Geotechnical Properties of Soil – Fibre Composites. A Review

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Abstract

Different types of fibres i.e., natural, and synthetic fibers of different geometries are now adopted for soil reinforcement. The benefits in relation to specific applications are reflected in the test methods to determine different soil-fibre composite properties and the mode of loading of the specimens. Consequently, the benefits in compression, shear and tension often differ. It is therefore important to document the series of literature in soil-fibre reinforcement to highlight the different factors affecting specific beneficial attributes of soil-fibre reinforcement. Based on the limited number of literatures reviewed, the findings suggest that for a broad range of soil types, the percentage reduction in mobilized friction angle upon wetting increased with soil density. Friction angle decreased with fibre inclusion, however marginal increase in mobilized friction angle was evident due to increase in the ratio of fibre dosage to binder dosage. The tensile strength increased with both increase in fibre dosage and the ratio of fibre dosage to binder dosage.

Keywords: *Polypropylene fibre; Residual soil; Shear strength; Tangential stress; Tensile strength.*

1 Introduction

The application of different types of natural and synthetically derived fibre for the improvement of strength, swelling pressure and stability of geotechnical infrastructure has grown steadily in the past decades. Documented applications of short length, discrete, randomly distributed natural, synthetic, and waste recycled fibres have focused on cases where planar reinforcement using geosynthetics is not feasible due to space limitation, localized and partially failed slope embankments and the repair of slope veneer (Mirzababaei et al., 2017a). Randomly distributed fibre ensures isotropic composite state and eliminates the potential planes of shear failure that can occur with planar reinforcement using geosynthetics (Yetimoglu and Salbas, 2003). The inclusion of polypropylene fibre for the improvement of the mechanical properties of weak soils was documented by Anagnostopoulos et al. (2014). Other documented engineering applications include fibre reinforcement for stabilization of soil slopes (Gregory and Chill, 1998), fibre reinforcement of embankment constructed with soils of low compression and shear strength, reduction of expansion and shrinkage induced cracks in highly active plastic clay and clayey soils (Ziegler et al., 1998), fibre reinforcement of stabilized road layers (Choubane et al., 2001), improvement of soil bearing capacity and soil erosion protection (Tang et al., 2007) and improvement of airport pavements (Webster and Santoni, 1997; Tingle et al., 1999). Anagnostopoulos et al. (2014) conducted series of consolidated drained and undrained direct shear tests on unreinforced and polypropylene fibre reinforced sandy silt and silty clay specimens at fibre dosage of 0.3% and 1.1% by weight of the dry soil. They reported significant increase in the shear strength, drained shear-induced soil volume contraction and strong dilation behaviour for high fibre doses. The beneficial effect of fibre reinforcement was evident in undrained shear condition. Pradhan et al. (2012) investigated the inclusion of randomly distributed polypropylene fibre on the direct shear strength, Unconfined Compression Strength (UCS) and California Bearing Ratio (CBR) of a clayey soil. They reported that soil-fibre reinforcement increased the peak and residual shear strength, UCS and CBR. For the fibre aspect ratio of 10, the optimum fibre content was 0.8% by weight of the dry soil. The shear strength of the fibre-reinforced sand at large imposed shear displacement has been studied by Heineck et al. (2005) and noted that although fibre-reinforced soil did not outperform the unreinforced sand in terms of initial stiffness, the mobilized shear strength was greater than that of the unreinforced soil, and no loss in mobilized shear strength was observed at large shear displacements of 250 mm.

Consoli et al. (2002) reported no strength deterioration for fibre-reinforced sands at large shear displacements using the ring shear test but observed breakage of the fibres into shorter lengths. Using a series of ring shear tests on fibre-reinforced bentonite, Casagrande et al. (2006) observed a constant shear strength after reaching a peak strength at 1 mm shear displacement that was continuous to a very large shear displacement of 50 mm, beyond which the strength decayed gradually. Mirzababaei et al. (2017b) also investigated the effect of large shear displacement on the shear strength of fibre-reinforced soft and stiff clays and reported the dependency of the effectiveness of fibre reinforcement of clays on the initial void ratio and the applied normal effective stress during the shearing stage. Freitag (1986) also added discrete fibre to clayey soil samples and showed that addition of fibre increased the strength and ductility of natural clayey soil, while the addition of nylon fibre by Kumar and Tabor (2003) resulted in a significant increase in the residual strength of silty clay soil. Residual soils which underlie large proportions of tropical and semi-arid parts of the world are products of in situ chemical weathering and leaching of rocks and thus their characteristics are dependent upon environmental factors of climate, parent rock material, topography, drainage, and age (Vaughan et al., 1988; Blight, 1988). These conditions are optimal in the tropics where well-drained regions produce reddish and brownish lateritic soils rich in iron and aluminium sesquioxides and kaolinitic clays. Heavily weathered residual soils often contain a significant percentage of silt and clay and can mobilize very high compressive and shear strength in dry and drained condition (Latifi et al., 2017; Rashid et al., 2017). Weathered tropical soils generally exhibit very low in situ shear strength and poor stability in the undrained environment or upon inundation and they have been associated with the failure of low-cost road embankments in semi-arid and tropical environments. Despite the associated high cost of cementitious road binders, the use of randomly distributed fibres for the improvement of low-cost tropical roads has very limited favourability, in part, because of limited literature specific to randomly distributed fibre reinforced tropical residual soils. Oderah and Kalumba (2016) investigated the effect of cycles of soaking and cycles of wetting and drying of randomly distributed sugarcane bagasse fibre on mobilized shear strength of well-graded medium dense, reddish-brown residual South African Klipheuwel sand. They observed a maximum reduction in mobilized shear strength of 15% for 1.0% fibre dosage due to inundation.

The effect of dry-soaked shear test on the shear strength parameters of the natural undisturbed soil is shown in Table 1. Minimal to no drop in the soil friction angle is evident due to inundation, also a significant percentage reduction in the cohesion of the soil is evident due to saturation. Saturation decreased the cohesion of the soil and had minimal to no effect in the friction angle of the soil. The effect of density on the percentage reduction in friction angle of the soil for direct shear test is shown in Figure 1. It was observed that most researchers performed direct shear tests on silty sands (SM) with an average density being 1 500 kg/m^3. The percentage reduction in mobilized friction angle upon wetting increased with soil density. The effect of fibre dosage and the ratio of fibre dosage to binder dosage on the percentage increase in friction angle of the soil for direct shear are shown in Table 2 and Figures 2 and 3. It was noted that percentage increase in mobilized soil friction angle decreased with an increase in fibre dosage, increase in fibre dosage resulted in approximately 60% increase in mobilized friction angle of the soil. However marginal increase in mobilized friction angle of the soil was evident due to increase in the ratio of fibre dosage to binder dosage, increase in the ratio of fibre dosage to binder dosage resulted in approximately 48% increase in the mobilized friction angle of the soil.

Table 1. Effect of dry-soaked shear test on the shear strength parameters of the natural soil.

Authors	**Soil type**	**Specimen density (kg/m^3)**	**Dry shear strength parameters**		**Soaked shear strength parameters**		**Reduction/Increase in shear strength parameters**	
			C (kPa)	Ø (°)	C' (kPa)	Ø′ (°)	ΔC (%)	ΔØ (%)
Huat et al. (2008)	MH	1 139	58	21	15	15	-74	-29
	SM	1 090	75	33	20	34	-73	+3
Kererat (2019)	SM	2 060	18	47.42	17	12.12	-6	-74
Hossain Md (2016)	SM	1 300	19.35	24.95	15	23.78	-22	-5
Mohamedzei and Aboud (2006)	MH-CH	1 550	150	24	65	0	-57	-100
Marinho et al. (2013)	SM	1 560	12	31	8.80	29	-27	-7
Liu et al. (2020)	Loess	1 385	8.13	25.12	1.46	21.34	-82	-15
Pavan et al. (2020)	SM (Tr-A)	1 850	794	26.15	385	37.70	-52	+44
	SM (Tr-B)		762	49.28	414	39.20	-46	-20
	SM (Tr-C)		787	34.60	373	39.20	-53	+13

*Note: (-) Reduction in percentage, (+) Increase in percentage, (Tr-A) 3 layers with dents, (Tr-B) 3 layers with cement and (Tr-C) 3 layers with dents and cement.

NB: All soils are classified in accordance with USCS (Unified Soil Classification System).

Table 2. Effect of stabilization and fibre-reinforcement on the shear strength parameters of the soil.

Authors	**Soil type**	**Specimen density (kg/m^3)**	**Stabilization Type and Optimum Dosage**	**Fibre Type and Dosage**	**Unstabilized unreinforced soil shear strength parameters**		**Stabilized reinforced soil shear strength parameters**		**Reduction/Increase in shear strength parameters**	
					C (kPa)	Ø (°)	C (kPa)	Ø (°)	ΔC (%)	ΔØ (%)
Wang et al. (2021)	CL	1 640	15% GS for 7 DC (NAT)	0.4% 12 mm BF	95.7	26.9	180.5	46.6	+89	+73
					C' (kPa)	Ø' (°)	C' (kPa)	Ø' (°)	ΔC' (%)	Ø' (%)
Abdi et al. (2021)	Kaolinite	1 550	5% LS for 28 DC (35°C)	0.1% 6 mm PF	70	27	650	13	+829	-52
					C (kPa)	Ø (°)	C (kPa)	Ø (°)	ΔC (%)	ΔØ (%)
Li et al. (2015)	CL	1 601	5% CS for 7 DC (37°C)	0.5% 12 mm PF	87	24.7	399	43.8	+359	+77
					C (kPa)	Ø (°)	C (kPa)	Ø (°)	ΔC (%)	ΔØ (%)
Kaniraj and Havanagi (2001)	SM	1 840	50% FS for 28 DC (NAT)	1% PET fibre	15.7	29.5	32.5	35.1	+107	+19
	50% FAS + 50% SW	1 128	for 28 DC (NAT)	1% PET fibre	C_{uu} (kPa)	$Ø_{UU}$ (°	C_{uu} (kPa)	$Ø_{UU}$ (°)	$ΔC_{uu}$ (%)	$ΔØ_{UU}$ (%)
					16.5	30.4	160	32.9	+870	+8
					4% CS + 0% GF		4% CS + 3% GF		ΔC (%)	ΔØ (%)
					C (kPa)	Ø (°)	C (kPa)	Ø (°)		
Maher and Ho (1993)	SP	1 700	4% CS for 28 DC (NAT)	3% GF	103	37	363	49	+253	+33
					C (kPa)	Ø (°)	C (kPa)	Ø (°)	ΔC (%)	ΔØ (%)
Mishra and Kumar (2018)	CL	1 740	15% FS 24hr DC (27°C)	1.2% 20-25 mm PET fibre	36	13.2	63	22.8	+75	+73
					C (kPa)	Ø (°)	C (kPa)	Ø (°)	ΔC (%)	ΔØ (%)
Praveen and Kurre (2021)	SC	1 700	3% CS + 10% FS for 24hr DC (25°C)	2% Coir fibre	18	21	15	35	-17	+67
					C (kPa)	Ø (°)	C (kPa)	Ø (°)	ΔC (%)	ΔØ (%)
Ahmadi et al. (2020)	CL	1 825	1% Nano-MgO	1% PF	62	17.2	167	38.7	+169	+125

*Note: (-) Reduction in percentage, (+) Increase in percentage, (CS) Cement Stabilization, (GS) Geopolymer Stabilization, (FS) Fly-Ash Stabilization, (LS) Lime Stabilization, (MgO) Magnesium Oxide, (BF) Basalt Fibre, (PF) Polypropylene Fibre, (GF) Glass Fibre, (PET) Polyethylene Terephthalate Fibre, (NAT) Natural Atmospheric Temperature and (DC) Days Curing.

NB: All soils are classified in accordance with USCS (Unified Soil Classification System).

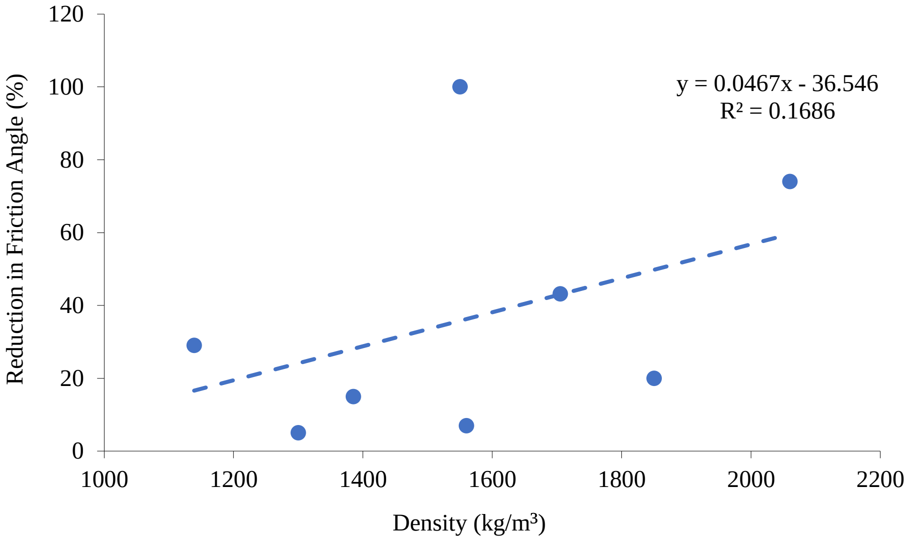

Figure 1. Effect of density on the percentage reduction in friction angle of the soil for direct shear test.

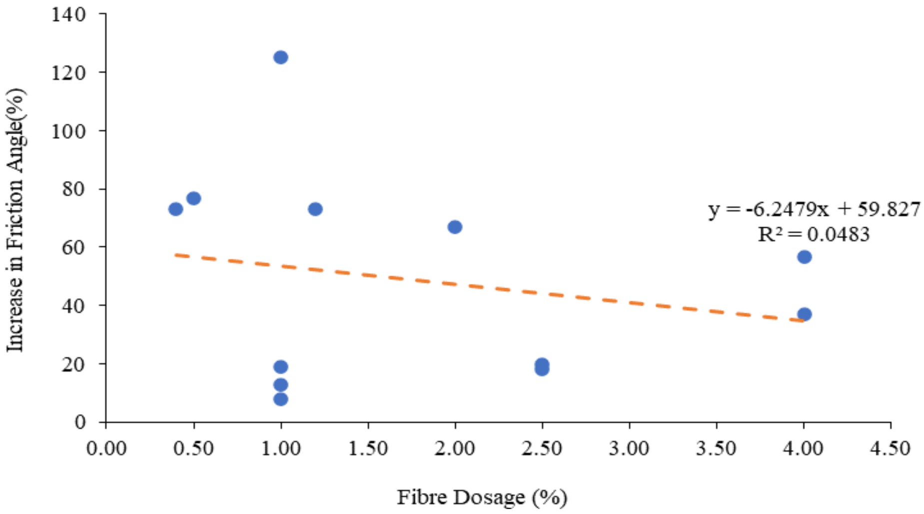

Figure 2. Effect of fibre dosage on the percentage increase in friction angle of the soil for direct shear test.

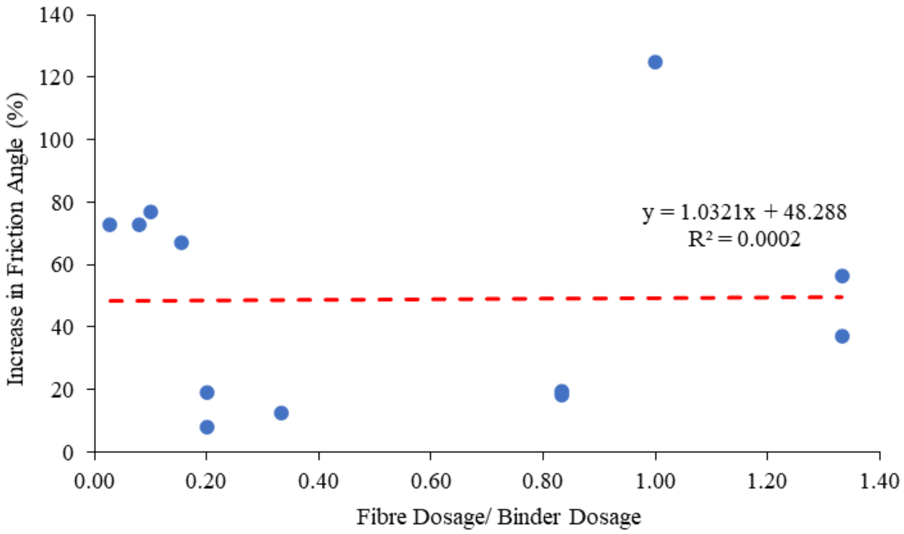

Figure 3. Effect of fibre dosage/ binder dosage on the percentage increase in friction angle of the soil for direct shear test.

Table 3 shows the effect of binder stabilization and fibre reinforcement on the indirect tensile strength of the soil, binder stabilization and fibre reinforcement increased the tensile strength of the soil. However, greatest strength improvements were associated with the type of soil adopted, binder used for stabilization, fibre and curing period. The effect of fibre dosage and the ratio of fibre dosage to binder dosage on the percentage increase in tensile strength of the soil are shown in Figures 4 and 5, respectively. It was noted that fibre dosage and the ratio of fibre dosage to binder dosage both increased with the percentage increase in tensile strength of the soil by approximately 64% and 60%, respectively.

Table 3. Effect of stabilization and fibre-reinforcement on the indirect tensile strength of the soil.

Authors	**Soil type**	**Specimen density (kg/m^3)**	**7 days ITS (kPa)**		**28 days ITS (kPa)**		**Reduction/ Increase in ITS (%)**	
			10% CS					
			0% PF	0.15% PF	0% PF	0.15% PF	7 days	28 days
Khattak and Alrashidi (2006)	CL-ML	1 812	400	520	540	500	+35	-4
	CL	1 907	610	620	840	1 280	+38	+107
	CH	1 594	120	220	280	360	+133	+64
	CL-ML	1 739	570	580	460	520	-19	-10
			7 days ITS @ 25°C (kPa)				Reduction/ Increase in ITS (%)	
			4% LS		4% LS + 1% GF		With 1% GF	
Al-Kiki et al. (2012)	CL	1 800	292		1 084		+271	
					4% LS +1% HF		With 1% HF	
					932		+219	
					4% LS + 1% PF		With 1% PF	
					788		+170	
			3 days ITS @ 27°C (kPa)				Reduction/ Increase in ITS (%)	
			Untreated Soil		CL + 15% FS + 1.2% PET fibre			
Mishra and Kumar (2018)	CL	1 740	70		160		+129	
			28 days ITS @ 27°C (kPa)				Reduction/ Increase in ITS (%)	
			CL + 5% LS		CL+ 5% LS + 1.5% PLF			
Dhar and Hussain (2019)	CL	1 540	65.9		157.1		+138	

*Note: (-) Reduction in percentage, (+) Increase in percentage, (CS) Cement Stabilization, (FS) Fly-Ash Stabilization, (LS) Lime Stabilization, (PF) Polypropylene Fibre, (GF) Glass Fibre, (PET) Polyethylene Terephthalate Fibre, (PLF) Plastic Fibre, (HF) Hay Fibre and (ITS) Indirect Tensile Strength.

NB: All soils are classified in accordance with USCS (Unified Soil Classification System).

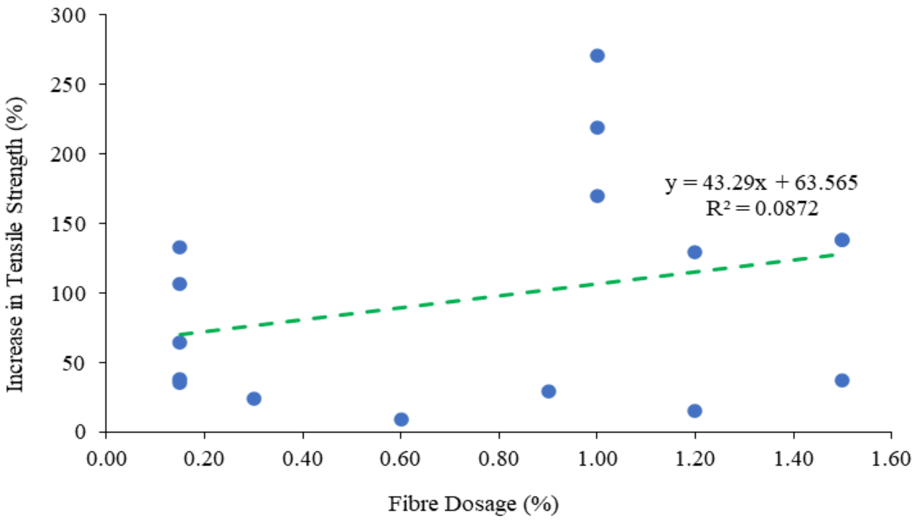

Figure 4. Effect of fibre dosage on the percentage increase in tensile strength of the soil for indirect tensile test.

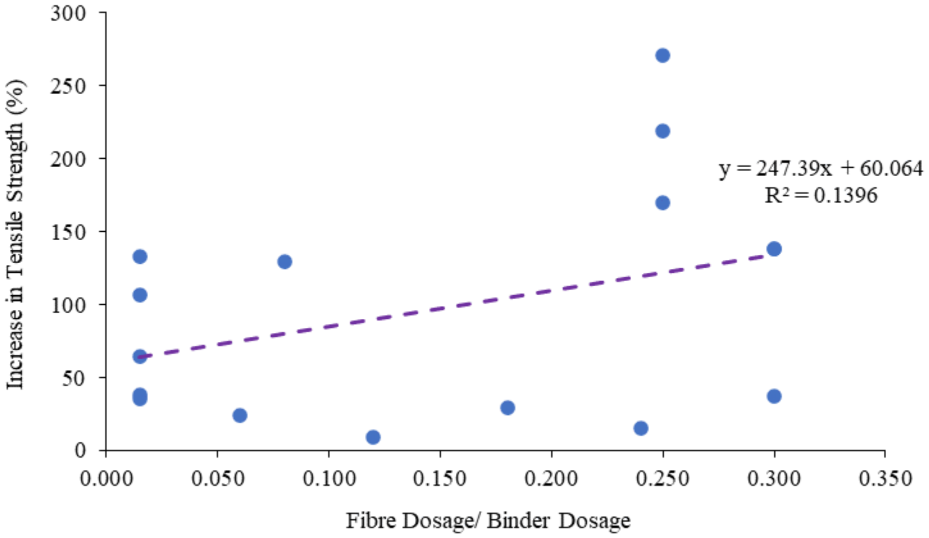

Figure 5. Effect of fibre dosage/ binder dosage on the percentage increase in tensile strength of the soil for indirect tensile strength test.

2 Conclusion

In the current study, the body of literature in soil-fibre composite behavior was reviewed and supported with more data from laboratory tests to highlight the following: the effect of compacted soil densities on the mobilized friction angle of the soil and the effect of fibre dosage and ratio of the fibre dosage to binder dosage on both the percentage increase on the mobilized friction angle and tensile strength of soil-fibre composites. Based on the limited number of literatures reviewed for a broad range of soil types, the following conclusions may be drawn out:

- The percentage reduction in mobilized friction angle upon wetting increased with soil density.
- Friction angle decreased with fibre inclusion, however marginal increase in mobilized friction angle was evident due to increase in the ratio of fibre dosage to binder dosage.
- The tensile strength increased with both increase in fibre dosage and the ratio of fibre dosage to binder dosage.

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