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Engineering Performance Review of Soil Reinforcement with Natural Fibers

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Abstract—*Reinforced earth technique is considered as an effective ground improvement method because of its cost effectiveness, easy adaptability and reproducibility. Randomly distributed fibers in soil are one of the latest techniques in which fibers of desired quality and type are added to the soil. Fiber inclusion causes significant modification and improvement in the engineering behaviour of soils. Use of natural material as reinforcing materials in soil is prevalent from a long time. The objective of this paper is to examine/critically review the past data, feasibility, cost benefits, applications, stability and difficulties of using natural fibers in soil reinforcement with reference to published literature.*

Keywords: *Fiber, Soil, Reinforcement*

1. INTRODUCTION

It is a well-known fact that soil is weak in tension and relatively strong in compression and shear. In a reinforced soil, the soil mass is reinforced by incorporating an inclusion (or reinforcement) that is strong in tensile resistance (S.M. Hejazi et al, 2012)[1]. Through soil-reinforcement interface bonding, the reinforcement restrains lateral deformation of the surrounding soil, increases its confinement, reduces its tendency for dilation, and consequently increases the stiffness and strength of the soil mass (Gray et al, 1988[2], Ranjan et al, 1996[3]).

Soil reinforcement using randomly mixed fibres is now a geotechnical engineering solution for many soil improvement field applications. Fibre reinforced soil behaves as a composite material in which fibres of relatively high tensile strength are embedded within the soil matrix (Ranjan et al, 1994)[4]. The tensile resistance of the fibres is mobilised when the composite is subjected to shear stresses, consequently, the tensile resistance of the fibre imparts greater strength to the soil. The fibre-soil interaction is shown in Fig. 1.

Many researchers have performed a variety of soil tests on fibre soil composites to determine the extent of improvement in strength with varying fibre and soil properties (Kumar et al, 1999[5], Santoni et al, 2001[6]). Predictive models have been developed to estimate the composite behaviour based on the properties of soil and fibre. So, the objective of reinforcing soil mass is to improve its stability, to increase its bearing capacity, to prevent shrinkage cracks, to reduce settlements and lateral deformation (Chaple et al, 2013[7], Prabakar et al, 2002[8]).

2. FIBERS AND SOIL REINFORCEMENT

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 (Li et al, 2005[9]). Mechanical reinforcement which stabilizes soil on slopes has been attributed to plant roots. The first modern form of soil reinforcement was developed by Henry Vidal in 1966.

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. 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.

In this review, reinforced soils are classified into two main groups:

- Systematically reinforced soil (using planar reinforcement), and
- Randomly distributed fiber reinforced soil.

It is emphasized that a single reinforcing mechanism cannot be used to explain the behavior of all reinforced soils, in fact, it is highly dependent on the type of reinforcement inclusions; however, the basic concept of soil reinforcement remains the same for all types of reinforcement (Shukla et al, 2009[10]). Fig. 2 presents a state of art review of methods of soil reinforcement.

The ratio of length L to thickness (or equivalent diameter) D of the fibre is called the aspect ratio a_r. Thus $\mathbf{a_{r\,=\,L/D}}$

3. NATURAL FIBERS

Natural fibres are extracted from plants. Use of natural fibers as reinforcing materials in soil is prevalent for a long time and they are abundantly used in many developing countries in cement composites and earth blocks because they are cheap, locally available, biodegradable and eco-friendly. Some natural fibers and their features in soil composites are briefly discussed:

Jute (Bast fibre)

Jute possesses high moisture absorbing capacity, high initial tensile strength, low extension at break, high roughness co-edfficient and biodegradable. Jute is abundantly grown in Bangladesh, China, India and Thailand. Jute fibers (shown in Fig. 3) 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. Jute is mainly environmental-friendly fiber that is used for producing porous textiles which are widely used for filtration, drainage, and soil stabilization. Bitumen is used for coating fibers to protect them from microbial attack and degradation.

Kulhar and Raisinghani, 2017[11] used different lengths (5–15 mm) of jute fibers in different percentages (0.5–2.0%) to reinforce sand. They concluded that jute fiber increases the Soaked CBR value. Maximum Soaked CBR value is observed with 5 mm long and 0.5% jute fiber, with an increase of more than 1.6 times of the plain sand CBR value.

Kulhar and Raisinghani, 2017[12] also reported that jute fibers are effective for improving the shear strength as well as ductility of the sand.

Coconut fibre or Coir fibre (Fruit fibre)

The coir fibers (shown in Fig. 4) are normally 50–350 mm long. 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. Coir retains much of its tensile strength when wet and flexible for processing. It has low tenacity but the elongation is much higher. 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. Chaple et al, 2013[7] have reported increase in bearing capacity of clayey soil with the inclusion coir fibers.

Sisal (Leaf fibre)

There are abundantly available renewable resources and also known as sisal hemp. Sisal fibers (shown in Fig. 5) are extracted from the leaves of the plants, which vary in size, between 6–10 cm in width and 50–250 cm in length. Plantation of Sisal prevents desertification of land (Ghavami et al, 1999[13]). 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. 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. Prabakar et al, 2002[8] found a significant improvement in shear strength parameters of soil due to inclusion of sisal fiber.

Palm fibers (Empty Fruit Bunch – EFB Fibre)

The palm fibers (shown in Fig. 6) 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. Fibers extracted from decomposed palm trees are found to be brittle, having low tensile strength and modulus of elasticity and very high water absorption. Amin et al, 2012[14] reported that a significant improvement in the shear strength parameters (C and Φ) and ductility of the clayey sand reinforced with palm fibers can be achieved.

Flax (Bast fibre)

Flax (shown in Fig. 7) is probably the oldest textile fiber known to mankind. It has been used for the production of linen cloth since ancient times. In an effort, Segetin et al, 2007[15], 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.

Barely straw (Stalk fibre)

Barley straw (shown in Fig. 8) is widely cultivated and harvested once or twice annually in almost all rural areas, but relatively few published data is available on its performance as reinforcement to soil or earth blocks. During the Egyptian times, straws or horsehairs were added to mud bricks. A mixture of barely straw with cement can form a sustainable low-cost building material, which also reduces atmospheric pollution (Kozlowski et al, 2011[16]). In addition to these benefits, the straw could act as a thermal insulation material for the unpleasant weather conditions to create pleasant indoor temperatures (Bouhicha et al, 2005[17]).

Bamboo (Grass fibre)

Bamboo fibres (shown in Fig. 9) are very strong in tension but have low modulus of elasticity, 33–40 kN/mm^2, and high water absorption, 40–45%, (Kozlowsky et al, 2011[16]). They are seldom eaten by pests or infected by pathogens. The cyclic load tests on sand subgrades undertaken by Prasad et al, 2012[18] showed that the maximum load carrying capacity associated with less value of rebound deflection is obtained for flyash reinforced subbase compared to unreinforced flyash subbase. Ramaswamy et al, 1983[19] 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.

Cane (Grass fibre)

Cane or sugarcane (shown in Fig. 10) 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. ‘‘Cement Board’’ produced from sugar cane waste has been recently introduced to the market (ati-composites.com[20]). The application of these fibers in soil reinforcement can be treated as an empty research area.

Table 1 shows summary of researches performed on natural- fiber reinforced-soil.

4. SYNTHETIC (MAN-MADE) FIBERS

Made from derivatives of petroleum, coal and natural gas, some of them are listed below:

- **Polypropylene (PP) fibers:** most widely used and reduce the swelling potential of expansive clays.
- **Polyester (PET) fibers:** most widely used and short PET fiber (64 mm) reinforced soil had high piping resistance.
- **Polyethylene (PE) fibers:** waste PE-based materials are used in land-fill.
- **Glass fibers:** used to reinforce cohesionless soils.
- **Nylon fibers:** extremely lightweight and most durable. Carpet waste could lead to wider use of fiber reinforced soil and more cost-effective construction.
- **Steel fibers:** not used in cold climates.
- **Polyvinyl alcohol (PVA) fibers:** has been used in fiber-reinforced concrete due to its weather resistant and chemical resistant properties.

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

The man made polymers are highly restraint to bacteria, alkalis and acid. However, above inclusions are generally expensive and non-biodegradable resulting higher costs with doubtful environmental effects. This problem can be solved by using locally available natural fibers.

5. SAMPLE PREPARATION

A mixing technique need to be developed for large scale production of fiber-reinforced soil mixtures. 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 (Allen et al, 1997[21]). 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.

It was found that the fibers could be mixed with sand more effectively in the moist state than in the dry state (Kulhar and Raisinghani, 2017[11]). 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 (Newman et al, 2003[22]).

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 i.e. embankment, sub-grade, sub-base etc., retaining walls, railway embankments, slope stability, earthquake and soil-foundation engineering.

7. RESEARCH WORKS FOR FUTURE

Further studies including especially large-scale tests are needed to better understand the behavior of fiber-reinforced soils (Yetimoglu et al, 2003[23]). 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. 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. It is emphasized that research on the use of fiber-reinforcement with cohesive soils has been more limited.

8. CONCLUSION

On the basis of review, it is concluded that strength and stiffness of the composite soil is improved by fiber inclusion. The strength and stiffness depends upon fibre parameters (ie, weight fraction, aspect ratio, surface friction), sand granulometry (particles shape, size and gradation) and confining stress. The sand-fibre composite can sustain large axial strain exhibiting greater ductility in the composite. Fiber inclusion to soil hinders the compaction process, causing a decrease in the maximum dry density. One of the significant effects of the inclusion of natural fibres in the soil matrix was the prevention of shrinkage cracks due to the drying process. In addition, the randomly distributed fibers also offers strength isotropy and limits the potential planes of weakness that can develop parallel to oriented reinforcement.

The short composite soil production has been facing the challenges of deficiency in scientific standard, clumping and balling of fibers, adhesion of fiber to soil, fiber cutting process at mass scale and to develop a suitable protection method to increase the durability of fiber. Major advantages of short fiber composite soils are availability, ease of construction, overall economy, time saving etc. Investigations on fiber clay composites has been more limited.

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Table 1: Physical properties of natural-fibers used as soil composite based on past research.

Fiber type					Fiber special property	Conclusions
Jute fibers					– Used for producing porous textiles which are widely used for filtration, drainage, and soil stabilization	– Fiber reduces the MDD while increases the OMC. CBR value is increased more than 1.6 times compared to the plain soil CBR value (of fine sand)
D µm	Density g/cm^3	E GPa	UTS MPa	Elongation at break (%)		
10-50	1.3-1.5	22	453-550	1.4-3.1		
Coir fibers					– 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	– 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
D µm	Density g/cm^3	E GPa	UTS MPa	Elongation at break (%)		
10–20	1.25–1.50	4–5	250	15-47		
Sisal fibers					– Traditional use as a reinforcement for gypsum plaster sheets -60% to 70% of water absorption	– 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
D µm	Density g/cm^3	E GPa	UTS MPa	Elongation at break (%)		
25-400	1.3-1.5	26-32	560	2.0-2.9		

Palm fibers					– Low cost, plenitude in the region, durability, lightweight, relative strength against deterioration – Low tensile strength and modulus with very high water absorption	– Fiber increases the UCS, CBR and shear strength parameters (C and Φ) of the soil soil – 3% palm fibers improve the compressive strength of composite bricks.
D µm	Density g/cm^3	E GPa	UTS MPa	Elongation at break (%)		
25-60	0.7-1.55	0.55	21-60	8-18		
Barley-straw fibers					– Widely cultivated and harvested in all over the world – Commonly used in producing composite soil blocks	– 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
D µm	Density g/cm^3	E GPa	UTS MPa	Elongation at break (%)		
1000-4000	0.87	-	-	-		

D: Diameter, E: elastic modulus, UTS: ultimate tensile strength

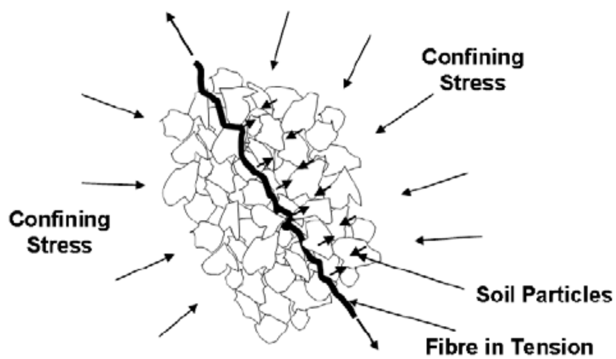

Fig. 1 Fibre-soil interaction; fibre in tension.

Table 2: Physical properties of synthetic-fibers used as soil composite based on past research.

Fiber type				Fiber special property	Soil types used in the literature	Conclusions
Polypropylene fibers (PP)				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
D µm	SG	E GPa	UTS MPa			
23-150	0.92	3-3.5	120-450			
Polyester fibers (PE)				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
D µm	SG	E GPa	UTS MPa			
30-40	1.35	10-30	400-600			
Polyethylene fibers (PET)				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
D µm	SG	E GPa	UTS MPa			
400-800	0.92	0.14-1	100-620			
Glass fibers				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
D µm	SG	E GPa	UTS MPa			
3-19	2.49-2.60	53-95	1500-5000			
Polyvinyl alcohol fibers				Weather resistance, better tensile strength to that of PP fiber, significantly lower	– Cemented river sand	Two times increase in both the UCS and the axial strain at peak strength when compared with the non-fiber-
D µm	SG	E GPa	UTS MPa			

100	1.3	25	1078	shrinkage from heat than nylon or polyester, a good adhesive property to cement; and high anti-alkali characteristics		reinforced specimen. Increase of ductility

D: Diameter, SG: specific gravity, E: elastic modulus, UTS: ultimate tensile strength

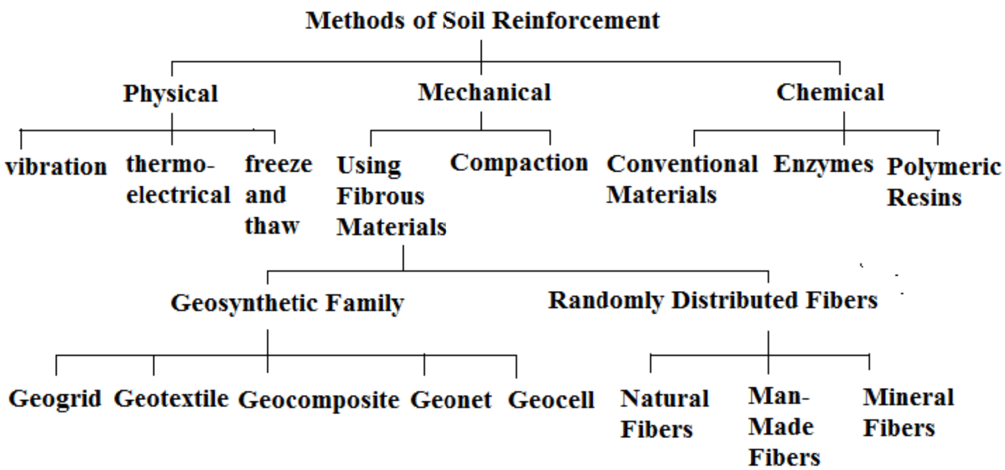

Fig. 2. Methods of soil reinforcement.

Fig. 3 Jute Fibres

Fig. 4 Coir Fibres

Fig. 5 Sisal Fibres

Fig. 6 Palm Fibres

Fig. 7 Flax Fibres

Fig. 8 Barley Straw Fibres

Fig. 9 Bamboo Fibres

Fig. 10 Cane Fibres