Strength and Compaction Behavior of Randomly Distributed Polypropylene Fiber Reinforced Expansive Clay

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Abstract. Experimental investigations were conducted to study the effects of randomly distributed polypropylene (PP) fiber inclusions on the mechanical behavior of expansive soil. Reinforced soil specimens were prepared at four different fiber contents (0.05%, 0.1%, 0.15% and 0.2%) and the aspect ratio of fibers (L/D) was kept as 250. A series of compaction tests, unconfined compressive strength (UCS) and split tensile strength (STS) tests were performed on the unreinforced and fiber reinforced soil specimens. The results proved that, the UCS and STS values increased to a greater extent with the inclusion of fibers to the expansive soil. The inclusion of monofilament type PP fibers within expansive soil contributes to increase the peak axial stress, improve the residual strength, and increase the modulus of elasticity, toughness and ductility of the soil. It was noticed that, the effect of polypropylene fiber inclusion on the compaction parameters was not much significant (less than 5% variation) due to light weight and less water absorption capacity of PP fibers. The highest UCS values were obtained with 0.15% fiber content with 12 mm length of fibers for that UCS values increased up to 51% of that of the unreinforced soil. Similar behavior was also observed for STS of soil-fiber mixtures with a gain of 59% in tensile strength. From the UCS and STS test results, some other parameters like secant modulus, shear modulus, resilient modulus and deformability index were also reported for both unreinforced and reinforced specimens. It was seen that, secant modulus of expansive soil increased up to 89% and resilient modulus was increased up to 17% on addition of 0.15% fibers. Similarly other parameters were also improved with the inclusion of PP fibers within the expansive soil.

Keywords: Monofilament fibers, Split tensile test (STS), Resilient modulus, Secant modulus, Deformability index.

1. Introduction

Civil engineering structures transfer their load on the soil mass through foundation. Construction of embankments, backfill of retaining walls, highway subgrades and landfill liners and covers require utilization of locally available soil due to high transportation charges in bringing the soil from some other site (Anggraini et al. 2015). Sometimes we come across such soils at project site which cannot be used as a construction material due to their low bearing capacity and shear strength e.g. black cotton soil. In that case we have to improve the soil quality for its further use.

This problem leads to development of various ground improvement techniques either using a chemical stabilization or a mechanical stabilization (Yixian et al. 2016). Strengthening of weak soil by adding chemical additives such as cement, lime, ground granulated blast furnace slag, bagasse ash and fly ash has been suggested by many researchers in past (Bell, 1996; Kaniraj & Havanagi, 2001). Another technique that is mechanical stabilization falls under the category of soil reinforcement. Soil reinforcement technique has been used since ancient times in the form of roots of tress, bamboos, straws etc. There are many ancient structures which are built using soil reinforcement technique like the Ziggurats of Mesopotamia and Great Wall of China (Patel & Singh, 2017).

Reinforcement of soil not only improves its compressive strength but also its tensile strength to a great extent. Reinforcement reduces the brittle behavior and post peak strength losses in the soil (Estabragh et al. ,2011). Reinforcement technique is also classified in to two categories, one is systematic reinforcement and another is randomly distributed reinforcement. Review of the literature reveals that, random inclusion of fibers is more advantageous as compared to systematically oriented reinforcement because the later creates weak zones in the soil mass. When a tensile crack appears in to the soil due to shrinkage or loading, the fiber is supposed to prevent the propagation of crack (Singh, 2014). Some researchers tried natural fibers like coir fiber, jute fiber with soil and some tried synthetic fibers like polyethylene, PET, polypropylene etc. Both natural and synthetic fibers increase the compressive as well as tensile strength of soil, but natural fibers are more prone to decay with time when buried under moist soil. Now a days, fiber reinforced soil is being used in various civil engineering projects like in landfill liners for crack control, in pavement applications, behind the retaining wall as a backfill material, in slope protection works and below shallow footings (Cai et al., 2006).

In this study, a series of laboratory investigations were carried out to evaluate the performance of monofilament polypropylene fibers with expansive black cotton soil. Unconfined compressive stress (UCS), Split tensile strength (STS) and standard proctor tests were performed to study the strength gain, failure pattern and compaction parameters of unreinforced and reinforced soils. A variety of soil indexes and modulus like secant modulus, resilient modulus, deformability index and shear modulus were also reported based on the UCS results.

2. Materials Used

2.1 Expansive soil

The expansive soil used in the present study was collected from Student Activity Center ground of SVNIT Campus, Surat. The soil is black cotton soil in appearance and it is classified as CH soil as per IS 1498-1970. The physical properties of this soil are shown in table 1.

Table 1 Physical properties of soil used in the study

Property	Value
Specific gravity	2.62
Grain size analysis	
Gravel (%)	0
Sand (%)	7
Silt (%)	72
Clay (%)	21
Consistency limits	
Liquid limit (%)	61.2
Plastic limit (%)	24.6
Plasticity index (%)	36.6
IS classification	CH
Compaction parameters	
OMC (%)	25.5
MDD (g/cc)	1.448

2.2 Polypropylene Fibers

Polypropylene is a commercially available synthetic fiber. Monofilament type fibers were used in this study. Physical and mechanical properties of these fibers are given in the table 2.

Table 2 Physical properties of polypropylene fiber used in the study

Property	Value
Average tensile strength (MPa)	340
Avg. diameter (mm)	0.048
Moisture absorption (%)	0 to 0.04
Melting point (℃)	167
Chemical resistance	Good
Unit weight (g/cc)	0.90
Electrical insulation	Excellent
Average length	12mm

3. Experimental Program

To study the effects of randomly distributed PP fiber addition in black cotton soil, virgin black cotton soil was mixed with four different dosages of fiber (i.e. 0.05%, 0.1%, 0.15% and 0.2%). The percentage of fibers and length of fibers were decided based on the previous studies carried out using polypropylene fibers. The fiber content (C_f) is calculated as per equation 1.

$$C_f = \frac{w_f}{w} \tag{1}$$

Where, w_f is the weight of fibers and w is the dry weight of soil. Hand mixing method was adopted to get a uniform mixture of soil and fibers. The fibers were in the form of bundles which opens up on rubbing action against moist soil. Mixing of fibers with moist soil gave more uniform texture than with dry soil, so first predetermined amount of water was added and mixed to get a uniform color of soil and then fibers were sprinkled over it and mixed by hand mixing.

Fig. 1. Split tensile test apparatus

First, compaction tests were performed so that UCS and STS samples can be prepared at predefined optimum moisture content and dry density. UCS and STS specimens were prepared having 100mm height and 50mm diameter. Later UCS and STS tests were conducted on both reinforced and unreinforced expansive soil. Split tensile test apparatus is used as shown in the Fig.1. The apparatus used in this study is made in accordance with many previous researchers (Thompson et al. 1966; Kumar et al. 2007; ASTM C496, 2011; Olgun, 2018; Dhar & Hussain, 2018). Based on the above research papers a metal loading strip was prepared as shown in the Fig.1. The thickness of the strip is 1.778mm and width is 6.35mm such that width/sample diameter ratio is kept 1/8 for proper distribution of load. The loading was applied using an UCS testing machine at a rate of 1.25mm per minute. The soil sample was kept horizontally below the loading frame as shown in the Fig. 1. The failure load is recorded. The tensile strength of the soil is calculated as per equation (2).

$$Split\ Tensile\ Strength\ (kPa) = \frac{2P}{\text{®}\, ld} \tag{2}$$

Where, l is the length of the specimen, P is the load at failure and d is the diameter of the specimen. The STS value is calculated for 3 identical specimens and an average value is reported here.

4. Results and discussion

As discussed in previous sections, a number of soil samples with and without fiber reinforcement were tested to study their strength and compaction behavior. The results of Compaction, UCS and STS are presented in the sub-sections.

4.1 Effect of fibers on compaction behavior

Fig. 2 presents the results of standard proctor test conducted on untreated and treated expansive soils. These tests were conducted to determine the optimum moisture content (OMC) and maximum dry density (MDD) of the soil samples to be prepared for UCS and STS tests. The curves show that MDD decreases and OMC increases on addition of fiber to the expansive soils. Only two fiber contents were analyzed (i.e. 0.05% and 0.2%) which are minimum and maximum fiber dosages. It can be concluded from the curves that even up to maximum fiber addition there is a slight variation in the OMC and MDD of expansive soils. For untreated soil OMC and MDD are 25.5% and 1.448 g/cc respectively which on addition of 0.2% fiber content changes to 26.2% and 1.420 g/cc i.e. less than 5% variation. So there is not a significant effect of fibers on the compaction behavior of expansive soil. This can be attributed to the light weight and less water absorption tendency of polypropylene fibers.

4.2 Effect of fiber addition on UCS and failure pattern

Table 3 shows the variation of UCS with variation in fiber dosages and also the gain in UCS values which is defined as a ratio of increase in UCS of reinforced soil to the UCS of unreinforced soil are presented along with. It is observed that the UCS increased with increase in fiber dosages up to 0.15% and then it decreased. According to the principles of fiber reinforcement of soil, the applied load is transferred to the interface between soil and fibers through friction (Olgun, 2013). As we increase the fiber content in the soil, the frictional interface between soil and fiber increases which contribute the increased shear strength of the soil. Another contribution is due to high tensile strength of fibers. They act like tree roots within the soil mass. Peak compressive strength of untreated soil is 269 kPa which increased up to 408 kPa (i.e. 51.67% gain in UCS). It can be seen from Fig. 3 that ductility of soil samples were increased due to inclusion of fibers to the soil. Also post peak strength losses were reduced with increased fiber content. The reduction in UCS after 0.15% fiber addition can be attributed to "balling effect". Balling effect is due to non-uniform mixing of fibers. After 0.15% fiber addition, it was not easy to uniformly mix the fibers with soil that causes lump formation which is called balling effect. These lumps are highly compressible and make soil more compressible.

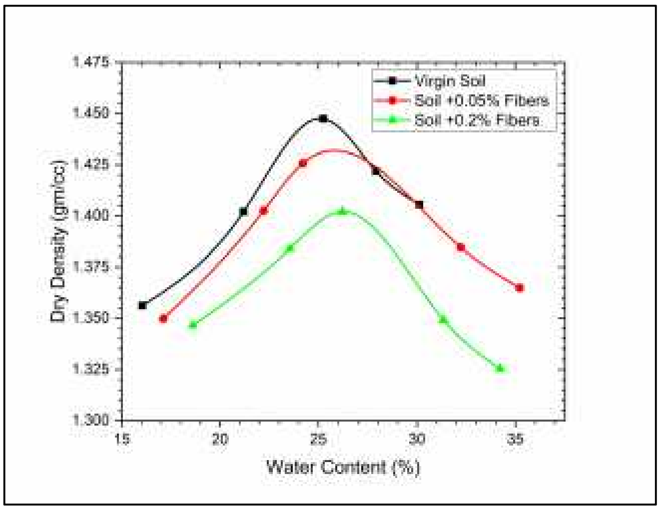

Fig. 2. Variation of dry density with water content

4.3 Effect of fiber inclusion on STS

Split tensile strength of unreinforced and reinforced soil with different fiber dosages is shown in Fig. 4. For untreated soil, STS is found 35.27 kPa, which got increased up to 56.02 kPa on addition of 0.15% fibers (i.e. 58.83% increment). It shows that fibers are more effective in increasing the tensile strength with respect to the compressive strength of unreinforced soil. The gain in tensile strength of soil-fiber mixture can be credited to high tensile strength of polypropylene fibers. Moreover, fibers works as a bridging agent between crack openings and reduces the further propagation of cracks, this effect is called the "bridging effect" of fibers as shown in Fig. 5.

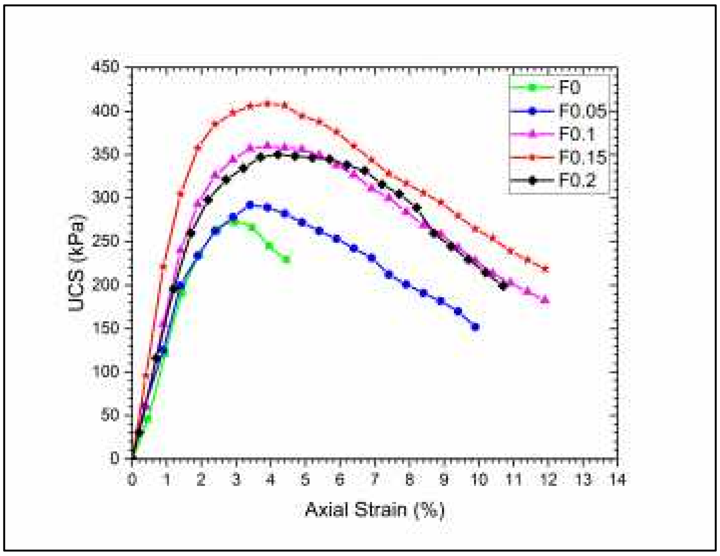

Fig. 3. Stress strain behavior for unreinforced and fiber reinforced soil

4.4 Effect of fiber inclusion on deformability index of soil

It is an index that reciprocates ductility and brittleness behavior of materials (Karaca and Onargan 2012). It is defined as per equation 3.

$$I_D = \frac{£_r}{£_u} \qquad (3)$$

Where ε_r is axial strain conforming to peak UCS value for reinforced specimen and ε_u is axial strain conforming to peak UCS value for unreinforced soil. It can be noticed from the table 4 that deformability index increased with increase in fiber content which confirms that addition of fiber makes soil more ductile in its failure behavior.

4.5 Effect of fiber inclusion on resilient modulus of soil

Resilient modulus is associated to elastic response of soil to the given stresses. In the design of pavement layers, resilient modulus of subgrade materials plays a key role. The ratio of cyclic deviator stress to the resilient strain is defined as resilient modulus. It reciprocates the stiffness of the pavement materials and helps in pavement design (Toohey et al., 2013).

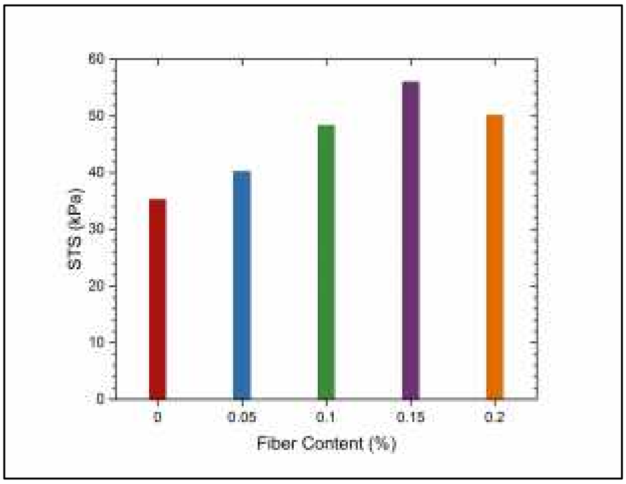

Fig. 4. Variation of STS with fiber content

Resilient modulus can be calculated from UCS value of soil as per equation 4 given by Thompson M.R. 1966.

$$M_r \text{ (MPa)} = 0.124 \times \text{UCS (kPa)} + 68.8 \quad (4)$$

The variation of resilient modulus with dosages of fiber is given in Table 4. It can be noticed that M_r for unreinforced soil is 102.28 MPa which is increased up to 119.58 MPa on addition of 0.15% fiber content (i.e. 16.91% increment in M_r).

Table 3 Results of UCS tests

Sample ID	UCS (kPa)	STS (kPa)	Gain in UCS (%)	Gain in STS (%)
Soil	269	35.27	-	-
Soil + 0.05% Fiber	293.5	40.25	8.70	14.12
Soil + 0.1% Fiber	360.48	48.38	33.51	37.17
Soil + 0.15% Fiber	409.5	56.02	51.67	58.83
Soil + 0.2% Fiber	350	50.2	29.63	42.33

4.6 Effect of fiber addition on secant modulus of soil

The ratio of half of peak compressive stress to the conforming axial strain is defined as the secant modulus (Dang & Khabbaz, 2018). The secant modulus for unreinforced and fiber reinforced soil is given in Table 4. It can be seen from the table that for unreinforced soil the value of secant modulus is 12.62 MPa which is increased on addition of polypropylene fibers up to 23.86 MPa for fiber content of 0.15% (i.e. 89% increment in secant modulus of soil). Further addition of fibers shows a reduction in secant modulus value because of their balling effect.

Fig. 5. Bridging effect of fibers

Fig. 6. Failure pattern of specimen in STS test

Table 4 Various modulus and indexes calculated using UCS value

Sample ID	Secant Modulus (MPa)	Resilient Modulus (MPa)	Shear Modulus (MPa)	Deformability Index (I_D)
Soil	12.62	102.28	4.21	-
Soil + 0.05% Fibers	14.02	105.19	4.67	1.16
Soil + 0.1% Fibers	17.11	113.50	5.70	1.29
Soil + 0.15% Fibers	23.86	119.58	7.95	1.35
Soil + 0.2% Fibers	16.37	112.20	5.46	1.43

4.7 Correlation between tensile and compressive strength

A linear relationship was found between unconfined compressive strength (kPa) and split tensile strength (kPa) of soil- fiber specimens. Fig. 7 shows the relationship between STS and UCS of fiber reinforced specimens with R^2 value of 0.97.

4.8 Effect of fiber addition on shear modulus of soil

Response of a soil mass to the stresses and design of any structure on it depends largely upon its shear modulus value, ignorance of which causes a lot of damage to structures (Saberian & Rahgozar, 2016). Shear modulus of each combination of soil and fiber is calculated based on the following relation given in equation 5 (Marmo & Rosati, 2016).

$$G(MPa) = \frac{\sigma_{xy}}{\varepsilon_{xy} + \varepsilon_{yx}} = \frac{\sigma_{xy}}{2\varepsilon_{xy}} = \frac{\sigma_{xy}}{\gamma_{xy}} = \frac{E_s(MPa)}{2(1+\nu)} = \frac{E_s(MPa)}{3} \quad (5)$$

Where Es = Secant Modulus, ε is the shear strain and σ_{xy} is the shear stress, and $\gamma_{xy}=\varepsilon_{xy} + \varepsilon_{yx} = 2\varepsilon xy$ (Selvadurai & Katebi, 2013).

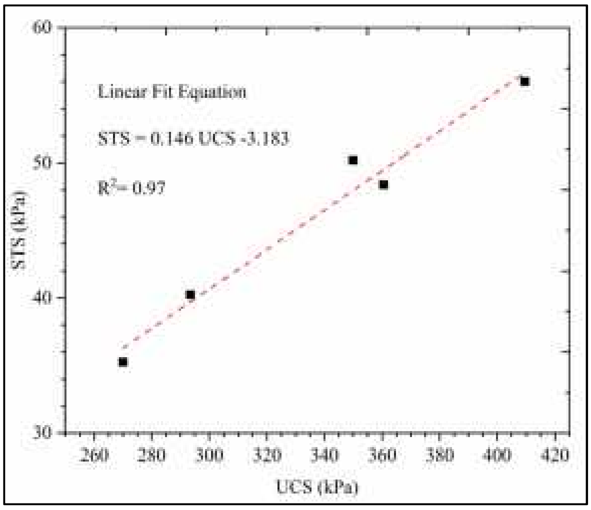

Fig. 7. Correlation between STS and UCS

A change in secant modulus with fiber dosage is shown in table 4. It was seen that shear modulus of soil is 4.21 MPa which is increased up to 7.95 MPa (approx. 89% increment) on addition of 0.15% PP fibers and on further addition of fibers it decreases.

5. Conclusions

Based on the experimental investigations conducted on unreinforced and reinforced soil specimens following conclusions are drawn:

- Effect of polypropylene fibers on compaction parameters is insignificant due to less than 5% variation in OMC and MDD on addition of 0.2% fiber content.
- Compressive strength of soil first increases on inclusion of fibers and after optimum fiber content it decreases due to balling effect. Maximum UCS is obtained for 0.15% fiber content with a gain in UCS of 51.67% w.r.t. unreinforced soil.

- Due to inclusion of fibers split tensile strength of soil increases by 58.83% on addition of 0.15% fiber content. It shows that effect of fibers is more on tensile strength than compressive strength of soil-fiber specimens.
- A linear correlation between STS and UCS of soil fiber specimens is obtained with an R^2 value of 0.97.
- Resilient modulus, secant modulus and shear modulus of soil-fiber specimens increases by 89%, 16.91% and 88.83% respectively on addition of 0.15% PP fibers in to the soil.
- Deformability index of soil goes on increasing with rise in fiber content which demonstrates that fiber addition makes the failure pattern of soil more ductile.

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