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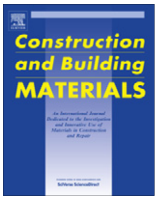

Review

A simple review of soil reinforcement by using natural and synthetic fibers

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ABSTRACT

Soil reinforcement is defined as a technique to improve the engineering characteristics of soil. In this way, using natural fibers to reinforce soil is an old and ancient idea. Consequently, randomly distributed fiber-reinforced soils have recently attracted increasing attention in geotechnical engineering for the second time. The main aim of this paper, therefore, is to review the history, benefits, applications; and possible executive problems of using different types of natural and/or synthetic fibers in soil reinforcement through reference to published scientific data. As well, predictive models used for short fiber soil composite will be discussed. On other words, this paper is going to investigate why, how, when; and which fibers have been used in soil reinforcement projects.

Contents

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1. Introduction

1.1. Essentialness of soil reinforcement

Soil can often be regarded as a combination of four basic types: gravel, sand, clay, and silt. It generally has low tensile and shear strength and its characteristics may depend strongly on the environmental conditions (e.g. dry versus wet) [1]. On the other hand, reinforcement consists of incorporating certain materials with some desired properties within other material which lack those properties [2]. Therefore, soil reinforcement is defined as a technique to improve the engineering characteristics of soil in order to develop the parameters such as shear strength, compressibility, density; and hydraulic conductivity [3]. Soil reinforcement can consist of stone columns, root piles or micro-piles, soil nailing and reinforced earth [4–6]. Mainly, reinforced earth is a composite material consisting of alternating layers of compacted backfill and man-made reinforcing material [6].

So, the primary purpose of reinforcing soil mass is to improve its stability, to increase its bearing capacity, and to reduce settlements and lateral deformation [7–9].

1.2. Different procedures of soil reinforcement

As it was mentioned, soil reinforcement is a procedure where natural or synthesized additives are used to improve the properties of soils. Several reinforcement methods are available for stabilizing problematic soils. Therefore, the techniques of soil reinforcement can be classified into a number of categories with different points of view. However, on the basis of reinforcing performance, Fig. 1 presents a state of art review of different procedures of soil reinforcement prepared by the authors.

The up–down arrows in this figure illustrate some unconventional methods of soil reinforcement achieved by the combination of randomly distributed fiber with chemical admixtures such as cement, lime and/or chemical resins.

Some of the methods appeared in Fig. 1 may have the disadvantages of being ineffective and/or expensive. So, new methods are still being researched to increase the strength properties and to reduce the swell behaviors of problematic soils [10]. It is emphasized that short fiber soil composites have recently attracted increasing attention in geotechnical engineering for the second time. This concept will be followed by this paper in the following. Consequently, studies on mechanical behavior of short fiber soil composite are comparatively new when compared to other research fields [11,12].

2. Fibers and soil reinforcement

2.1. Definition

The standard fiber-reinforced soil is defined as a soil mass that contains randomly distributed, discrete elements, i.e. fibers, which provide an improvement in the mechanical behavior of the soil composite [13].

Fiber reinforced soil behaves as a composite material in which fibers of relatively high tensile strength are embedded in a matrix of soil. Shear stresses in the soil mobilize tensile resistance in the fibers, which in turn imparts greater strength to the soil [14–16].

Mainly, the use of random discrete flexible fibers mimics the behavior of plant roots and contributes to the stability of soil mass by adding strength to the near-surface soils in which the effective stress is low [17–19]. In this way, laboratory and some in situ pilot test results have led to encouraging conclusions proving the potential use of fibers for the reinforcement of soil mass providing an artificial replication of the effects of vegetation [20–24].

2.2. Classification

A comprehensive literature review shows that short fiber soil composite can be considered as a coin with two sides (see Fig. 1). One side includes the randomly direct inclusion of fibers into the matrix, i.e. soil mass. Another side comprises the oriented fibrous materials, e.g. Geo-Synthetics family [6,25,26]. It is emphasized that the former concept is not as well-known as the second, not only in optimizing fiber properties, fiber diameter, length, surface texture, etc., but also in reinforcing mechanism [25].

McGown et al. classified soil reinforcement into two major categories including ideally inextensible versus ideally extensible inclusions. The former includes high modulus metal strips that strengthens soil and inhibits both internal and boundary deformations. Catastrophic failure and collapse of soil can occur if reinforcement breaks. Ideally extensible inclusions include relatively low modulus natural and/or synthetic fibers, plant roots; and geosynthetics. They provide some strengthening but more importantly they present greater extensibility (ductility); and smaller loss of post-peak strength compared to the neat soil [6,27].

2.3. Brief history

The stabilization of soils has been performed for millennia. For instance, the Mesopotamians and Romans separately discovered that it was possible to improve the ability of pathways to carry traffic by mixing the weak soils with a stabilizing agent like pulverized limestone or calcium [28].

Alternatively, the presence of plant roots is a natural means of incorporating randomly oriented fiber inclusions in the soils. These plant fibers improve the strength of the soils and the stability of natural slopes [29–33]. Therefore, the concept of fiber reinforcement was recognized more than 5000 years ago. For example, ancient civilizations used straw and hay to reinforce mud blocks in order to create reinforced building blocks [34]. There are several examples of reinforcing the soil like Great Wall of China (earliest example of reinforced earth using branches of trees as tensile elements), ziggurats of Babylon (woven mats of read were used), etc. [35].

In the modern history of soil stabilization, the concept and principle of soil reinforcement was first developed by Vidal. He demonstrated that the introduction of reinforcing elements in a soil mass increases the shear resistance of the medium [36,37]. Consequently, efforts for using fibrous materials, as mimicry of the past, were started. Since the invention by Vidal in 1966, nearly 4000 structures have been built in more than 37 countries so far using the concept of earth reinforcement [38,39].

Firstly, polyester filaments before staple fibers entered to the geotechnical engineering market under the traditional brand of "Texsol". This product was used in retaining walls and for slope protections. However, randomly distributed fiber-reinforced soils, known as short fiber soil composites, have recently attracted increasing attention in many geotechnical engineering applications, not only in scientific research environment, but also at executive real field [40]. Synthetic staple fibers have been used in soil since the late 1980s, when the initial studies using polymeric fibers were conducted [13].

At final, it can be concluded that the concept of reinforcing soil with natural fibers was originated in ancient times. However, short natural and synthetic fiber soil composites have recently attracted increasing attention in geotechnical engineering for the second time. Therefore, they are still a relatively new technique in geotechnical projects.

3. Case studies of fibers

3.1. Natural fibers

At the present time, there is a greater awareness that landfills are filling up, resources are being used up, the planet is being polluted and that non-renewable resources will not last forever. So, there is a need to more environmentally friendly materials. That is why there have been many experimental investigations and a great deal of interest has been created world wide on potential applications of natural fibers for soil reinforcement in recent years. The term "eco-composite" shows the importance role of natural fibers in the modern industry [41].

Mainly, what part of the plant the fiber came from, the age of the plant; and how the fiber was isolated, are some of the factors which affect the performance of natural fibers in a natural fiber-reinforced soil [42].

It is necessary to mention that natural fibers have been used for a long time in many developing countries in cement composites and earth blocks because of their availability and low cost [43–45]. At this point, some natural fibers and their features in soil projects are briefly described:

3.1.1. Coconut (coir) fiber

The outer covering of fibrous material of a matured coconut, termed coconut husk, is the reject of coconut fruit. The fibers are normally 50–350 mm long and consist mainly of lignin, tannin, cellulose, pectin and other water soluble substances. However, due to its high lignin content, coir degradation takes place much more slowly than in other natural fibers. So, the fiber is also very long lasting, with infield service life of 4–10 years. The water absorption of that is about 130–180% and diameter is about 0.1–0.6 mm [42].

Coir retains much of its tensile strength when wet. It has low tenacity but the elongation is much higher [46]. The degradation of coir depends on the medium of embedment, the climatic conditions and is found to retain 80% of its tensile strength after 6 months of embedment in clay. Coir geo-textiles are presently available with wide ranges of properties which can be economically utilized for temporary reinforcement purposes [47]. Mainly, coir fiber shows better resilient response against synthetic fibers by higher coefficient of friction. For instance, findings show that coir fiber exhibits greater enhancements (47.50%) in resilient modulus or strength of the soil than the synthetic one (40.0%) [48]. Ayyar et al. and Viswanadham have reported about the efficacy of randomly distributed coir fibers in reducing the swelling tendency of the soil [49,50].

Ravishankar and Raghavan confirmed that for coir-stabilized lateritic soils, the maximum dry density (MDD) of the soil decreases with addition of coir and the value of optimum moisture content (OMC) of the soil increases with an increase in percentage of coir. The compressive strength of the composite soil increases up to 1% of coir content and further increase in coir quantity results in the reduction of the values. The percentage of water absorption increases with an increase in the percentage of coir. Tensile strength of coir-reinforced soil (oven dry samples) increases with an increase in the percentage of coir [48,51].

Khedari et al. introduced a new type of soil–cement block reinforced with coir fibers with low thermal conductivity [52].

Black cotton soil treated with 4% lime and reinforced with coir fiber shows ductility behavior before and after failure. An optimum fiber content of 1% (by weight) with aspect ratio of 20 for fiber was recommended for strengthening the BC soil [53].

3.1.2. Sisal

Sisal is a lingo-cellulosed fiber [54] in which its traditional use is as a reinforcement for gypsum plaster sheets in building industry with 60–70% of water absorption and diameter about 0.06–0.4 mm. Sisal fibers are extracted from the leaves of the plants, which vary in size, between 6–10 cm in width and 50–250 cm in length. In general, Brazil, Indonesia and East African countries are the world's main producers of sisal fibers [55].

Ghavami et al. found that inclusion of 4% sisal, or coconut fiber, imparted considerable ductility and slightly increased the compressive strength. It was also found that introduction of bitumen emulsion did not improve the bonding between the soil and fibers; but did significantly improve soil durability [43].

Prabakar and Siridihar used 0.25%, 0.5%, 0.75% and 1% of sisal fibers by weight of raw soil with four different lengths of 10, 15, 20 and 25 mm to reinforce a local problematic soil. They concluded that sisal fibers reduce the dry density of the soil. The increase in the fiber length and fiber content also reduces the dry density of the soil. As well it was found that the shear stress is increased non-linearly with increase in length of fiber up to 20 mm and beyond, where an increase in length reduces the shear stress. The percentage of fiber content also improves the shear strength. But beyond 0.75% fiber content, the shear stress reduces with increase in fiber content [56].

Sisal fiber reinforced soils stabilized with cement were used as a building material by Mattone. The author emphasizes on natural and ecological aspects of the innovation [57].

3.1.3. Palm fibers

The palm fibers in date production have filament textures with special properties such as low costs, plenitude in the region, durability, lightweight, tension capacity and relative strength against deterioration [58]. Fibers extracted from decomposed palm trees are found to be brittle, having low tensile strength and modulus of elasticity and very high water absorption [59].

Unconfined compression strength (UCS), California Bearing Ratio (CBR) and compaction tests were performed on neat and palm fiber reinforced soil samples by Marandi et al. They reported that at a constant palm fiber length, with increase in fiber inclusion (from 0% to 1%), the maximum and residual strengths were increased, while the difference between the residual and maximum strengths was decreased. A similar trend was observed for constant palm fiber inclusion and increase in palm fiber length (from 20 mm to 40 mm) [60].

Jamellodin et al. found that a significant improvement in the failure deviator stress and shear strength parameters (C and Φ) of the soft soil reinforced with palm fibers can be achieved. It is observed that the fibers act to interlock particles and group of particles in a unitary coherent matrix thus the strength properties of the soil can be increased [61].

Ahmad et al. mixed palm fibers with silty sand soil to investigate the increase of shear strength during triaxial compression. The specimens were tested with 0.25% and 0.5% content of palm fibers of different lengths (i.e. 15 mm, 30 mm and 45 mm). Reinforced silty sand containing 0.5% coated fibers of 30 mm length exhibited approximately 25% increase in friction angle and 35% in cohesion compared to those of unreinforced silty sand. In addition, palm fibers coated with acrylic butadiene styrene thermoplastic increased the shear strength of silty sand much more compared to uncoated fibers [62].

Sallehan and Yaacob found that the addition of 3% palm fibers improve the compressive strength of composite bricks. Water absorption test results indicated a small increase in water absorption with the increase in the palm fiber content [63].

3.1.4. Jute

Jute is abundantly grown in Bangladesh, China, India and Thailand. Jute fibers are extracted from the fibrous bark of jute plants which grow as tall as 2.5 m with the base stem diameter of around 25 mm. There are different varieties of jute fibers with varying properties [59].

Jute is mainly environmental-friendly fiber that is used for producing porous textiles which are widely used for filtration, drainage, and soil stabilization [64]. For instance, GEOJUTE® is the commercial name of a product woven from jute fibers used for soil stabilization in pavement engineering [65].

Aggarwal and Sharma used different lengths (5–20 mm) of jute fibers in different percentages (0.2–1.0%) to reinforce soil. Bitumen was used for coating fibers to protect them from microbial attack and degradation. They concluded that jute fiber reduces the MDD while increases the OMC. Maximum CBR value is observed with 10 mm long and 0.8% jute fiber, an increase of more than 2.5 times of the plain soil CBR value [66].

Islam and Ivashita showed that jute fibers are effective for improving the mortar strength as well as coherence between block and mortar [67].

3.1.5. Flax

Flax is probably the oldest textile fiber known to mankind. It has been used for the production of linen cloth since ancient times [68]. Flax is a slender, blue flowered plant grown for its fibers and seeds in many parts of the world [59].

In an effort, Segetin et al. improved the ductility of the soil–cement composite with the addition of flax fibers. An enamel paint coating was applied to the fiber surface to increase its interfacial bond strength with the soil. Fiber length of 85 mm along with fiber content levels of 0.6% was recommended by the authors [69].

"Uku" is a low-cost flax fiber-reinforced stabilized rammed earth walled housing system that has been recently designed as a building material. In this way, a mobile flax machine is used enabling the fast and mobile processing of flax leaves into flax fibers [70].

3.1.6. Barely straw

Barley straw is widely cultivated and harvested once or twice annually in almost all rural areas in all over the world and could be used in producing composite soil blocks with better characteristics, but relatively few published data is available on its performance as reinforcement to soil or earth blocks. It is important to know that during the Egyptian times, straws or horsehairs were added to mud bricks, while straw mats were used as reinforcements in early Chinese and Japanese housing construction [63,71,72]. From the late 1800s, straw was also used in the United States as bearing wall elements [73]. Barely straw is claimed to be the most cost-effective mulch practice to retain soil in artificial rainfall tests [74].

Bouhicha et al. proved the positive effects of adding straw in decreasing shrinkage, reducing the curing time and enhancing compressive strength if an optimized reinforcement ratio is used. Flexural and shear strengths were also increased and a more ductile failure was obtained with the reinforced specimen [75].

A mixture of barely straw with cement can form a sustainable low-cost building material, which also reduces atmospheric pollution [76]. In addition to these benefits, the straw could act as a thermal insulation material for the unpleasant weather conditions to create pleasant indoor temperatures [75].

Two types of natural fibers including wheat straw, barley straw and wood shavings were used by Ashour et al. to make a novel plaster material composed of cohesive soil and sand. They concluded while fibers have remarkable effect on the strength and ductility of plasters, their effects on the elastic modulus of plasters are relatively small [77].

Abtahi et al. showed that barley straw fibers are most effective on the shear strength of the soil than Kenaf fibers. The optimized fiber content was 1% [78].

3.1.7. Bamboo

Bamboo fiber is a regenerated cellulose fiber. It is a common fact that bamboo can thrive naturally without using any pesticide. The fiber is seldom eaten by pests or infected by pathogens. So, scientists found that bamboo owns a unique anti-bacteria and bacteriostatic bio-agent named "Bamboo Kun" [79]. It is important to know that the root rhizomes of bamboo are excellent soil binders which can prevent erosion [80,81].

Bamboo fibers are remarkably strong in tension but have low modulus of elasticity about 33–40 kN/mm^2 and high water absorption about 40–45% [59,82].

The tests undertaken by Coutts showed that the bamboo fiber is a satisfactory fiber for incorporation into the cement matrix [52,83]. Therefore, Ramaswamy et al. studied the behavior of concrete reinforced with bamboo fibers. The results show that these fibers can be used with advantage in concrete in a manner similar to other fibers [52,84]. It seems that the combination of cement and the root rhizomes of bamboo open a new window for soil reinforcement process.

3.1.8. Cane

Cane or sugarcane belongs to grass family and grows up to 6 m high and has a diameter up to 6 cm and bagasse is the fibrous residue which is obtained in sugarcane production after extraction of the juice from the cane stalk. The fiber diameter is up to 0.2–0.4 mm. However, waste cane fiber has limited use in most typical waste fiber applications because of the residual sugars and limited structural properties within the fiber. But, the residual sugars can result a detrimental impact on the finished product, i.e. a stiffer bonding phase generates in the composite structure. Therefore, "Cement Board" produced from sugar cane waste has been recently introduced to the market [85]. The authors recommend the application of these fibers in soil reinforcement as an empty research area. Table 1 shows summary of researches performed on natural-fiber reinforced-soil.

Table 1
Summary of researches performed on widely-used natural-fibers to reinforce soil.

Fiber type	D (μm)	SG (g/cm^3)	E (GPa)	UTS (MPa)	Length (mm)	Optimized fiber percentage	Fiber special property	Soil types used in the literature	Conclusions	References
Coir fibers	10–20	1.15–1.33	4–5	250	Randomly distributed: 10–500 mm and 50 mm	1% by weight with aspect ratio of 20	– Retains much of its tensile strength when wet – Low tenacity but high elongation – Keeps 80% of its tensile strength after 6 months of embedment in clay	– Black cotton – Lateritic soil – Clay	– Fibers decrease the MDD of the soil while increase the OMC – The compressive and tensile strength of the composite soil increases up to 1% of coir content – Fiber–soil–cement block has low thermal conductivity	[42–53]
Sisal fibers	25–400	1.2–1.45	26–32	560	10, 15, 20 and 25; 20 mm: optimized	0.75%	– Traditional use as a reinforcement for gypsum plaster sheets −60% to 70% of water absorption.	– Clay – Silty sand	– Fiber imparts considerable ductility and slightly increases the compressive strength – The shear strength of the composite soil is increased non-linearly with increase in length of fiber up to 20 mm and 0.75% fiber content	[54–57]
Palm fibers	25–60	1.3–1.46	0.55	21–60	15, 20, 30, 40 and 45; 30 mm: optimized	0.5%	– Low cost, plenitude in the region, durability, lightweight, relative strength against deterioration – Low tensile strength and modulus with very high water absorption	– Silty sand	– Fiber increases the UCS, CBR and shear strength parameters (C and Φ) of the soft soil – 3% palm fibers improve the compressive strength of composite bricks.	[58–63]
Jute fibers	10–50	1.44–1.46	22	453–550	5, 10, 15 and 20; 10 mm: optimized	0.8%	– Used for producing porous textiles which are widely used for filtration, drainage, and soil stabilization – Soft clay (expansive soil)	– Clay	– Fiber reduces the MDD while increases the OMC. CBR value is increased more than 2.5 times compared to the plain soil CBR value	[68–70]
Barley-straw fibers	1000–4000	2.05	–	–	Randomly distributed: 10–500 mm	1%	– Widely cultivated and harvested in all over the world – Commonly used in producing composite soil blocks	– Clayey silty soil – Clayey sandy soil – Silty sand	– Fiber decreases shrinkage, reduces the curing time and enhances compressive strength if an optimal reinforcement ratio is used. Flexural and shear strengths are also increased and a more ductile failure can be obtained	[63–78]

D: Diameter, SG: specific gravity, UTS: ultimate tensile strength, some of fiber properties can be found in Ref. [2].

3.2. Synthetic (man-made) fibers

3.2.1. Polypropylene (PP) fibers

Polypropylene fiber is the most widely used inclusion in the laboratory testing of soil reinforcement [86–91]. Currently, PP fibers are used to enhance the soil strength properties, to reduce the shrinkage properties and to overcome chemical and biological degradation [92–94].

Puppala and Musenda indicated that PP fiber reinforcement enhanced the unconfined compressive strength (UCS) of the soil and reduced both volumetric shrinkage strains and swell pressures of the expansive clays [94].

From the experiments on field test sections in which a sandy soil was stabilized with PP fibers, Santoni and Webster concluded that the technique showed great potential for military airfield and road applications and that a 203-mm thick sand fiber layer was sufficient to support substantial amounts of military truck traffic. Field experiments also indicated that it was necessary to fix the surface using emulsion binder to prevent fiber pullout under traffic [95].

Consoli et al. investigated the load–settlement response carried out on a thick homogeneous stratum of compacted sandy soil reinforced with PP fibers. The PP-reinforced specimens showed a marked hardening behavior up to the end of the tests, at axial strains larger than 20%, whereas the non-reinforced specimens demonstrated an almost perfectly plastic behavior at large strain. This improvement suggests the potential application of fiber reinforcement in shallow foundations, embankments over soft soils, and other earthworks that may suffer excessive deformation [96].

Setty and Rao and Setty and Murthy carried out tri-axial tests, CBR tests and tensile strength tests on silty sand and black cotton soil, reinforced with PP fibers. The test results illustrated that both of the soils showed a significant increase in the cohesion intercept and a slight decrease in the angle of internal friction with an increase in fiber content up to 3% by weight [60,97,98].

The effects of PP fiber inclusions on the soil behavior could be visually observed during the triaxial testing [99] and/or UCS testing [5] shown in Fig. 2. Axial deformation of the unreinforced specimen resulted in the development of a failure plane, while PP reinforced specimens tended to bulge, indicating an increase in the ductility of fiber–soil mixture [99].

The efficacy of combination of fly ash and PP fibers in reducing swelling and shrinkage characteristics has been also reported [89,100,101]. The available reports show that PP fiber reinforcements reduce the swelling potential of expansive clays.

In an extensive study, Yetimoglu et al. conducted a set of CBR tests on geotextile-reinforced sand specimens overlying soft clay under PP-reinforced soil. They concluded that the penetration value at which the piston load was the highest tended to increase with increasing fiber reinforcement content. In addition, the test

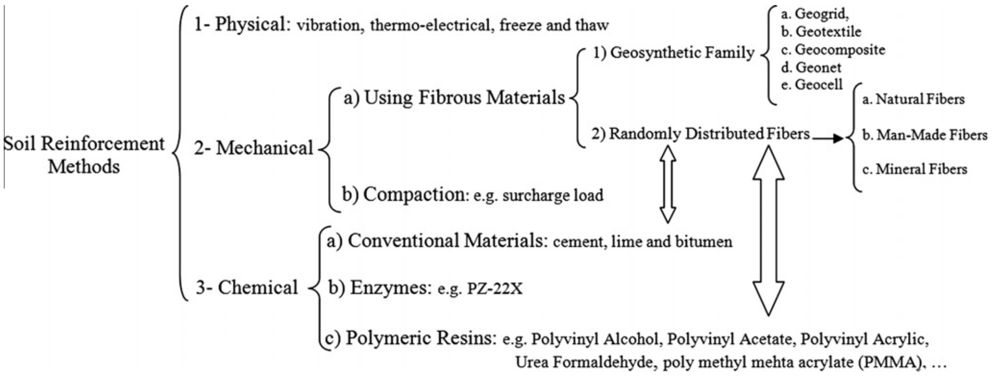

Fig. 1. Different procedures of soil reinforcement.

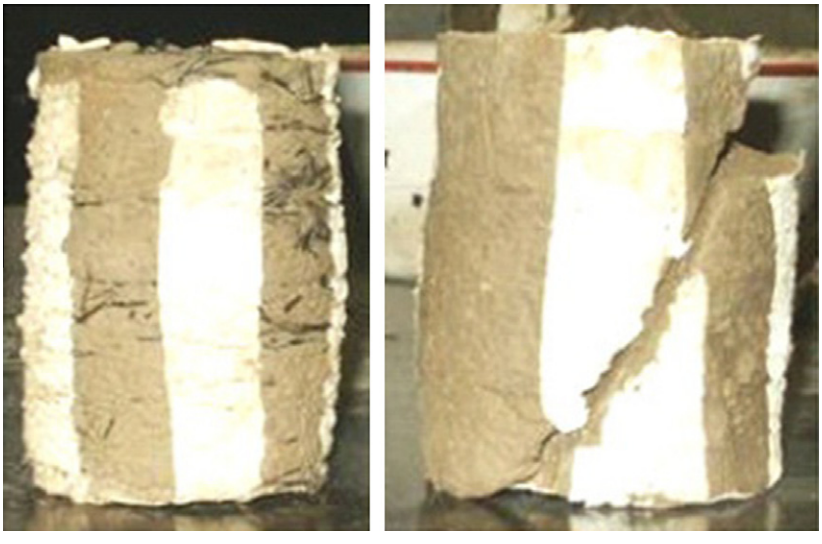

Fig. 2. Specimen deformation pattern for (left) unreinforced clay soil specimens and (right) clay soil reinforced with 0.25% PP of 19 mm: Freilich et al. [99].

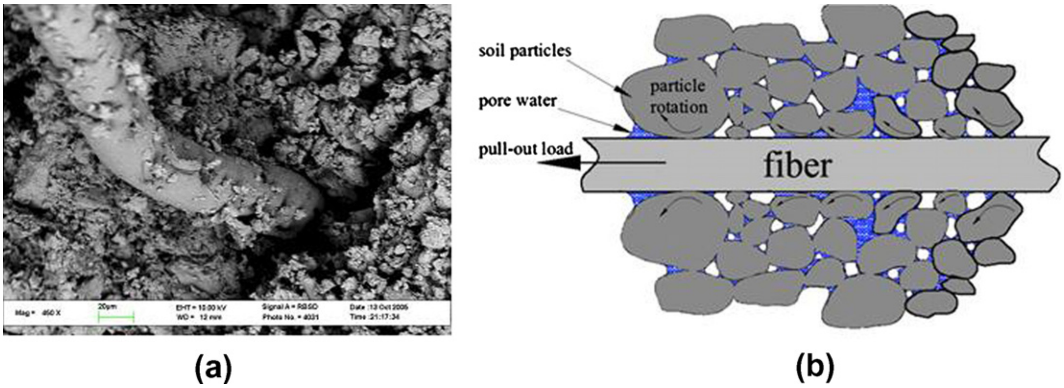

Fig. 3. (a) SEM photomicrograph of soil particles attached on fiber surface after pull-out test and (b) sketch drawing of interfacial mechanical interactions between soil particles and fiber: Tang et al. [107].

results showed that increasing fiber reinforcement content could increase the brittleness of the fiber-reinforced sand fill–soft clay system providing higher loss of post-peak strength [91].

Tang et al. reinforced kaolinite soil with PP fibers and observed an increase in the unconfined compressive strength [102].

PP reinforced sand has been tested in conventional triaxial compression and extension. The contribution of fibers to the strength was reported remarkable in compression while limited in extension confirming that it depends primarily on their orientation with respect to tensile strains [103].

Consoli et al. conducted a set of drained standard triaxial tests on artificially cemented sand specimens reinforced with randomly oriented PP fibers. The fiber reinforcement increased peak strength just up to a certain cement content (up to about 5%), increased ultimate strength, decreased stiffness, and changed the cemented sand brittle behavior to a more ductile one. The triaxial peak strength increase due to fiber inclusion is more effective for smaller amounts of cement, while the increase in ultimate strength is more efficacious when fiber is added to sand improved with higher cement contents [104].

Zaimoglu found that the mass loss in PP reinforced soils (12 mm, 0.75% of total dry soil) was almost 50% lower than that in the un-reinforced soil. It was also illustrated that the unconfined compressive strength of specimens subjected to freezing–thawing cycles generally increased with the increasing fiber content [105].

Ghazavi and Roustaie showed that the addition of 3% polypropylene fibers (12 mm) results in the increase of UCS of the soil before and after applying freeze–thaw cycles by 60–160% and decrease of frost heave by 70% [106].

Tang et al. investigated the micromechanical interaction behavior between soil particles and reinforcing PP fibers. They concluded that the interfacial shear resistance of fiber/soil depends primarily on the rearrangement resistance of soil particles, effective interface contact area, fiber surface roughness and soil composition. As well, a soil–fiber pull out test apparatus was made by the authors [107]. Fig. 3 illustrates the real and the schematic of fiber and soil interaction.

3.2.2. Polyester (PET) fibers

Consoli et al. indicated that inclusion of PET fiber in fine sand improves both peak and ultimate strength which is dependent on fiber content [108].

Kumar et al. tested highly compressible clay in UCS test with 0%, 0.5%, 1.0%, 1.5% and 2.0% flat and crimped polyester fibers. Three lengths of 3 mm, 6 mm and 12 mm were chosen for flat fibers, while crimped fibers were cut to 3 mm long. The results indicate that as the fiber length and/or fiber content increases, the UCS value will improve. Crimping of fibers leads to increase of UCS slightly [109]. These results are well comparable to those found by Tang et al. [102].

The study on soil fly ash mixture reinforced with 0.5% and 1% polyester fibers 20 mm in length was conducted in India by Kaniraj and Havanagi, which indicated the combined effect of fly ash and fiber on soil [110,111]. Kumar et al. indicated the effect of polyester fiber inclusion on expansive soil with optimized dose of lime and fly ash [110,112].

Maheshwari mixed polyester fibers of 12 mm in length with highly compressible clayey soil vary from 0% to 1%. The results indicated that reinforcement of highly compressible clayey soil with randomly distributed fibers caused an increase in the ultimate bearing capacity and decrease in settlement at the ultimate load. They concluded that the soil bearing capacity and the safe bearing pressure (SBP) both increase with increase in fiber content up to 0.50% and then it decreases with further inclusion of fibers [113].

Japanese scientists have been found that short PET fiber (64 mm) reinforced soil had high piping resistance, and that the short fiber reinforced soil layer increased the stability of levee against seepage of rainfall and flood [114].

3.2.3. Polyethylene (PE) fibers

The feasibility of reinforcing soil with polyethylene (PE) strips and/or fibers has been also investigated to a limited extent [91,115–118]. It has been reported that the presence of a small fraction of high density PE (HDPE) fibers can increase the fracture energy of the soil [119]. Nowadays, GEOFIBERS®, typically 1–2 in. long discrete PP and/or PE fibrillated or tape strands, are mixed or blended into sand or clay soils [120,121]. But, it is important to know that some researchers have applied the term "Geofiber" for PP fibers used in soil reinforcement [e.g. 89,99,121].

Sobhan and Mashand demonstrated the importance of using toughness as a measure of performance. These studies showed that increases in tensile strength with added HDPE strips were not realized but large increases in toughness resulting from increased strain capacity was observed. With increasing toughness, much of the expected performance benefits due to fiber inclusion are in the post-peak load portion of the stress–strain behavior. Thus, as the fibers develop tension, an improved stress–strain response is the result. However, improvements in fatigue behavior were not noted [118,122].

Kim et al. used PE waste fishing net (0%, 0.25%, 0.5%, 0.75%, and 1%) to reinforce lightweight soil derived from dredging process.

They found that the maximum increase in compressive strength was obtained for a waste fishing net content of about 0.25% [123].

Choudhary et al. reported that the addition of reclaimed HDPE strips to local sand increases the CBR value and secant modulus. The maximum improvement in CBR and secant modulus is obtained when the strip content is 4% with the aspect ratio of 3, approximately three times that of an unreinforced system. As well, base course thickness can be significantly reduced if HDPE strip reinforced sand is used as sub-grade material in pavement engineering [119].

As it can be seen environmental purposes are the main reason of using PE fibers and/or strips in geotechnical engineering to landfill the waste PE-based materials.

3.2.4. Glass fibers

Consoli et al. indicated that inclusion of glass fibers in silty sand effectively improves peak strength [23,110].

In another work, Consoli et al. examined the effect of PP, PET and glass fibers on the mechanical behavior of fiber-reinforced cemented soils. Their results showed that the inclusion of PP fiber significantly improved the brittle behavior of cemented soils, whereas the deviatoric stresses at failure slightly decreased. Unlike the case of PP fiber, the inclusion of PET and glass fibers slightly increased the deviatoric stresses at failure and slightly reduced the brittleness [124].

Maher and Ho studied the behavior of kaolinite–fiber (PP and glass fibers) composites, and found that the increase in the UCS was more pronounced in the glass fiber-reinforced specimens [125].

Conversely, Al-Refeai reported that PP fiber outperformed glass fiber [126]. Maher and Ho found that the inclusion of 1% glass fiber to 4% cemented sand resulted in an increase of 1.5 times in the UCS when compared to non-fiber-reinforced cemented sand [127].

Nowadays, fiberglass threads termed "roving" can be used to reinforce cohesionless soils. The volume of fiberglass fibers is generally between 0.10% and 0.20% of the weight of the soil mixture by weight. Experimental studies have indicated that embedded roving increases soil cohesion between 100 and 300 kN/m^2. It is interesting to know that the fiberglass roving is an effective promoting seed adhesion and root penetration [128].

3.2.5. Nylon fiber

Kumar and Tabor studied the strength behavior of nylon fiber reinforced silty clay with different degree of compaction. The study indicates that peak and residual strength of the samples for 93% compaction are significantly more than the samples compacted at the higher densities [110,129].

Gosavi et al. reported that by mixing nylon fibers and jute fibers, the CBR value of soil is enhanced by about 50% of that of unreinforced soil, whereas coconut fiber increases the value by as high as 96%. The optimum quantity of fiber to be mixed with soil is found to be 0.75% and any addition of fiber beyond this quantity does not have any significant increase in the CBR value [48,130].

Murray et al. conducted a laboratory test program to evaluate the properties of nylon carpet waste fiber reinforced sandy silt soil. Increasing the triaxial compressive strength by 204% with 3% carpet fibers and ductility of soil were reported by the authors [131]. As well, field trials have showed that shredded carpet waste fibers (to 70 mm long) can be blended into soil with conventional equipment. The availability of low cost fibers from carpet waste could lead to wider use of fiber reinforced soil and more cost-effective construction [132–134].

3.2.6. Steel fibers

Steel fiber reinforcements found in concrete structures are also used for the reinforcement of soil–cement composites [69,135,136]. In addition, steel fibers can improve the soil strength but this improvement is not compared with the case of using other types of fibers [106,137].

However, Ghazavi and Roustaie recommended that in cold climates, where soil is affected by freeze–thaw cycles, polypropylene fibers are preferable to steel fibers. Since, polypropylene fibers possess smaller unit weight than steel fibers. In other words, the former fibers decrease the sample volume increase more than steel fibers [106].

3.2.7. Polyvinyl alcohol (PVA) fibers

Polyvinyl alcohol (PVA) fiber is a synthetic fiber that has recently been used in fiber-reinforced concrete, since its weather resistance, chemical resistance (especially alkaline resistance), and tensile strength are superior to that of PP fiber. PVA fiber has a significantly lower shrinkage from heat than nylon and/or polyester. It has a specific gravity of 1.3 g/cm^3, a good adhesive property to cement; and high anti-alkali characteristics. For this reason, it is suitable for using PVA fiber as a soil reinforcing material [138]. Therefore, the inclusion of PVA fiber seems to produce more effective reinforcement in terms of strength and ductility when compared to other fibers under the same cementation.

Park et al. found that the addition of 1% polyvinyl alcohol (PVA) fiber to 4% cemented sand resulted in a two times increase in both the UCS and the axial strain at peak strength when compared to non-fiber-reinforced specimen [138,139]. As well, Park reported that at 1% fiber dosage, the values of ductility are greater than four, regardless of cement ratios [190].

Table 2 shows summary of researches performed on synthetic-fiber reinforced-soil.

4. Sample preparation

The mixing of fibers through soil composites is not well discussed in the literature [69,140]. But, the major area of concern is the tangling of fibers, which often makes it very difficult to obtain a homogenous mixture. If adequate mixing techniques cannot be developed, large scale production of fiber-reinforced soil mixtures will not be feasible [69]. Some information is provided by Allen that folding fibers through a soil matrix is the most effective method of mixing. This can be done with the use of a front-end loader, bobcat or similar device with a bucket attachment [140].

Mainly, there are two methods which can be taken when investigating the mixing of fiber with a soil composite. Fibers can either be mixed through the soil matrix material manually or a mechanical means of mixing can be used. The mechanical procedure can be divided into three categories including cultivator mixing, concrete mixer and tumble mixer [69].

Many published experimental studies implicitly assume that the fibers are randomly oriented throughout the soil mass. Such a distribution of orientation would preserve the soil strength isotropy and eventually avoid or delay formation of localized deformation planes. However, it has been found that the most common procedure for preparing reinforced specimens, moist tamping, leads to preferred sub-horizontal orientation of fibers [141]. Similar results have been found for vibrated fiber reinforced specimens [142]. Since rotations of principal stress and strain rate axes almost always occur within a soil mass, the consequence of an assumed isotropy would be the overestimation of soil design strength for certain loadings [103].

5. Predictive models of fiber-reinforced soil

Fiber reinforced soil structures have been conventionally designed using composite approaches to characterize the contribution of fibers to stability. In these cases, the mixture is considered

Table 2
Summary of researches performed on widely-used synthetic-fibers to reinforce soil.

Fiber type	D (μm)	SG (g/cm^3)	E (GPa)	UTS (MPa)	Length (mm)	Fiber percentage	Fiber special property	Soil types used in the literature	Conclusions	References
Polypropylene fibers	23–150	0.92	3–3.5	120–450	6, 12, 18, 24, 35 and 50	0–3%	Hydrophobic, non-corrosive and resistant to alkalis, chemicals and chlorides, economical, the most widely used inclusion in soil reinforcement	– Sand – Silty sand – Clayey Soil – Black Cotton	Fibers enhance the soil strength and ductility, reduce the swelling and shrinkage properties and overcome chemical and biological degradation, improve the freeze–thaw resistance	[92–107]
Polyester fibers	30–40	1.35	10–30	400–600	3, 6, 12, 20 and 64	0–1%	Hydrophobic, non-corrosive and resistant to alkalis, chemicals and chlorides, relatively economical compared to PP fibers	– Fine sand – Clayey soil	Fibers improve both peak and ultimate strength of the soil, crimping of fibers leads to increase of UCS slightly, the UCS value will improve as the fiber length and/or fiber content increases	[108–114]
Polyethylene fibers	400–800	0.92	0.14–1	100–620	12, 25 and 50	0–4%	Plastic materials usually made of Polyethylene, economical especially in waste management	– Clayey soil – Sand	Fibers can increase the fracture energy, the CBR value, the toughness and the secant modulus of the soil	[115–123]
Glass fibers	3–19	2.49–2.60	53–95	1500–5000	25	0–1%	A fiber with high modulus of elasticity	– Silty sand –Sand	Fiber increases soil cohesion between 100 and 300 kN/m^2. 1% glass fiber to cemented sand resulted in an increase of 1.5 times in the UCS compared to non-fiber-reinforced cemented sand. Fiber in silty sand effectively improves peak strength	124–128
Polyvinyl alcohol fibers	100	1.3	25	1078	12	1%	Weather resistance, better tensile strength to that of PP fiber, significantly lower shrinkage from heat than nylon or polyester, a good adhesive property to cement; and high anti-alkali characteristics	– Cemented river sand	Two times increase in both the UCS and the axial strain at peak strength when compared with the non-fiber-reinforced specimen. Increase of ductility	[138,139,190]

D: Diameter, SG: Specific Gravity, UTS: ultimate tensile strength, some of fiber properties can be found in Ref. [2].

as a homogenous composite material. The contribution of the fibers has been typically quantified by an equivalent friction angle and cohesion of soil. A comprehensive literature review shows that composite models have been proposed by several investigators including mechanistic models [143,144], a statistical model [145], and an energy-based limit analysis model [146]. An overview of these composite models is presented in the following.

Gray and Ohashi proposed a force equilibrium model based on the results of a series of direct shear tests conducted on certainly fiber-orientation reinforced sands. Along the shear plane, the shearing of soil is assumed to cause fiber distortion, thereby mobilizing its tensile resistance (see Fig. 4). The model assumes that fiber length, interface friction and confining pressure are large enough to avoid pullout failure. Consequently, the fiber-induced tension σ_t can be expressed as a function of fiber modulus E_f, interface frictional resistance along fiber τ_f, fiber diameter d_f and thickness of the shear zone z, as follows:

$$\sigma_t = (4E_f\tau_f z/d_f)(\sec\varphi - 1)^{0.5} \quad (1)$$

where φ is the friction angle of the soil. Thus, the mobilized tensile strength, t, is given by:

$$t = (A_f/A)\sigma_t \quad (2)$$

where A_f and A are area of fibers in shear and total area of soils in shear, respectively. Therefore, the shear strength increase ΔS, due to the fiber-reinforcement of the composite can be determined from force equilibrium considerations, and can be proposed by the following equation if fibers are perpendicular to the shear plane:

$$\Delta S = t(\sin\theta + \cos\theta\tan\varphi) \quad (3)$$

where θ is the angle of shear distortion. The extended equation developed for the case in which the fibers are oblique can be found in Ref. [143].

Maher and Gray further expanded the model proposed by Gray and Ohashi to randomly-distributed fibers by incorporating statistical concepts. The average embedment length for randomly distributed fiber was adopted as ¼ of the fiber length on either side of the failure plane. So, the average number of fibers N_s, intersecting the unit area of the shear plane can obtained as:

$$N_s = (2 \times v_f)/(\pi d_f^2) \quad (4)$$

where v_f is the volumetric fiber content. It is proved that the tensile stress developed in fibers can be obtained from:

$$\sigma_t = 2(\sigma_n\tan\delta) \times (L_f/d_f) \quad (5)$$

where σ_n is confining stress acting on the fibers and δ is the angle of skin frictional resistance. The shear strength increase ΔS, due to fiber-reinforcement can be calculated through the following:

$$\Delta S = N_s(\pi d_f^2/4)[2(\sigma_n\tan\delta) \times (L_f/d_f)](\sin\theta + \cos\theta\tan\varphi)(\xi) \quad (6)$$

where ξ is an empirical coefficient depending upon sand parameters.

Unfortunately, the two models are valid only for extensible fiber with a frictional surface. Commonly used polymeric fibers have relatively high tensile strength and deformation modulus but relatively low interface friction. Consequently, these models may be inadequate when failure is governed by the pullout of fibers. As well, the two models require determination of the thickness of the shear zone as an input parameter, which is difficult to quantify.

Ranjan et al. derived an expression for the shear strength of fiber reinforced soil using a regression analysis of test results from a series of triaxial compression tests. Fiber content, fiber aspect ratio, fiber–soil interface friction; and shear strength of unreinforced soil were identified as the main variables influencing the shear strength. The shortcoming of Ranjan's model is that it does not reflect the mechanisms of fiber-reinforcement and relies heavily on a simple set of experimental results.

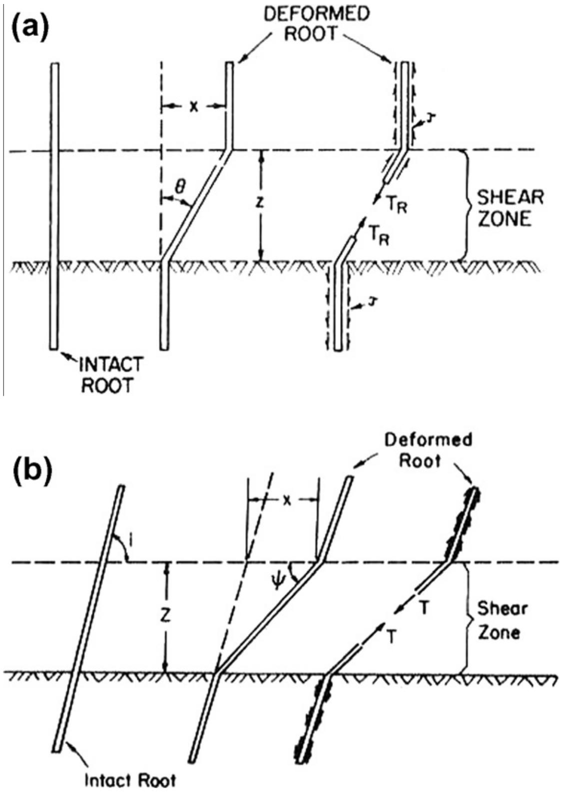

Fig. 4. Model of flexible, elastic fiber across the shear zone: (a) vertical fiber; (b) oblique fiber with given orientation angle to the direction of shear (after [13,143]).

Michalowski and Zhao proposed an energy-based homogenization technique to define the macroscopic failure stress of the fiber–soil composites. They assumed that fiber slippage occurs on the both ends of the fibers and tensile rupture takes place in the middle of the fibers. The model considers only energy dissipation due to fiber–soil slippage and to fiber tensile rupture. So, the energy dissipation rate, d, due to fiber slippage and extension in a single fiber oriented in direction θ is given by:

$$d = \pi \cdot d_f \cdot s^2\sigma_n\tan\delta\langle\dot{\varepsilon}_\theta\rangle + 0.25\pi \cdot d_f^2(1 - 2s)\sigma_{fu}\langle\dot{\varepsilon}_\theta\rangle \quad (7)$$

where σ_{fu} is the yield stress of the fiber material, while, s is the length of the portion of fiber over which slippage occurs. The strain rate $\langle\dot{\varepsilon}_\theta\rangle$ in the direction of the fiber equals to zero if fiber is in compression. The total energy dissipation rate per volume of the soil, D, is the integral of (7) over the volume of fiber soil composite. This is given by:

$$D = v_f\sigma_{fu}M(1 - \sigma_{fu}/(4s \times p\tan\delta))\dot{\varepsilon}_1/3 \quad (8)$$

where p is the mean of the maximum and minimum principal stresses and M can be obtained through:

$$M = (0.5 + \varphi/\pi + \cos\varphi/\pi)\tan^2(\pi/4 + \varphi/2) - 0.5 - \varphi/\pi - \cos\varphi/\pi \quad (9)$$

It is clear that if pure slippage occurs with no yielding of fibers, Eq. (8) can be simplified to:

$$D = 1/3 \times v_f \cdot (L_f/d_f) \cdot M \cdot p \cdot \tan\delta \cdot \dot{\varepsilon}_1 \quad (10)$$

More extensions about this model can be found in Ref. [146]. The model discussed is identified as 'composite' model because the prediction of the equivalent shear strength of the composite uses parameters obtained from characterization of fiber-reinforced soil specimens.

Zornberg proposed a ‘discrete’ framework to predict the equivalent shear strength of the fiber–soil composite by using parameters obtained from the independent characterization of soil specimens and of fiber specimens. Under shearing, fiber reinforcement contributes to the increase of shear resistance by mobilizing tensile stress within fibers. Accordingly, the equivalent shear strength of fiber-reinforced specimens, S_{eq}, can be defined as:

$$S_{eq} = S + \alpha \cdot t = c + \sigma_n \tan\varphi + \alpha \cdot t \tag{11}$$

where α is an empirical coefficient that accounts for the partial contribution of fibers (assumed $\alpha = 1$ for randomly distributed fibers); t is the fiber-induced tension defined as the tensile force per unit area induced in a soil mass by randomly distributed fibers; S is the shear strength of the unreinforced soil; and c and φ are the shear strength parameters of unreinforced soil. The expression of t can be derived for different failure modes. At low confining stress when failure is governed by the pullout of the fibers, $S_{eq.p}$ can be estimated as:

$$S_{eq.p} = c_{eq.p} + (\tan\varphi)_{eq.p} \cdot \sigma_n \tag{12}$$

$$C_{eq.p} = (1 + \alpha \cdot v_f \cdot (L_f/d_f) \cdot c_{i,c}) \cdot c \tag{13}$$

$$(\tan\varphi)_{eq.p} = (1 + \alpha \cdot v_f \cdot (L_f/d_f) \cdot c_{i,\varphi}) \cdot \tan\varphi \tag{14}$$

The interaction coefficients, $c_{i,c}$ and $c_{i,\varphi}$, commonly used in soil reinforcement literature for continuous planar reinforcement, are adopted herein to relate the interface shear strength to the shear strength of the soil. The interaction coefficients are defined as:

$$c_{i,c} = a/c \tag{15}$$

$$C_{i,\varphi} = \tan\delta/\tan\varphi \tag{16}$$

where a is the adhesive component of the interface shear strength between soil and the polymeric fiber, and $\tan\delta$ is the frictional component. The above expressions yield a bilinear shear strength envelope, which is shown in Fig. 5 [13,147].

Models based on a volumetric homogenization technique but limited to the description of non-linear elastic behavior have been presented by Ding and Hargrove for monotonic loading [148] and by Li and Ding in cyclic loading conditions [149]. A complete constitutive law for soils reinforced with continuous filament (Texsol) has been presented by Villard et al. [103,150] and Prisco and Nova employing the superposition of sand and fiber effects [151]. The model proposed by Villard et al. is the only one that recognizes the importance of fiber orientation as a parameter governing the effectiveness of fiber inclusion. Recently, a two dimensional Distinct Element Method (DEM) has been developed for the micromechanical analysis of mixtures of granular materials and flexible fibers [152,153]. Numerical analysis with finite difference code has been performed by Babu et al. [154]. Abtahi et al. extended the shear lag theory proposed by Cox to explain the role of fiber length and fiber diameter in short fiber soil composites. Thus it was found that by increasing the fiber length and deceasing fiber diameter, the CBR value will improve [16,155,156]. In another work, Diambara et al. presented a model based on the rule of mixtures of composite materials at conventional triaxial soil tests. The model considers that the fibers behave linear elastically and the soil, when unreinforced, obeys the simple linear elastic perfectly plastic Mohr–Coulomb model [103]. As well, using artificial neural network (ANN) to predict the role of fiber parameters on shear strength of short fiber soil composites has been successfully reported by Abtahi et al. [157,158].

Recently, Consoli et al. have developed a model linking the unconfined compressive strength (q_u) of the fiber-cemented sandy soil with fiber content (F) and adjusted cement/porosity ratio (C_{iv}/η). More details are available in Ref. [159].

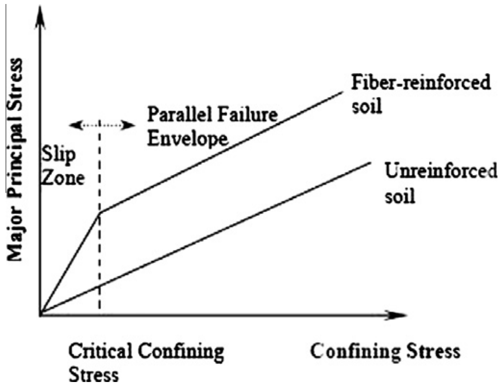

Fig. 5. Shear strength envelope of fiber-reinforced soil: after Gray and Ohashi [143].

6. Applications

A comprehensive literature review shows that using natural and/or synthetic fibers in geotechnical engineering is feasible in six fields including pavement layers (road construction), retaining walls, railway embankments, protection of slopes, earthquake and soil-foundation engineering. A brief discussion about some cases is presented in the following.

6.1. Pavement layers

In 1991, the US ARMY Corps of Engineers demonstrated the improved performance of untreated and chemically stabilized soil layers by using GEOFIBERS® soil reinforcement in pavement engineering. The 30 cm fiber-reinforced silty sand section provided a 33% increase in the number of traffic passes versus the similar un-reinforced section [121].

Grogan and Johnson showed that the inclusion of Geofiber allowed up to 90% more traffic passes until failure in the clay, 60% passes until failure in the modified sand, and some enhanced traffic performance was reported for the silty sand [160,161].

It is necessary to mention that PP Geofibers can be mixed with subgrade soils. Their inclusion raises the maximum density about 5% and reduces the optimum moisture content of the compacted soil mixture about 5% as well [128].

Tingle et al. concluded from full-scale field tests that fiber-stabilized sands were a viable alternative to traditional road construction materials for temporary or low-volume roads. They used a field mixing procedure more or less similar to that of Santoni and Webster [29,95,162].

There is an available report (2008) stating that aprons, taxiways, and a helipad have been stabilized by using high-early strength Portland cement and PP fibers with screened native soil at the Bradshaw Field Training Area in the Northern Territory, Australia [163].

Finally, the most important findings of some research works are that the use of synthetic and/or natural fibers in road construction can significantly increase pavement resistance to rutting, as compared to the resistance of non-stabilized pavement over a weak subgrade [48].

6.2. Retaining walls and railway embankments

Park and Tan showed that use of PP fibers of 60 mm reinforced silty-sand-soil-wall increases the stability of the wall and decreases the earth pressures and displacements of the wall. They also reported that this effect is more significant when short fiber soil is used in combination with geogrid [164].

Some researchers found that using Geofibers with the combination of geogrids can lead to the economical construction of high vertical walls for railway embankments in low-lying built-up areas [164].

Nowadays, short fiber composite retaining walls are conventional in Europe promoting seed adhesion and root penetration [128].

6.3. Protection of slopes and foundation engineering

Mainly, soils mixed with randomly distributed fibers can be used as patches in the localized repair of failed slopes as it can accommodate the irregular shape of failed slopes. In the reinforcement of soil veneer such as landfill covers, fiber reinforcement eliminates the need of anchorage that exists with planar reinforcement [165], as well reduces the erosion gullies [128]. The mixture of sand and fiber can be sprayed onto a problematic slope like shotcrete, creating a free-draining gravity retention structure. For instance, a nominal rate of 20 m/s is recommended for glass fibers [128].

Fiber reinforcement has also been used in combination with planar geosynthetics for reinforced slopes or walls. By increasing the shear strength of the backfill materials, fiber reinforcement reduces the required amount of planar reinforcement and may eliminate the need for secondary reinforcement. Fiber reinforcement has been reported to be helpful in eliminating the shallow failure on the slope face and reducing the cost of maintenance [13,166].

Obviously, an increase in allowable slope angle would reduce the space and the amount of soil needed for a slope. This concept can be occurred by using fibers in slope engineering. The reduction of soil volume (V) can be calculated from:

$$V = 0.5L \cdot H^2(1/\tan\alpha_1 - 1/\tan\alpha_2) \quad (17)$$

where L is the length, H is the height, and α_1 and α_2 are the allowable slope angles for the unreinforced and reinforced soil, respectively. For example, for a 1 km long, 10 m high slope, the increase of the slope angle from 20° to 30° would save over 50,000 m^3 of soil and reduce the width of the slope by 10 m. This could directly translate into cost and time savings and reduced environmental impact [134]. This result has also been proven by finite element model (FEM) verifying the effectiveness of using PP fibers to reinforce slopes [167].

Another concept of using fibers in civil engineering is the construction of foundations in soils with poor bearing capacities, where the costs of a deep foundation solution can be incompatible with the overall costs for low-budget building projects. In these cases, alternatives for the improvement of local soil through the addition of cementitious agents or through the inclusion of oriented or randomly distributed discrete elements such as fibers might be used [168].

6.4. Earthquake engineering

The toughness and ductility of the fiber-reinforced soils are beneficial for anti-earthquake geo-structures [169]. According to Makiuchi and Minegishi, in Japan there are two types of earth-reinforcement techniques using synthetic fibers. In the first technique, continuous filament yarns are employed for non-cohesive granular soils. For instance, TEXSOL product belongs to this group developed firstly in France [29,170]. In this type, the filaments are mixed with fine sand at the specified moisture content by jet-mixing equipment and the fiber–sand mixture is built up in the field. The successful field applications of the TEXSOL method have been described by Leflaive [171]. The second earth-reinforcement technique is that of using short length staple fibers introduced by Japanese Research Institute of Public Works in 1997 [29,172].

7. Executive problems

The following executive problems are involved with using fibers in soil reinforcement:

7.1. Lack of scientific standard

In spite of the quantity of research conducted into the resultant characteristics of using fiber and shavings for soil improvement, there are still no scientific standard or techniques specialized for real field projects [60,138].

7.2. Clumping and balling of fibers

Local aggregation (clumping) and folding of fibers (balling) are two problems concerned with fiber–soil composites. In this way, fiber lengths beyond 2-in. (51 mm) were not found to significantly improve soil properties and proved more difficult to work with in both laboratory and field experiments [163]. As well, a successful tumble mixing technique has been identified which is able to improve soil composite uniformity and the ease of manufacture [69].

7.3. Adhesion of fiber and soil

Mainly, adhesion at the fiber–matrix interface has been found to be governed by the following three factors [43]: (a) the shear resistance of the soil due to the surface form and roughness of the fiber; (b) the compressive friction forces on the surface of the fiber due to shrinkage of the soil; and (c) the cohesive properties of the soil. Further, each of these three factors is affected by dimensional changes of the natural fiber which can occur due to changes in moisture and temperature [43]. Such changes in fiber dimension can occur during the curing stage of the soil–fiber composite material and this then determines a possible mechanism resulting in a poor interfacial bond. During the mixing and drying stages of production, the hydrophilic nature of the natural fibers can lead it to absorb water and effectively push out on the soil matrix. Then near the end of the curing (drying) period, the fiber loses the water that has absorbed, causing it to shrink back. Because the matrix is now set, a void is formed around the periphery of the fiber and a weakened interfacial bond can result [43,69,172]. Fig. 6 illustrates this mechanism.

Therefore, in looking for an additive to improve the bonding characteristics of fiber soil composites, it is required that the treatment reduces the transfer of water between the matrix and the fiber. Possible additives identified from the literature include water resistant coatings such as asphalt emulsion, rosin–alcohol mixture, paints [173], bituminous materials [43,69,173], a water soluble acrylic, a polystyrene coating [174] and acrylonitrile butadiene styrene (ABS) [189]. Khazanchi et al. with their study of wall panels consisting of soil, 2.5% cement and polystyrene coated wheat straw, reported fiber bond strength of 1.3 MPa. With the same material but using bitumen and acrylic coatings, they also achieved bond strengths of 0.1–0.12 and 0.08–0.125 MPa, respectively. In this study untreated fibers gave bond strengths in the range of 0.07–0.08 MPa [69,174].

8. Advantages

In comparison with systematically reinforced soils, randomly distributed fiber reinforced soils exhibit some advantages. Mainly, preparation of randomly distributed fiber reinforced soil mimics

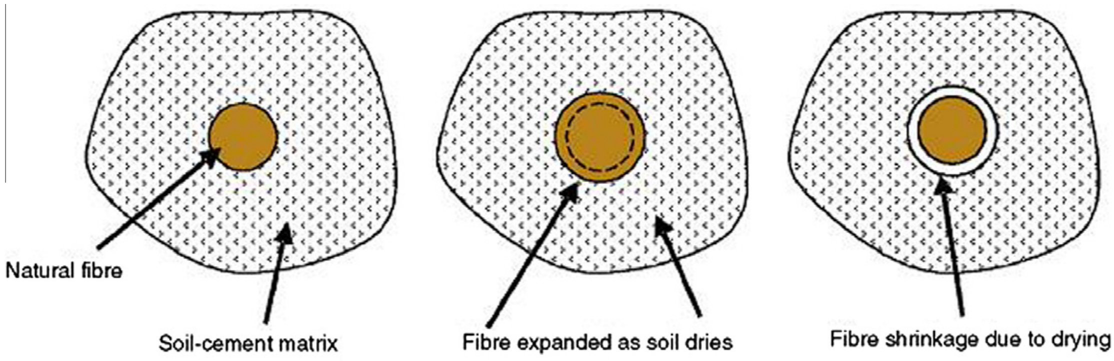

Fig. 6. Schematic of the effect of fiber deformation due to moisture changes.

soil stabilization by admixture. Discrete fibers are simply added and mixed with the soil, much like cement, lime, or other additives [90]. Randomly distributed fibers offer strength isotropy and limit potential planes of weakness that can develop parallel to oriented reinforcement [90,109,144].

Fiber materials are cost competitive compared with other materials [37,175,176]. Unlike lime, cement and other chemical stabilization methods, the construction using fiber-reinforcement is not significantly affected by weather conditions [13].

The materials that can be used for fiber-reinforcement are widely available. Plant roots, shredded tires, and recycled waste fibers can also be used as reinforcement in addition to factory-manufactured synthetic fibers [13,131,177].

One of the primary benefits of the inclusion of the fiber reinforcement includes inhibition of tensile crack propagation after initial formation. Ref. [60] believes that prior to cracking, the fibers appeared to have no noticeable effect on the material behavior, because, the inclusion of fibers changes the failure mechanism by preventing the formation of tension cracks [104]. Miller and Rifai reported that the shrinkage crack reduction and hydraulic conductivity of compacted clay soil have been increased with an increase in fiber content [107,178].

It is proven that vegetable fibers used with cement mortar can produce high-performance fiberboard, which can be used as a substitute for asbestos-cement. A higher economy can be achieved when vegetable fibers are used together with soil to form load-bearing structures [43,179].

It has been confirmed that the addition of fibers significantly increases the liquefaction strength of sand [180]. This means that fiber inclusions increase the number of cycles required to cause liquefaction during undrained loading [103,181,182].

It has also been found that some vegetable fibers as an admixture can reduce the thermal conductivity and weight of building blocks [52].

A report is available stating that randomly distributed geofibers (0.25% and 0.50% with aspect ratios of 15, 30 and 45) are useful in restraining the swelling tendency of expansive soils [89].

Some researchers have reported that fibers change the stress–strain behavior from strain softening to strain hardening for sandy silt. Fiber inclusions also impede the compaction process, causing a reduction in the maximum dry density of reinforced specimens with increasing fiber content. The strength losses associated with in-service saturation are significantly reduced with fiber reinforcement [131].

Fiber reinforcements, however, could reduce soil brittleness providing smaller loss of post-peak strength [90,60]. The change in the ductility of the soil specimens can be defined using a brittleness factor, which quantifies the differences in the stress–strain curves of the soil. The brittleness factor is defined as the ratio of the peak principal stress ratio to the residual principal stress ratio minus unity:

$$I_B = [(\sigma_1 - \sigma_3)_{peak}/(\sigma_1 - \sigma_3)_{residual}] - 1 \tag{18}$$

The value of I_B ranges from 1 to 0, where 0 represents perfectly ductile behavior. The brittleness factor for unreinforced clay specimens ranged from 0.61 to 0.35, while the factor ranged from 0.26 to 0.01 for reinforced soil specimens [13,99,108].

Recently, Abtahi et al. have applied short fibers to increase the bearing capacity of composite soils stabilized with polyvinyl alcohol and polyvinyl acetate at saturated conditions. Although, the chemical resins generally improve the bearing capacity of the composite soils at dry conditions, their performances at soaked conditions are doubtful. Thus, fibers can protect the resin-stabilized soil at saturated conditions by the phenomenon of "interlocking effect" [183–186]. The same investigations have been done by Marin et al. to use sheep's wool fibers and alginate polymer to reinforce a local clayey soil [187].

9. Research works for future

It should be pointed out that since the influences of engineering properties of soil and fiber and the scale effects on the stress–strain–strength characteristics of fiber reinforced soils have not been investigated fully, the actual behavior of fiber reinforced soils is not yet well known. Hence, further studies including especially large-scale tests are needed to better understand the behavior of fiber-reinforced soils [90]. As well, further studies are necessary to elucidate the fracture mechanism, the effect of prior treatment of the fibers and the durability of the composite at long term and under more severe conditions [75,119].

In particular, the effects of drainage and pore pressures on the effective strength of the fiber–soil mixture, and creep along the fiber–soil interface, are of particular interest [99].

In addition, further study is needed to optimize the size and the shape of fibers and/or strips, e.g. crimp magnitude and crimp frequency. Measurement of durability and aging of fibers in soil composites is recommended. Large scale test is also needed to determine the boundary effects influence on test results [119]. Very few studies have been carried out on freezing–thawing behavior of soils reinforced with discrete fiber inclusions [105].

It is suggested that large volumes of recycled waste fibers can be used as a value-added product to enhance the shear strength and load deformation response of soils [131]. In this way, using recycled waste tire cords in soil reinforcement seems to be attractive.

More investigations on the performance of composite soils reinforced with polyvinyl alcohol (PVA) fibers are required. It is important to know that the studies on behavior of soils reinforced with randomly distributed elements under cyclic loading are very limited in the literature [188].

More research is needed to further understand the potential benefits and limitations and to allow fibers' application to more complex geotechnical structures [91,103,104,160].

It is emphasized that research on the use of fiber-reinforcement with cohesive soils has been more limited. Although fiber-reinforcement was reported to increase the shear strength of cohesive soils, such improvement needs additional evaluation because the load transfer mechanisms on the interface between fibers and clayey soils are not clearly understood [13].

10. Conclusion

This paper was going to review the concept of using discrete randomly distributed fibers in soil, i.e. short fiber soil composites. In this way, both natural (coir, sisal, palm, jute, flax, straw, bamboo; and Cain) and synthetic fibers (PP, PE, PET, Nylon, Glass, PVA; and Steel) that have been yet used to reinforce soil were investigated. In a simple process, fibers, typically at a dosage rate of 0.2–4% by weight, are added and mixed into silt, clay, sand, or lime and cement stabilized soil.

All of the papers listed above have generally shown that strength and stiffness of the composite soil is improved by fiber reinforcement. It can be concluded that the increase in strength and stiffness was reported to be a function of:

- Fiber characteristics; such as; aspect ratio, skin friction, weight fraction; and modulus of elasticity.
- Sand characteristics; such as shape, particle size and gradation.
- Test condition; such as; confining stress.

On the basis of predictive models presented in this paper, it is clear that the strength of fiber reinforced soil increases with increase in aspect ratio, fiber content, fiber modulus; and soil fiber surface friction.

Direct shear tests, unconfined compression tests and conventional triaxial compression tests have demonstrated that shear strength is increased and post-peak strength loss is reduced when discrete fibers are mixed with the soil.

In other words, discrete, randomly distributed fiber inclusions significantly increase the peak shear strength, reduce the post-peak strength loss, increase the axial strain to failure, and, in some cases, change the stress–strain behavior from strain softening to strain hardening. Fiber inclusions also impede the compaction process, causing a reduction in the maximum dry density of reinforced specimens with increasing fiber content. The strength losses associated with in-service saturation are significantly reduced with fiber reinforcement.

Altogether, it is necessary to mention that research on the use of fibers with cohesive soils has been more limited. Although fiber-reinforcement was reported to increase the strength of cohesive soils, such reinforcement needs additional evaluation because the load transfer mechanisms on the interface between fibers and clayey soils are not clearly understood.

Several researchers have recently attempted to study the combined effect of fiber and other chemical binders (e.g. fly ash, cement, lime, poly vinyl acetate, poly vinyl alcohol; and urea formaldehyde) on granular or clayey soils. The main reason is that while chemical binders improve the stability of the soil, at the same time, they decrease the ductile behavior of the soil. Fibers, in this way, help to reduce the brittleness factor of the composite soil. Thus, a brittleness factor was introduced in this paper ranging from 1 to 0, where 0 represents perfectly ductile behavior.

Authors conclude that lack of scientific standard, clumping and balling of fibers and adhesion of fiber to soil are the three major executive problems involved with the short composite soil production.

Availability, economical benefits, easy to work and rapid to perform; and feasibility of using in all weather conditions are the general advantages of short fiber composite soils. The technical benefits of using fibers in soil reinforcement include: preventing the formation of the tensile cracks, increasing hydraulic conductivity and liquefaction strength, reducing the thermal conductivity and weight of building materials, restraining the swelling tendency of expansive soils; and decreasing the soil brittleness.

As well, a comprehensive literature review shows that using natural and/or synthetic fibers in geotechnical engineering is feasible in six fields including pavement layers (road construction), retaining walls, earthquake engineering, railway embankments, protection of slopes; and soil-foundation engineering.

At final, it is emphasized that short fiber composite soil is still a relatively new technique in geotechnical projects as a mimics of the past.

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