compare your observations about the fibre orientation with those reported by the researchers as presented in this chapter.

5.8 List the potential application areas for fibre reinforcement.

5.9 Describe the techniques for preparing the laboratory test specimens of fibre-reinforced soil.

5.10 What kind of fibre orientations is present in rolled-compacted fibre-reinforced construction fills?

5.11 What considerations are required for the selection of fibres?

5.12 What are the different approaches for design of fibre-reinforced soil structures? Discuss their merits and demerits.

5.13 How can you determine the lateral earth pressure on a retaining wall from fibre-reinforced cohesionless soil backfill?

5.14 For a fibre-reinforced sand backfill supported by a 10-m high retaining wall with a vertical back face, consider the following:

Angle of internal friction of sand, $\phi = 35^\circ$
Total unit weight of fibre-reinforced sand, $\gamma = 16.85\ \text{kN/m}^3$
Fibre-reinforced soil-wall interface friction angle, $\delta = 15^\circ$
Fibre-soil interface friction angle, $\phi_i = 20^\circ$
Fibre aspect ratio, $a_\text{r} = 75$
Volumetric fibre content, $p_\text{vf} = 1.25\%$

Determine the total active earth pressure from the fibre-reinforced sand backfill on the retaining wall, assuming the fibre-reinforced sand behaves as an isotropic material.

5.15 For a fibre-reinforced foundation sand bed supported by a 0.75-m wide surface strip footing, consider the following:

Angle of internal friction of sand, $\phi = 35^\circ$
Total unit weight of fibre-reinforced sand, $\gamma = 16.85\ \text{kN/m}^3$
Fibre-reinforced soil-wall interface friction angle, $\delta = 15^\circ$
Fibre-soil interface friction angle, $\phi_i = 20^\circ$
Fibre aspect ratio, $a_\text{r} = 75$
Volumetric fibre content, $p_\text{vf} = 1.25\%$

Determine load-bearing capacity of the surface strip footing resting over the fibre-reinforced sand bed, assuming the fibre-reinforced sand behaves as an isotropic material.

5.16 How can you control the desiccation cracks in clay liners and covers?

5.17 Define the following terms and explain their practical significance:

(a) Traffic benefit ratio
(b) Layer reduction ratio
(c) Crack intensity ratio
(d) Crack reduction factor

5.18 What considerations are required to design fibre-reinforced pavement layers?
5.19 How can fibres help in using sand in top courses of a pavement?
5.20 Describe a practical method for improving the foundation soil using fibre inclusions.
5.21 What is the effect of fibre inclusions into the soil backfill on the lateral earth pressure against a retaining wall?
5.22 Can the use of fibres reduce the seepage through water-retaining structures? Explain with the help of a neat sketch.
5.23 What is soil piping? What is the effect of fibres on piping resistance of soil?
5.24 Discuss the effect of fibre content on the hydraulic conductivity of medium plasticity soil when it is reinforced with fibres.
5.25 With the help of a neat sketch, discuss the effect of fibre content on crack reduction factor when fibres are included in clay layers?
5.26 Visit a local construction site where the soil is being reinforced with fibres. Based on your observation, write a technical note, and identify the key aspects of the application technique.
5.27 Why should water be added prior to inclusion of fibres into soil for creating the fibre-reinforced soil?
5.28 List some major cares and considerations required for field applications of fibre-reinforced soils.
5.29 What is the most effective method of fibre inclusions in soil? What are the difficulties in mixing fibre and soil in a rotating drum mixer as the cement concrete is prepared?
5.30 What do you mean by optimum mixing moisture content? What is its practical significance and how you can estimate it?
5.31 Describe the procedure for an embankment construction using the fibre-reinforced soil.
5.32 How can you increase the durability of natural fibres for their use as soil reinforcement?
5.33 What are the benefits of inclusion of fibres into dredged sediments while dewatering them through geotextile tubes?
5.34 Discuss the quality control considerations for applications of fibre-reinforced soils.

Answers to Selected Questions

5.1 (d)
5.2 (c)
5.3 (b)
5.4 (a)
5.5 (c)
5.14 166.8 kN/m
5.15 856.4 kPa

References

Ahmad F, Bateni F, Azmi M (2010) Performance evaluation of silty sand reinforced with fibres. Geotext Geomembr 28(1):93–99

Babu GLS, Vasudevan AK (2008) Seepage velocity and piping resistance of coir fibre mixed soils. J Irrig Drainage Eng ASCE 134(4):485–492

Cabalar AF, Karabash Z (2015) California bearing ratio of a subbase material modified with tire buffings and cement addition. J Test Eval 43(6):1279–1287

Chandra S, Viladkar MN, Nagrale PP (2008) Mechanistic approach for fiber-reinforced flexible pavements. J Transp Eng ASCE 134(1):15–23

Consoli NC, Vendruscolo MRA, Prietto PDM (2003) Behaviour of plate load tests on soil layers improved with cement and fibre. J Geotech Geoenviron Eng ASCE 129(1):96–101

Consoli NC, Bassani MAA, Festugato L (2010) Effect of fiber-reinforcement on the strength of cemented soils. Geotext Geomembr 28(4):344–351

Das A, Viswanadham (2010) Experiments on the piping behaviour of geofiber-reinforced soil. Geosynth Int 7(4):171–182

Diambra A, Russell AR, Ibraim E, Wood DM (2007) Determination of fibre orientation distribution in reinforced sands. Geotechnique 57(7):623–628

Diambra A, Ibraim E, Wood DM, Russell AR (2010) Fibre reinforced sands: experiments and modelling. Geotext Geomembr 28(3):238–250

Edil TC, Bosscher PJ (1994) Engineering properties of tire chips and soil mixtures. Geotech Test J 17(4):453–464

Falorca IMCFG, Pinto MIM (2011) Effect of short, randomly distributed polypropylene microfibers on shear strength behaviour of soils. Geosynth Int 18(1):2–11

Falorca IMCFG, Gomes LMF, Pinto MIM (2011) A full-scale trial embankment construction with soil reinforced with short randomly distributed polypropylene microfibers. Geosynth Int 18 (5):280–288

Gelder C, Fowmes GJ (2016) Mixing and compaction of fibre- and lime-modified cohesive soil. Ground Improv 169, GI2:98–108

Gosavi M, Patil KA, Mittal S, Saran S (2004) Improvement of properties of black cotton soil subgrade through synthetic reinforcement. J Inst Eng India 84(2):257–262

Gray DH, Al-Refeai T (1986) Behaviour of fabric versus fiber reinforced sand. J Geotech Eng ASCE 112(8):804–820

Harr ME (1962) Groundwater and seepage. McGraw-Hill, New York

Heineck KS, Coop MR, Consoli NC (2005) Effect of microreinforcement of soils from very small to large shear strains. J Geotech Geoenviron Eng ASCE 131(8):1024–1033

Hoover JM, Moeller DT, Pitt JM, Smith SG, Wainaina NW (1982) Performance of randomly oriented fiber-reinforced roadway soils – a laboratory and field investigation. In: Iowa DOT Project Report HR-211. Department of Civil Engineering, Engineering Research Institute, Iowa State University, Ames

Ibraim E, Diambra A, Russell AR, Wood DM (2012) Assessment of laboratory sample preparation for fibre reinforced sands. Geotext Geomembr 34:69–79

Jha JN, Choudhary JN, Gill KS, Shukla SK (2014) Behaviour of plastic waste fibre-reinforced industrial wastes in pavement applications. Int J Geotech Eng 8(3):277–286

Kumar P, Singh SP (2008) Fiber-reinforced fly ash subbases in rural roads. J Transp Eng ASCE 134(4):171–180

Lindh E, Eriksson L (1990) Sand reinforced with plastic fibers – a field experiment. In: Proceedings of the international reinforced soil conference, British Geotechnical Society, Glasgow, UK, pp 471–473

Maher MH, Ho YC (1994) Mechanical properties of kaolinite/fiber soil composite. J Geotech Eng ASCE 120(8):1381–1393

Meyerhof GG, Hanna AM (1978) Ultimate bearing capacity of foundations on layered soils under inclined load. Can Geotech J 15(4):565–572

Michalowski RL (2008) Limit analysis with anisotropic fibre-reinforced soil. Geotechnique 58 (6):489–501

Michalowski RL, Cermak J (2002) Strength anisotropy of fiber-reinforced sand. Comput Geotech 29(4):279–299

Miller CJ, Rifai S (2004) Fiber reinforcement for waste containment soil liners. J Environ Eng ASCE 130(8):891–895

Nasr AM (2014) Behaviour of strip footing on fibre-reinforced cemented sand adjacent to sheet pile wall. Geotext Geomembr 42(6):599–610

Noorzad R, Amini PF (2014) Liquefaction resistance of Balolsar sand reinforced with randomly distributed fibres under cyclic loading. Soil Dyn Earthq Eng 66(11):281–292

Park T, Tan SA (2005) Enhanced performance of reinforced soil walls by the inclusion of short fiber. Geotext Geomembr 23:348–361

Perkins SW, Edens NQ (2002) Finite element and distress models for geosynthetic-reinforced pavements. Int J Pavement Eng 3(4):239–250

Perkins SW, Berg RR, Christopher BR (2002) Paved roads. In: Shukla SK (ed) Chapter 7 in Geosynthetics and their applications., Thomas Telford, London, pp 185–201

Potyondy JG (1961) Skin friction between various soils and construction materials. Geotechnique 11(4):339–353

Reddy SB, Krishna AM (2015) Recycled tire chips mixed with sand as lightweight backfill material in retaining wall applications: an experimental investigation. Int J Geosyn Ground Eng 1(4):31.1–31.11

Santoni RL, Webster SL (2001) Airfields and roads construction using fibre stabilization of sands. J Transp Eng ASCE 127(2):96–104

Santoni RL, Tingle JS, Webster SL (2001) Engineering properties of sand–fibre mixtures for road construction. J Geotech Geoenviron Eng ASCE 127(3):258–268

Sarbaz H, Ghiassian H, Heshmati AA (2014) *CBR* strength of reinforced soil with natural fibres and considering environmental factors. Int J Pavement Eng 15(7):577–583

Spritzer JM, Khachan MM, Bhatia SK (2015) Influence of synthetic and natural fibres on dewatering rate and shear strength of slurries in geotextile tube applications. Int J Geosyn Ground Eng 1(3):26.1–26.14

Tingle JS, Santoni RL, Webster SL (2002) Full-scale field tests of discrete fibre-reinforced sand. J Transp Eng ASCE 128(1):9–16

Vesic AS (1975) Bearing capacity of shallow foundations. In: Winterkorn HF, Fang H (eds) Chapter 3 in Foundation Engineering Handbook. Van Nostrand Reinhold, New York, pp 121–147

Wasti Y, Butun MD (1996) Behaviour of model footings on sand reinforced with discrete inclusions. Geotext Geomembr 14(10):575–584

Zornberg JG (2002) Discrete framework for limit equilibrium analysis of fibre-reinforced soil. Geotechnique 52(8):593–604