



An investigation on the geomechanical properties of fiber reinforced cohesive soils

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ABSTRACT

In recent years, the use of natural and synthetic fibers in soil improvement has become widespread in soil mechanics applications. Easy to use and low cost fibers have been the subject of many geotechnical researches in recent years. In this study, results of previous mechanical experiments performed on fiber-cohesive soil mixtures were reviewed in a systematic approach. Based on the data derived from the experimental studies available in the literature, it has been observed that various soil properties including soil strength have improved with increasing density of the fibers up to a certain level. The percentage of added fiber has a significant effect on improving soil properties. Based on statistical analysis, simple correlation relationships were suggested based on the investigated test database.

1. INTRODUCTION

Many soil improvement methods are practiced today for improving the properties of soils. The choice of suitable method depends upon the type of soil, material available, durability and sustainability. Out of these various materials, natural or synthetic fibers can also be used for soil improvement (Patil and Pusadkar 2019).

The first documented engineering use of natural fibers in a road construction was reported in 1926 by the South Carolina Highways Department, undertaking a series of field tests on the use of woven cotton fabrics as a simple type of geotextile to reduce cracking and raveling failure of roads. From that time, various different materials were used as soil improvement technique. In recent years, soil reinforcement with synthetic and natural fibers are gaining importance since the demand for ground improvement is increasing due to growing construction sector. The use of natural fibers, such as bamboo, jute and coir as soil reinforcing materials has been prevalent for a long time in several South Asian nations. Synthetic fibers such as polypropylene, polyester, polyethylene and glass fibers have also been used for soil reinforcement (Mali and Singh 2014).

Since the fibers have higher tensile strengths than natural cohesive soils, fiber-ground mixtures can achieve

much greater shear strength values than fiber-free soils. Fibers are thought to be efficient, especially on soils close to the surface where effective tensile and shear strength is low due to smaller confining stress.

2. GENERAL PROPERTIES OF FIBERS

Fibers, which have been used for soil reinforcement, have many advantages as listed below (Darvishi 2014):

- Mixing fibers with the soil is as easy as mixing other materials such as cement and lime used for stabilization.
- If homogeneous mixing is achieved, the fibers provide isotropic strength in the soil.
- Environment conditions have relatively low impact on fiber reinforced soils.

With the advances in chemistry, synthetic fibers are being produced in large quantities and becoming commercially available day by day. Synthetic fibers can be produced according to required specifications. For example, geometry of synthetic fibers can be controlled, shape of fibers and surface conditions can be changed in order to improve friction properties of fibers. Most synthetic fibers do not biodegrade when exposed to difficult environmental effects such as UV light, moisture and temperature (Krenchel 1973).

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2.1. General Properties of Polypropylene Fibers

Polypropylene is a 100% synthetic fiber, which is transformed from 85% propylene. The monomer of polypropylene is propylene.

Polypropylene fibers are low cost products having good impact resistance. They have low friction coefficients and provide very good electrical insulation. Besides, polypropylene fibers have good chemical resistance. Although polypropylene fibers melt at 160-170°C, they maintain most of their mechanical properties up to that temperatures. Polypropylene fibers are resistant to strong acids and bases. They retain their rigidity even after many bends. On the other side, polypropylene has some disadvantages such as low UV resistance, high thermal expansion, low weather resistance and oxidation susceptibility. The physical properties of polypropylene fibers are shown in Table 1.

Table 1. Physical properties of polypropylene fibers

Property	Value
Tensile strength (gf/den)	3.5 to 5.5
Elongation (%)	40 to 100
Abrasion resistance	Good
Moisture absorption (%)	0 to 0.05
Softening point (°C)	140
Melting point (°C)	165
Relative density	0.91
Thermal conductivity (W/mK)	6.0
Electric insulation	Excellent

3. LITERATURE REVIEW

Nataraj and McManis (1997) investigated the strength and deformation characteristics of soils reinforced with randomly distributed fibrillated fibers. The laboratory tests were conducted on a cohesive soil. The main properties of the clay tested in this study are shown in Table 2.

Table 1. Properties of the clay

Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	C (kPa)	φ (°)	w _{opt} (%)
44	18	26	84	19.5	17.9

The fibers used in this study are 25 mm long and are produced by American Synthetic Industry Corporation. In many studies, the diameter, strength or type of fiber was considered, but in this study, same type of fibers were used throughout the experimental study. Fibers were mixed into the soil by hand or by mechanical mixer. In this study, the mixture of soil and fibers was taken to a large metal pan and uniformly mixed by adding a certain amount of water. Fiber density was examined as 0.1%, 0.2% and 0.3% of dry soil weight.

In the compaction tests, the relationship between dry unit weight and moisture density was investigated by comparing fiber reinforced and unreinforced soils. The increase in fiber density increased the dry unit volume weight slightly and decreased the moisture density. The clay specimens were compacted with a 178 N compaction force in 3 layers using 30 blows per layer.

Clay specimens were prepared at maximum dry unit weight and optimum moisture ratio and they were subjected to unconfined compression tests. Three

different size specimens were tested (33mm×72 mm, 70 mm ×140 mm, and 100 mm × 117 mm).

According to the test results, the strength of all reinforced clay specimens increases with increasing moisture content. The strength of clay samples with a fiber content of 0.2% and 0.3% is significantly higher than that of a sample with a fiber content of 0.1%.

Clay specimens with and without fibers were subjected to direct shear tests in 64 mm and 100 mm cutting boxes. The specimens were prepared at maximum dry unit weight and optimum moisture content. The clay specimens which have 0.3% fiber content reached higher shear stress values than the other specimens. California Bearing Ratio tests were conducted on reinforced and unreinforced clay specimens at maximum dry densities and moisture contents (ASTM D 698).

The CBR value for the unreinforced clay specimen increased from 8.44 to approximately 12.6 for specimens with a 0.3% fiber content.

Puppala and Musenda (2000) conducted unconfined compressive tests using Irving (PI = 55) and San Antonio (PI = 46) clays. The results indicated increased strength and ductility of the soil with increasing fiber content. The effect of fiber length was also evaluated and it was found that as the length of the fibers was increased from 2.54 mm to 5.08 inches, the strength and axial strain at failure also increased.

The shear strength of the fiber-reinforced sand at large shear displacement has been investigated by Heineck et al. (2005), who reported that although fiber-reinforced soil did not outperform the unreinforced sand in terms of initial stiffness, its shear strength was superior to that of the unreinforced soil with no loss even at large shear displacements of 250 mm.

Abdi et al. (2008) studied the consolidation settlement and swelling characteristics of clays with inclusion of 5, 10, and 15 mm polypropylene fibers at fiber content of 1%, 2%, 4% and 8% by weight of dry soil. They concluded that addition of randomly distributed polypropylene fibers resulted in reducing the consolidation settlement of the clay soil. Length of fibers had an insignificant effect on this soil characteristic, whereas fiber contents proved more influential and effective. Inclusion of polypropylene fibers to the clay soil resulted in reducing the amount of swelling after unloading. The effect was proportional to the fiber content. But at constant fiber contents, the amount of swelling was not significantly affected by increasing fiber length.

Jiang et al. (2010) performed tests on a cylindrical clayey soil sample of 61.8 mm diameter. Fibers of 0.02-0.05 mm diameter and 15, 20 and 25 mm length were mixed at 0%-0.4% densities and a series of shear strength experiments were performed. At the end of the experiments, it was observed that the cohesion value and the internal friction angle increased with increasing fiber density and length.

Sravya and Suresh (2016) observed that the effect of synthetic-fibers in the restricted swelling of expansive soils. One-dimensional swell-consolidation tests were carried out to determine the behavior changes in the soil samples. It is noticed that increasing fiber content causes

a decrease in swelling pressure while increasing the unconfined compressive strength (UCS) and CBR values.

Mirzababaei et al. (2018) carried out a series of multi-stage drained reverse direct shear tests. The soft clay samples reinforced with 0.25% and 0.50% polypropylene fibers of 6 mm, 10 mm and 19 mm in length. Results showed an increase of the shear strength with the increase of fiber content and length.

Ma et al. (2018) studied the fiber reinforced clay in different fiber content and different confining pressure. Laboratory triaxial tests were carried out to investigate the reinforcement mechanism. The test results showed that the shear strength of fiber reinforced clay was greater than that of pure clay.

Soltani et al. (2018) reported the effect of two kind of tape-shaped fibers. In this investigation, two different fiber widths (2.5 mm, and 7 mm) were used as the reinforcement for the expansive soil. The fiber contents used this study were 0.5%, 1%, and 1.5%. Each fiber type has two lengths/aspect ratios (15/2.5 and 30/2.5) for fiber-A type, and (15/7 and 30/7) for fiber-B type. In case of constant width for a given fiber type it was observed that the direct function of improvement of expansive soil is fiber content and length.

Tong et al. (2019) investigated the addition of fibers improves the shear strength of the reinforced clay and effectively improves the deformation resistance of the fiber-reinforced clay. The addition of fibers increased the internal friction angle and cohesion of the clay.

Benziane et al. (2019) carried out a series of direct shear box tests to compare unreinforced and reinforced soil with different contents of fibers. The experimental results showed that the mechanical characteristics was improved with the addition of polypropylene fibers.

Hussein and Ali (2019) studied the effect of adding polypropylene fiber on the behavior of expansive soil. In this study Unconfined Compression Test, One-Dimensional Consolidation Test, Swelling Test, Sieve Analysis and Cycle Swell Shrink Test were carried out and test results were saved. The results showed that the increase in percentage of polypropylene fiber (PPF) led to decrease the swelling and to increase the unconfined compression strength.

Test data obtained from many experimental studies available in the literature were compiled in Table 3 and graphs were presented with a series of regression equations (Ertugrul and Canoğulları 2019). In the regression equations LL denotes the liquid limit of the soil and d_f denotes the fiber density in percent.

Considering the data for the effect of fiber density on the cohesion, following regression model was fitted:

$$c = \alpha + \beta*(LL/PL) + \gamma*(d_f)$$

Coefficients (with 95% confidence bounds):

$$\alpha = 115.3 (66.2, 164.4)$$

$$\beta = -17.45 (-39.61, 4.712)$$

$$\gamma = 18.93 (11.07, 26.8)$$

On behalf of the goodness of fit, R-square value is found as 0.9043.

Considering the data for the effect of fiber density on the internal friction angle of soil, following regression model was fitted:

$$\Phi = \zeta + \eta*(LL/PL) + \psi*(d_f)$$

Coefficients (with 95% confidence bounds):

$$\zeta = 41.57 (36.85, 46.3)$$

$$\eta = -6.088 (-8.219, -3.957)$$

$$\psi = 0.3998 (-0.3562, 1.156)$$

On behalf of the goodness of fit, R-square value is found as 0.8949.

Table 3. A summary of previous test results

LL/PL ratio	Fiber density, d_f (%)	c (kPa)	ϕ (°)
36.4/18.6 (Tang et al. 2007)	0	75,5	27,5
	0.05	95,9	28,2
	0.15	103	29,7
	0.25	115,6	31,6
44/18 (Nataraj and McManis 1997)	0	84	19,5
	0.3	122,5	32
50/21 (Pradhan et al 2012)	0	40	26
	0.1	90	30.1
	0.2	90	40.9
	0.3	95	44.1
	0.4	96	44.4
	0.5	50	52
65/27.6 (Naeini and Sadjadi 2008)	0	97	27.3
	1	105	34.2
	2	109.9	36.3
	3	103.7	37.1
	4	100.6	37.3
72/29.9 (Naeini and Sadjadi 2008)	0	160.9	20.3
	1	163.2	25.6
	2	168	27.4
	3	163	28.1
78.58/31.5 (Naeini and Sadjadi 2008)	4	149	28.5
	0	185	17.4
	1	190.4	22.5
	2	194	24
52.9/27.5 (Maheshwari 2011)	3	190	24.7
	4	188	25.3
	0	59	5.5
	0.2	70	18.65
26.93/20.19 (Bo et al. 2013)	0.5	76	26.58
	1	64	23.65
	1.5	62	13.69
74/27 (Mirzababaei 2018)	0	49.16	34.07
	0.1	94.01	35.71
	0.2	138.29	36.36
	0.3	228.35	35.95
32.6/16.8 (Wei et al. 2018)	0	6.1	25
	0.25	33	22
	0.5	43	25.7
57.1/19.7 (Wang et al. 2019)	0.2	380	32
	0.25	368	33
	0.3	350	33
74/27 (Mirzababaei 2018)	0	64	21
	0.4	72.32	24.57
	0	6.1	25
38.94/20.43 (Ma et al. 2018)	0.25	28.7	26.9
	0.5	41.1	24.1
	0	34.9	25.5
74/27 (Mirzababaei 2018)	0.2	35.96	25.9
	0.4	41.26	28.2
	0.6	44.81	30
	0.8	48.75	27.2
	1.0	45.72	26.5

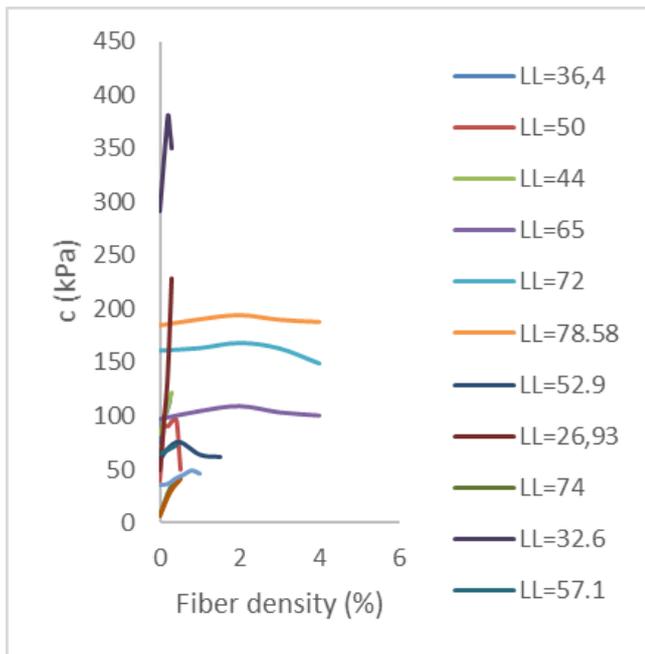


Figure 1. Effect of soil – fiber density on cohesion

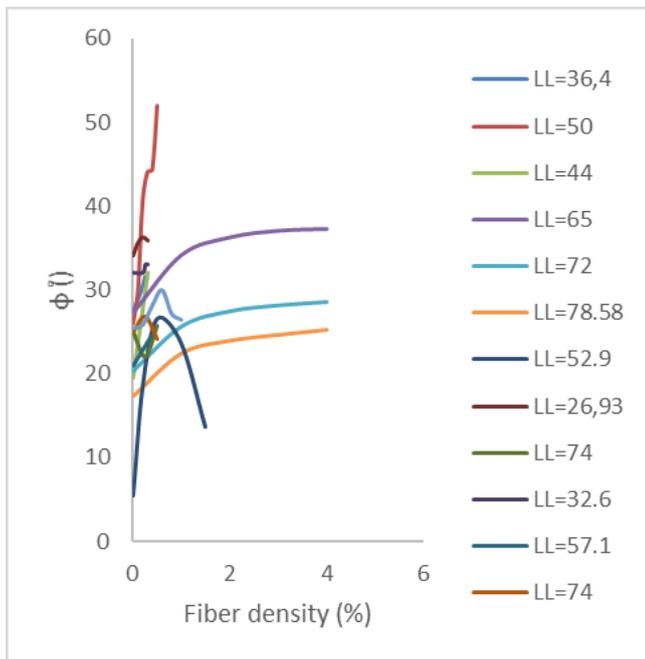


Figure 2. Effect of the soil – fiber density on the friction angle

4. CONCLUSION

Soil improvement techniques are used to improve the engineering properties of soils. These techniques vary by the application methods and soil types that can be improved. The addition of geosynthetic materials (fibers, geomembranes and geotextiles) is a new improvement technique that ensures uniformity in the soil during construction. In recent years, the use of fiber in soil improvement has become widespread. Easy to use and low cost fibers have been the subject of many geotechnical researches. Since the fibers have higher tensile strengths than natural cohesive soils, fiber-ground mixtures can achieve much greater shear strength values than fiber-free soils. The over-all effects of random fiber inclusion on clays observed, suggests

potential applications of fiber reinforced soils in shallow foundations, embankments over soft soils, liners, covers and other earthworks that may suffer excessive deformations.

Clays are known for their high compressibility and low shear strength. Previous studies have mainly evaluated the effects of additives such as sand, cement and lime on these properties of clay and the results have shown that soil properties have improved.

In this study, results of experiments on fiber - added cohesive soils are investigated. Test data obtained from many previous studies available in the literature were compiled within the scope of this study and graphs were presented with a series of regression equations.

According to the performed analyses, it was been observed that the shear strength of the reinforced soils increases with fiber content , the consolidation settlement of clayey soils mixed with polypropylene fibers were decreased considerably. Fiber length has a small effect on this soil property, while fiber density has been observed to be quite effective on the mechanical and consolidation characteristics of the untreated soil.

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