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Engineering properties of expansive soil treated with polypropylene fibers

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Abstract. Expansive soils are renowned for their swelling-shrinkage property and these volumetric changes resultantly cause huge damage to civil infrastructures. Likewise, subgrades consisting of expansive soils instigate serviceability failures in pavements across various regions of Pakistan and worldwide. This study presents the use of polypropylene fibers to improve the engineering properties of a local swelling soil. The moisture-density relationship, unconfined compressive strength (UCS) and elastic modulus (E_{50}), California bearing ratio (CBR) and one-dimensional consolidation behavior of the soil treated with 0, 0.2, 0.4, 0.6 and 0.8% fibers have been investigated in this study. It is found that the maximum dry density of reinforced soil slightly decreased by 2.8% due to replacement of heavier soil particles by light-weight fibers and the optimum moisture content remained almost unaffected due to non-absorbent nature of the fibers. A significant improvement has been observed in UCS (an increase of 279%), E_{50} (an increase of 113.6%) and CBR value (an increase of 94.4% under unsoaked and an increase of 55.6% under soaked conditions) of the soil reinforced with 0.4% fibers, thereby providing a better quality subgrade for the construction of pavements on such soils. Free swell and swell pressure of the soil also significantly reduced (94.4% and 87.9%, respectively) with the addition of 0.8% fibers and eventually converting the medium swelling soil to a low swelling class. Similarly, the compression and rebound indices also reduced by 69.9% and 88%, respectively with fiber inclusion of 0.8%. From the experimental evaluations, it emerges that polypropylene fiber has great potential as a low cost and sustainable stabilizing material for widespread swelling soils.

Keywords: swelling soils; polypropylene fiber; soil improvement; unconfined compressive strength; California bearing ratio; free swell; swell pressure; compressibility

1. Introduction

Swelling soils contain clay minerals like montmorillonite and illite, which are capable of absorbing large amount of water. Such soils show large volumetric changes in form of expansion and shrinkage when subjected to wet-dry cycles of environment (Sharma and Sivapullaiah 2016). These volumetric changes resultantly cause huge damage to civil engineering structures like airport runways, earthen dams and footings by exerting enough stresses on it (Holtz 1983, Aziz *et al.* 2015, Loehr *et al.* 2000, Taha *et al.* 2018, Shariati *et al.* 2019). Until 1940s, the soil engineers could not identify the problematic role of swelling soils and the ultimate cause of structural damages was credited to the soil settlement under foundations and to the poor construction methods. The cause of damages to various structures by the swelling soils was first discovered by U. S. Bureau of Reclamation (Chen 1975).

Expansive soils contain montmorillonite clay mineral that exhibit large volume change (shrinkage-swelling) when exposed to the changes of moisture content and this behaviour is most apparent near ground surface because of environmental and seasonal variations. The swelling and shrinking mechanism of expansive soils is quite complicated and depends on many factors such as clay content, plasticity, moisture content and climatic conditions (Houston *et al.* 2011, Fatahi *et al.* 2013). Swelling soils are found worldwide, mainly in the arid and semi-arid regions like Canada, China, India, Pakistan, Australia, South Africa, United States etc. (Mishra *et al.* 2008, Mohanty *et al.* 2017). The yearly cost of reported damages caused by natural catastrophes in USA like storms, cyclones, floods and seismic activities was commutatively two times lesser than that of the damages instigated by swelling soils (Chen 1975). In Pakistan, swelling soils exist in several regions such as Sialkot, Chakwal, D.G. Khan, D.I. Khan, Narowal, Gujranwala etc. (Rashid 2015). Various soil improvement techniques have been developed to mitigate the swelling problems by using different types of chemical additives, freeze-thaw phenomena, vacuum pumping, geosynthetic reinforcement etc. (Guney *et al.* 2007, Wang *et al.* 2017, Ahmad *et al.* 2010, Thomas and Rangaswamy 2020). When some synthetic fiber (geotextile) of high tensile strength is

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mixed with soil then the geo-engineering characteristics of soil are improved and the reinforced soil is known as fiber-reinforced soil (Mandal and Murti 1989, Changizi and Haddad 2015). Rice straw, wheat straw, bamboo, wood and reeds were some of the natural materials being used in ancient times to improve the strength properties of soil (Xu *et al.* 2004). With the advent of geotextile and its swift development, various types of geotextile have been utilized as main reinforcement agents for soil improvement purposes (Cai *et al.* 2006, Jiang *et al.* 2010, Estabragh *et al.* 2011, Tang *et al.* 2012). Common types of geotextile are locally available in today's market such as glass, carbon, polyester, asbestos, nylon, polyacrylonitrile, polyethylene and polypropylene (Shen 1995). Among these synthetic fibers, mass long fiber is utilized as geogrid or geotextile to improve the engineering properties of soil while a small quantity of short fiber is used for the improvement of tensile strength of asphalt and concrete (Kaufmann *et al.* 2004, Park 2011).

Across the world, PP fibers are being produced in tons of quantities but instead of being used for constructional purposes, it is majorly thrown away as a waste in huge quantities producing huge environment footprint (Cutright *et al.* 2013). Therefore, such wastes should be effectively utilized for the soil stabilization purposes as well as it can also reduce the environmental pollution.

In the recent past, several studies have been conducted on use of polypropylene (*PP*) fibers to improve engineering properties of problematic clayey soils. According to Ramasamy and Arumairaj (2013), *PP* fiber is the most commonly used synthetic material around the world due to its low cost, hydrophobic and chemically inert nature. It has been noticed from the literature that the maximum dosage of PP fibers to investigate its effect on engineering properties of expansive soils has been 1% of the dry weight of soil. As shown in Table 1, the optimal dosage of *PP* fibers varies from 0.25 to 1% to enhance different engineering properties of expansive soil such as consistency limits, compaction characteristics, compressibility and shear strength. In view of the advantages and promising characteristics, the fiber-reinforced soils are recognized as a feasible ground improvement technique with a great potential of their application in several areas of geotechnical engineering.

To authors' knowledge, there is a limited database available in Pakistan on strength and deformation behavior of local swelling soils reinforced with fibers. The current study presents an experimental investigation carried out to explore the mechanical behavior of an expansive soil treated with PP fibers. The effect of stabilizing fibers on compaction, strength and deformation behavior of the test soil has been presented in detail.

Table 1 Improving engineering characteristics of expansive soils using PP fibers

Reported by	Property	Optimal dosage of PP fibers	Improvement in soil property
Soğancı (2015)	UCS	1%	135%
	% swell		-227%
Olgun (2013)	Crack reduction	0.75%	69.9%
Ramasamy and Arumairaj (2013)	UCS	0.75%	138%
	CBR		170%
Malekzadeh and Bilsel (2012a)	UCS	1%	140%
	Tensile strength		280%
	% swell		236%
Jiang *et al.* (2010)	UCS	0.3%	150%
	Cohesion		130%
	Friction angle		120%
Viswanadham *et al.* (2009)	Swell pressure	0.25 - 0.5%	-240%
	Heave		-370%
Tang *et al.* (2007)	UCS	0.25%	138%
	Cohesion		153%
	Friction angle		114%

Table 2 Physical properties of the soil used in this study

Properties	Unit	Value
Natural moisture content	%	5.6
Specific gravity, G_s	-	2.71
Liquid limit, *LL*	%	53
Plastic limit, *PL*	%	22
Plasticity index, *PI*	%	31
Maximum dry density, *MDD*	kN/m^3	18.1
Optimum moisture content, *OMC*	%	11.8
USCS soil classification	-	CH

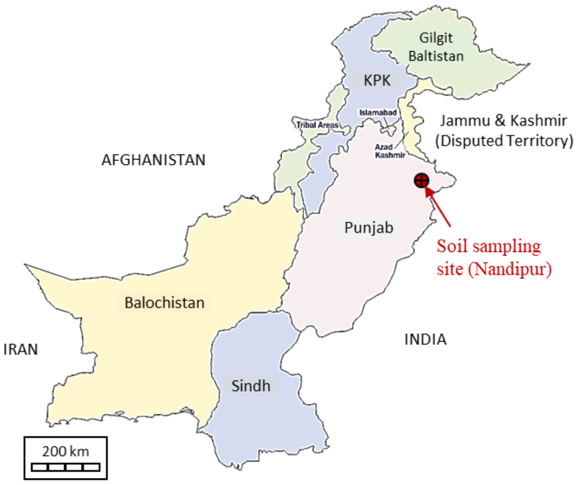
2. Materials and methods

2.1 Soil sampling and physical properties

The soil used in this study was obtained from Nandipur town of Gujranwala region (Latitude: 32.166351, Longitude: 74.195900), Punjab, Pakistan. The soil was collected from a depth of approximately 1.0 m below the existing ground surface. The sampling location and view of the collection site is shown in Fig. 1. Soil sample was air-dried and pulverized to pass through 75 μm prior to the laboratory testing. The gradation curve in shown in Fig. 2 and the soil was classified as high plastic clay (ASTM D-4318 2017, ASTM D-2487 2011) or expansive clay (Holtz and Gibbs 1956). Table 2 describes the physical properties of soil specimen used in this study.

2.2 Chemical and microscopic analysis of the soil

The mineralogical composition of the test soil through petrographic analysis by FORCIMAT-TS equipment has been shown in Fig. 3(a) which clearly shows the presence of *Illite* mineral in large amount (52%), and the montmorillonite mineral (37%), quartz mineral (8%) and the other minerals in trace amounts. According to Surjandari and Dananjaya (2018), if montmorillonite mineral content is greater than 35%, then the soil belongs to the class of swelling soils. Therefore, the soil being used in this study belongs to swelling soil group.



(a)

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Fig. 1 (a) Sampling location and (b) test soil

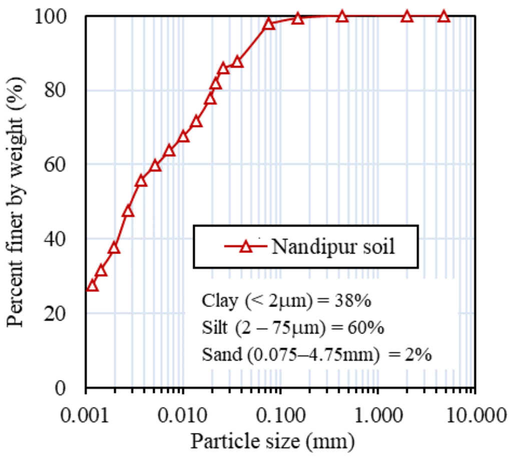
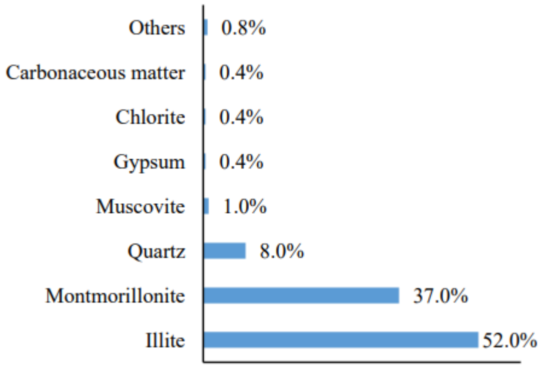


Fig. 2 Particle size distribution of the test soil

X-ray diffraction (XRD) analysis of pure soil was conducted by D8 Advance Bruker equipment as shown in Fig. 3(b). The XRD diffractogram substantiates the presence of swelling clay minerals in soil (i.e.,, *Illite* and *Montmorillonite*). High peaks in XRD graph indicate the high concentration of that mineral present in sample. Illite mineral has highest peak, then comes up montmorillonite and quartz mineral. The abundant presence of Illite minerals in Nandipur soil was also reported by Khan *et al.* (2017). The peaks of the XRD pattern correspond to the characteristic interplanar spacing of the crystalline phases



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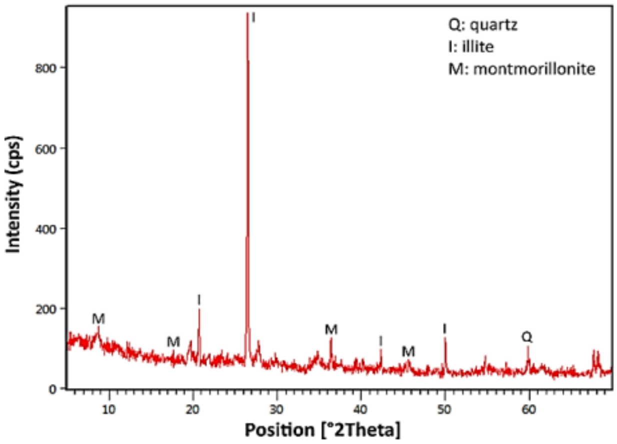


(b)

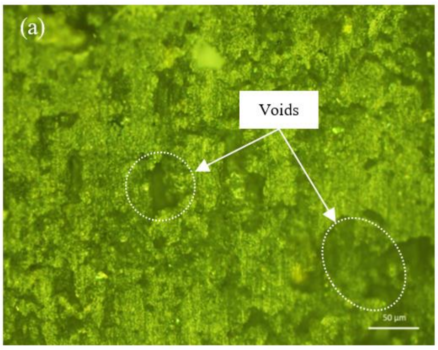
Fig. 3 (a) Chemical (petrographic) and (b) XRD analysis of the soil sample

and the shape of the strong and sharp diffraction peaks indicates that the specimens are well crystallized.

Fig. 4(a) shows the optical microscopic image of pure soil taken at a magnification level of 100x. It shows the inability of clay particles to make a compact unit resulting in high void ratio and high porosity of soil sample correlating to lower maximum dry density achieved during the laboratory compaction test. Scanning electron microscopy (SEM) image (Fig. 4(b)) taken at a magnification level of 10,000x shows that the micro-structure of test soil comprises of many cracks and cavities. Due to the presence of such macro-pores and cracks in the soil matrix, the soil strength decreases when it is subjected to moist condition and the flaky particles of clay gather in almost parallel formations to form a dispersed structure.

2.3 Polypropylene fibers

Polypropylene *(PP)* fiber is a type of geosynthetic material being abundantly produced worldwide to about 4.1 million tons (The Fiber Year 2009). These fibers are used in the manufacturing of blankets, knitwear, outerwear fabrics, carpeting and filter fabrics. PP fibers are rod-shaped and generally have a uniform and homogeneous section of around 40 μm as shown in Fig. 5. These fibers has a very high tensile and flexural strength and proved to be very effective in dealing with swelling issues of soil (Ayyar *et al.*



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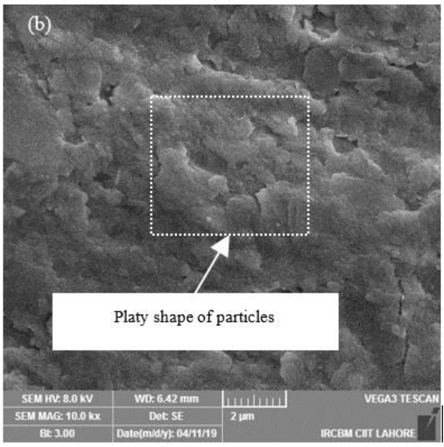

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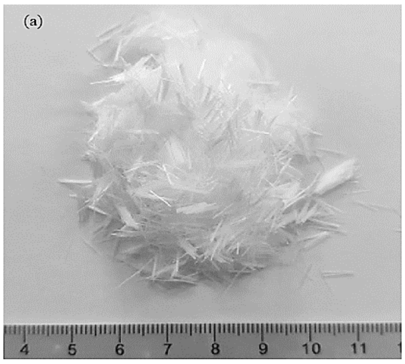
Fig. 4 (a) Optical microscopic image at 100x magnification and (b) SEM image at 10,000x magnification



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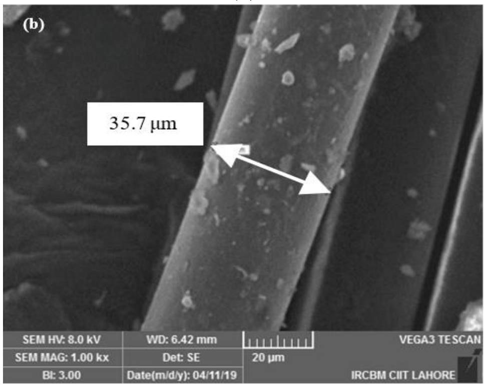


(b)

Fig. 5 (a) Full size image of PP fiber and (b) SEM image of PP fiber at 1000x magnification

Table 3 Properties of the PP fibers used in this study

Properties	Unit	Value
Fiber type	-	Single fiber
Average length	mm	12
Average diameter	mm	0.04
Specific gravity	-	0.91
Unit weight	g/cm^3	0.9-0.91
Breaking tensile strength	MPa	358
Modulus of elasticity	MPa	3400
Fusion point	°C	176
Burning point	°C	595
Acid and alkali resistance	-	Very good
Water absorption	%	Nil
Dispersibility	-	Excellent

1989, Vessely and Wu 2002).

PP fibers of 12 mm length was used in thus study having a very low specific gravity of 0.91, high melting point of 176°C, high burning point of 595°C and are also highly resistant to acidic and alkaline environment. The properties of PP fibers as supplied by the manufacturer (Bloom Enterprises, Pakistan) are described in Table 3.

2.4 Testing plan

A number of laboratory tests have been carried out on the reinforced soil mixtures with PP fiber contents of 0%, 0.2%, 0.4%, 0.6% and 0.8% by weight of the soil. The samples were prepared at the respective optimum moisture contents and maximum dry densities. The tests were conducted at the Geotechnical Engineering Laboratory of Department of Technology, The University of Lahore, Pakistan. The list of laboratory tests performed and their relevant ASTM standards are given below:

- Modified Proctor Tests (ASTM D1557 2012)
- Unconfined Compression Tests (ASTM D2166 2016)
- California Bearing Ratio Tests (ASTM D1883 2016)
- 1-D Consolidation Tests (ASTM D2435 2011)

3. Results and discussions

3.1 Effects of PP fibers on compaction characteristics

The compaction curves of the soil samples as obtained from modified Proctor tests are shown in Fig. 6(a). A linera regression analysis in Fig. 6(b) reveals the effect of PP fiber inclusion on maximum dry density (MDD) and optimum moisture content (OMC) of soil samples. Based on the test results, it is observed that the MDD of virgin soil decreased by 2.7% (i.e., from 18.1 kN/m^3 to 17.6 kN/m^3) with the addition of fibers up to to 0.8%.

The reason behind the decreasing trend of MDD values lies in the reduction of average density of reinforced soil samples due to the increasing percentages of PP fiber in soil sample. PP fibers having low specific gravity (i.e., 0.91)

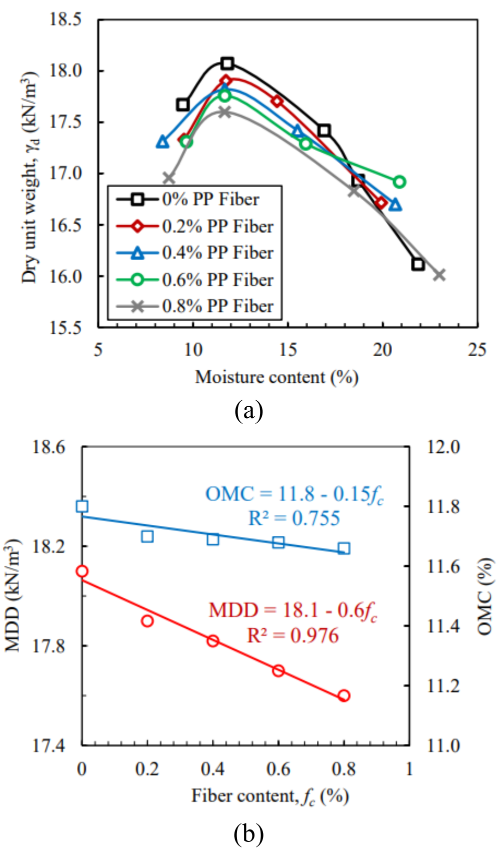


Fig. 6 Compaction charatiestics of soil treated with PP fibers

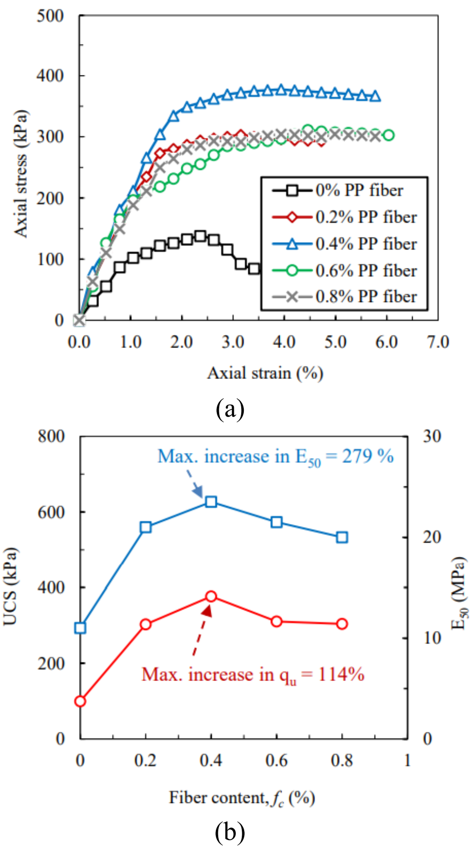


Fig. 7 Unconfined compression test results of soil samples at different fiber contents

replace the heavier particles of soil (G_s = 2.71) in a unit volume, resultantly decreasing the overall unit weight of the soil mix. However, the OMC of fiber-reinforced soil samples did not show a significant change with the fiber addition (i.e., from 11.8 to 11.7%) due to the non-absorbent nature of the fibers. Ramasamy and Arumairaj (2013), Soğancı (2015) and Viswanadham *et al.* (2009) have reported similar trends of MDD and OMC relationships of soil samples reinforced with various percentages of fibers.

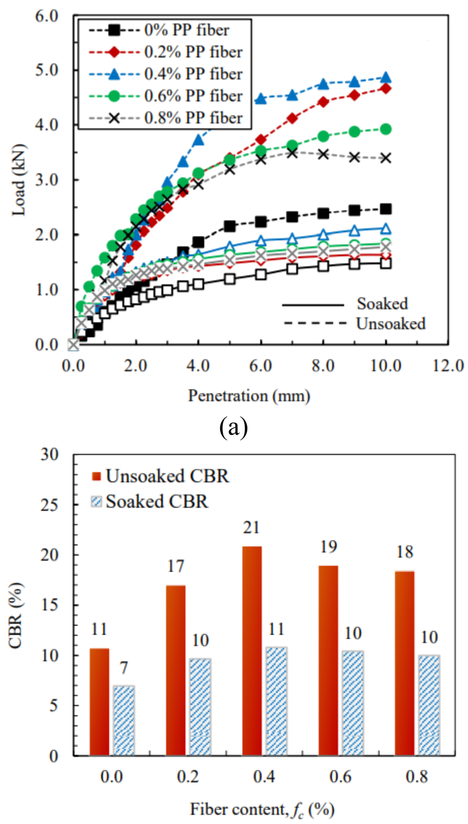
3.2 Effect of PP fibers on UCS and E_{50} of the soil

The stress-strain relationships of unreinforced and reinforced soil samples obtained from unconfined compression tests are given in Fig. 7(a). The results show that the addition of PP fiber-reinforcement considerably increases the unconfined compressive strength (q_u) and failure strain of the soil. The increase in the percentage of reinforcement beyond 0.4% and up to 0.8% makes it possible to obtain a marked improvement in resistance compared to that of the soil without reinforcement. However, this improvement reaches its optimal value (at 0.4%). Therefore, the increase in the percentage of PP fiber beyond this value reduces the resistance compared to the optimum but contributes to the overall improvement of the resistance as compared to that of the unreinforced soil. It is also observed that failure strain of pure soil sample is increased by 1.63 times (i.e., from 2.4% to 3.9%) when treated with 0.4% fiber content, and it further increases by 1.28 times (i.e., from 3.9% to 5.0%) with the addition of fiber content up to 0.8%. Therefore, it can be stated that the fiber-reinforced soil exhibits more ductile behaviour than the unreinforced soil.

Fig. 7(b) presents the values of q_u and E_{50} obtained from the UCS tests. It is observed that the inclusion of reinforcement up to the optimum fiber content of 0.4% significantly enhances the peak stress q_u of unreinforced soil sample by 3.8 times (i.e., from 99 kPa to 377 kPa), however the contribution of further increase in fiber content to peak stress was insignificant. At fiber content higher than the optimum, the q_u reduces from 377 kPa to 304 kPa up to 0.8% fiber addition. The reduction in q_u is mainly due to the modification of the nature of the connections between PP fibers and the soil matrix (composite material, different texture). According to the specifications proposed by Das and Sobhan (2013), the soil sample treated with 0.4% fiber content changes from medium quality to hard quality subgrade (i.e., q_u greater than 360 kPa). Similar findings have also been reported by Jiang *et al.* (2010), Malekzadeh and Bilsel (2012a), Pradhan *et al.* (2012), Ramasamy and Arumairaj (2013), Rivera-Gómez *et al.* (2014), Sravya and Suresh (2016) and Tang *et al.* (2007). Similarly, the elastic modulus E_{50} of soil sample increased by 2.1 times (i.e., from 11 MPa to 23.5 MPa) when treated with 0.4% fiber content and decreased from 23.5 MPa to 20 MPa up to the addition of 0.8% fiber content. Based on the specifications of young's modulus proposed by Obrzud (2010), the unreinforced soil sample lies in the category of stiff to very stiff quality (E_{50} = 11 MPa) but the sample gradually changed to the category of hard quality (E_{50} = 23.5 MPa) after treatment with 0.4% fiber content.

3.3 Effect of PP fiber on CBR of the test soil

The CBR test results are presented in the form of load-penetration curves obtained under unsoaked and soaked conditions as shown in Fig. 8(a). It can be seen that the load-bearing capacity of soil sample reinforced with fiber percentages (0%, 0.2%, 0.4%, 0.6% and 0.8%) was significantly increased under both soaked and unsoaked conditions. The optimum dosage of fiber is found to be 0.4%. The CBR values of the test samples have been calculated for the load corresponding to the penetration of 2.5 mm and 5.0 mm, and the greater of these values have been adopted as CBR value (ASTM D1883 2016). In the present research, the CBR values of fiber reinforced soil at 5.0 mm penetration are observed to be greater than those at 2.5 mm penetration under both unsoaked and soaked conditions. This clearly shows that the PP fiber reinforcement is more effective in improving the soil strength at larger deformations by increasing the resistance to penetration. Fig. 8(b) shows that with the increased percentage of fiber in soil sample up to 0.4% content, the unsoaked CBR strength increase by 1.9 times and soaked CBR strength by 1.6 times, followed by a rapid decrease in strength due to the replacement of heavier soil particles by light-weight fibers. The reason behind the higher values of unsoaked CBR as compared to soaked CBR was an additional resistance offered by the surface tensile forces to the plunger penetration which is diminished in soaked condition. Soaked CBR test is generally conducted to simulate the worst possible field conditions. Chegenizadeh and Nikraz (2011), Pradhan *et al.* (2012), Ramasamy and Arumairaj (2013), and Sravya and Suresh (2016) have presented similar findings in their research work.



(a)

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Fig. 8 CBR test results of soil samples under unsoaked and soaked conditions

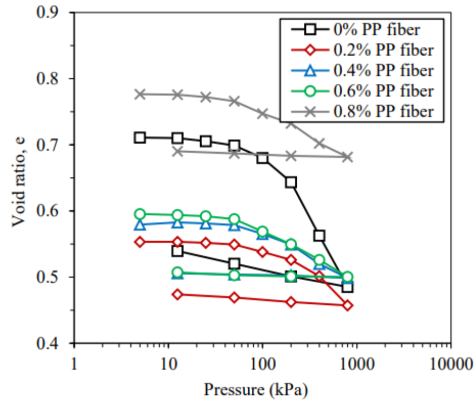
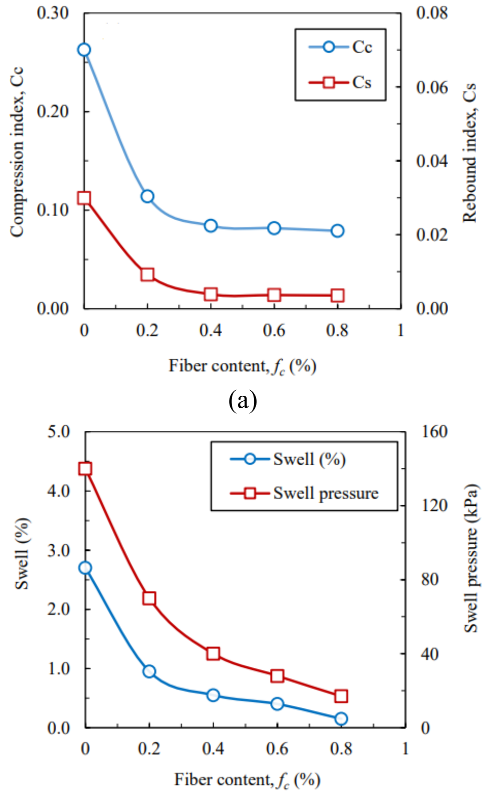


Fig. 9 One-dimensional conolidation test results



(a)

(b)

Fig. 10 Deformation characeteristics of the soil samples at various contents of PP fibers

3.4 Effects of PP fibers on consolidation characteristics of the test soil

One dimensional consolidation tests were conducted on fiber-reinforced soil samples and the void ratio vs. pressure curves so obtained are shown in Fig. 9. It can be seen that the curves become flatter with the addition of PP fibers as it provides sufficient confinement to soil particles and not allowing their dislocation / reorientation. As all the samples were compacted at the void ratios corresponding to their respective MDD and OMC, which varied with varying fiber content, the initial void ratios of different samples were not the same.

Compression and rebound indices of pure soil considerably reduced with fiber addition as shown in Fig. 10(a). The max reduction of such soil parameters is observed at 0.4% fiber content and remained almost constant afterwards, as the Cc reduced by 2.9 times and Cs by 6.5 times. The reason behind this significant reduction has been explained before. Furthermore, it is observed that the percentage swell and swelling pressure of pure soil continuously decreases with the increase in fiber addition as shown in Fig. 10(b). Based on the specifications proposed by USBR (1998), the soil sample treated with optimal dosage of 0.4% fiber changes from medium-swelling class to low-swelling class, as the swell percentage of this sample is 0.9% which is less than the proposed permissible limit of 1.5% (low-swelling class). Al-Wahab and El-Kedrah (1995), Malekzadeh and Bilsel (2012b), Nataraj and McManis (1997), Soğancı (2015) and Viswanadham *et al.* (2009) have also reported similar results.

4. Soil-fiber interaction mechanism

Wang (2006) stated that soils stabilized with chemical agents such as cement and lime are stiffer and stronger than unreinforced soils, however, the tensile cracking still remains as a major mode of failure. Therefore, the addition of fibers can be a suitable method to control the opening and propagation of cracks in clayey soils. In the experimental results presented in this study, significant increase in strength and decrease in swell potential has been observed with the inclusion of PP fibers in the soil. According to Hejazi *et al.* (2012) and Olgun (2013), the possible reason for the considerable improvement in strength and deformation characteristics of fiber-treated soils is that the fibers have very high tensile resistance and the soil-fiber bridging action can spread the load over a larger surface area, and hence the respective volume change is limited. Similarly, Fatahi *et al.* (2013) have reported that decrease in shrinkage-induced radial and axial strains for fiber-reinforced clay soil can be attributed to reduced reactive clay content (due to the addition of fibers) per unit volume of treated soil. Further, greater tensile strengths associated with soil-fiber interaction (as shown in Fig. 11) impart additional strength against the soil volume change contributing to the reduced shrinkage.

The mechanical behavior at the interface between fiber surface and soil matrix and the corresponding reinforcing mechanism has been well explained by Consoli *et al.* (2005), Tang *et al.* (2016) and Garg *et al.* (2020). It is also important to mention here that the use of fiber contents beyond an optimal value can cause detrimental effects to soil behavior. Moghal *et al.* (2017) has reported that the addition of fibers higher than 0.2% to a fly ash treated soil caused an increase in swell potential. This destabilizing effect of fiber can be attributed to large void formation due to high fiber dosage and/or poor mixing of fibers. In any case, fiber content beyond an optimal value is always

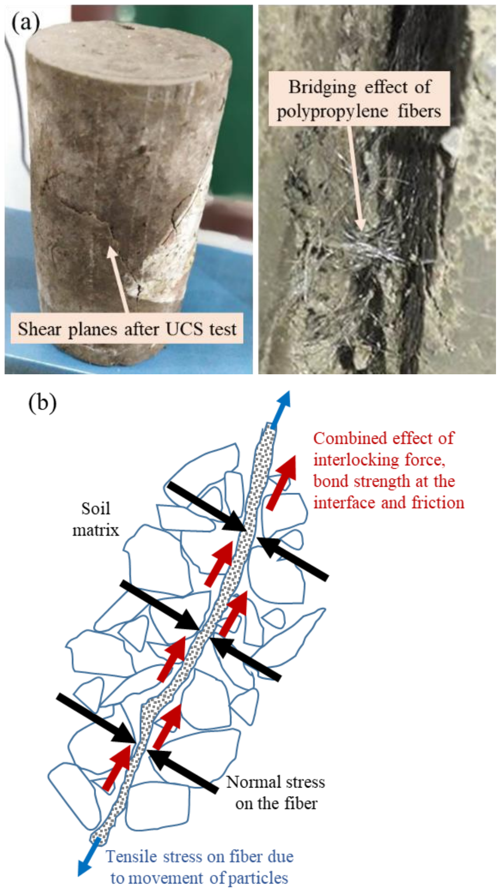


Fig. 11 (a) Soil-fiber composite in soil sample and (b) schematic diagram showing the reinforcing mechanism

difficult to handle in the laboratory for specimen preparation and may be equally unworkable in the field as well (Shukla 2017).

Based on the SEM spectroscopy and microstructural analysis of untreated and fiber-treated soils, Changizi and Haddad (2015) and Tang *et al.* (2007) have found that clay minerals get attached to the surfaces of the fibers and hence contribute to bond strength and friction between the fiber and soil matrix. They also observed some cracks (scratches and pits) on the surface of the fibers while their exposure to mixing and loading. They have noticed that these uneven surfaces further lead to increased frictional resistance between the soil and fibers, resulting in an increased shear strength of fiber-treated soils. Fibers were not found to be broken during the shear tests (rather they were extended) which indicates that the fibers play an important role in load transfer during compression and tension. It is therefore concluded that the soil-fiber interaction depends primarily on the soil composition, fiber surface roughness, orientation of fibers and effective interface contact area.

5. Field applications

A comprehensive literature review shows that using natural and/or synthetic fibers is feasible in almost all geotechnical engineering applications such as; pavements, backfill of retaining walls, liquefaction mitigation, embankments, slopes and foundation soils. According to Hejazi *et al.* (2012), the general advantages of fiber composite soils are the availability, economical benefits, easy to work and rapid to perform, and feasibility of using in all weather conditions. Moreover, PP fibers are the most commonly used synthetic material around the world due to its low cost, hydrophobic and inert nature, and no chemical and biological degradation (Ramasamy and Arumairaj 2013). Therefore, the availability of low cost fibers could lead to wider use of fiber reinforced soil and more cost-effective construction (Wang 2006). As reported by Li (2005), fiber materials are cost competitive compared with other materials due to the fact that unlike various chemical stabilization methods, the construction operation of fiber-reinforced soil is not significantly affected by weather conditions.

For field application and quality control of soils treated with fibers, the quality of mixing is very important to avoid any planes of weakness (oriented reinforcement) or areas with insufficient fiber contents (Shukla 2017). As far as lab mixing of fiber-reinforced soils is concerned, the hand mixing method facilitates easy and uniform mixing and allows fibers to merge properly with the soil mass. However, many researchers have reported that obtaining a homogeneous soil-fiber matrix in the field is a difficult task. Maher and Ho (1994) identified the use of mechanical mixers as the most viable field method with a potential disadvantage of dragging or snaring of fibers on the blades, but this issue can possibly be overcome by oscillatory or helical mixing actions. Likewise, Hejazi *et al.* (2012) reported that local aggregation (clumping) and folding of fibers (balling) are two problems associated with fiber–reinforced soils and therefore a tumble mixing technique has been identified to improve soil composite uniformity. They have also suggested that fiber lengths beyond 50 mm do not significantly improve soil properties and are more difficult to handle in both laboratory and field. Though a significant research work has been conducted to explore the characteristics of fiber-treated soils, there are still no codes of practice or standardized techniques for its field applications, especially in developing countries.

6. Conclusions

From the experimental results and review of the published literature presented in this paper, it can be stated that the polypropylene fibers have significant potential in improving strength and deformation characteristics of expansive clays. Table 4 summarizes the quantitative findings of this study related to the effectiveness of fiber treatment for improving the engineering properties such as compaction characteristics, strength and stiff, compressibility and CBR of cohesive soils. An optimum value of 0.4% fiber content is suggested to improve the soil characteristics.

The following main conclusions are drawn from this study:

• Max dry density of reinforced soil sample slightly decreased by 2.8% due to the replacement of heavier soil particles by light-weight fibers in a unit volume. Similarly, the optimum moisture content almost remained constant (a maximum decrease of 1.2% with 0.8% fiber contents) due to non-water-absorbent nature of the fibers.

• Inclusion of 0.4% polypropylene fibers has shown significant improvement in the unconfined compressive strength (an increase of 279%), elastic modulus (an increase of 113.6%) and California bearing ratio (an increase of 94.4% under unsoaked and an increase of 55.6% under soaked conditions) of the reinforced soil samples and thereby providing a better quality subgrade for the construction of flexible pavements on such soils.

• Free swell and swell pressure of the soil also significantly reduced (94.4% and 87.9%, respectively) with the addition of 0.8% fiber content which eventually converts the soil sample from medium swelling to low swelling class. Compression (Cc) and rebound (Cs) indices of the soil was also reduced by 69.9% and 88% respectively with fiber inclusion of 0.8%.

• Though a significant research work has been conducted to explore the characteristics of fiber-treated soils, there are still no codes of practice or standardized techniques for its field applications, especially in developing countries.

• A review of published literature has been presented to elaborate the mechanism behind considerable improvement in strength and deformation characteristics of fiber-treated soils based on microstructural analysis of untreated and treated soil. The issues related to cost, durability and field mixing of fiber-treated soils have also been discussed in detail.

Table 4 Effects of PP fibers on engineering properties of expansive clay used in this study

Properties		Fiber contents (%)			
		0.2	0.4	0.6	0.8
		% increase or decrease			
Compaction Characteristics	MDD	-1.1	-1.5	-2.2	-2.8
	OMC	-0.8	-0.9	-1.0	-1.2
Strength and Stiffness	UCS	204.8	279	212.5	206
	E_{50}	90.9	113.6	95.5	81.8
Compressibility	Cc	-56.5	-67.9	-68.9	-69.9
	Cs	-69.1	-86.9	-87.7	-88
	Free swell	-64.8	-79.6	-85.2	-94.4
	Swell pressure	-50	-71.4	-80	-87.9
CBR	Unsoaked CBR	58.2	94.4	76.6	71.3
	Soaked CBR	38.9	55.6	50.0	43.9

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References

Ahmad, F., Bateni, F. and Azmi, M. (2010), "Performance evaluation of silty sand reinforced with fibres", *Geotext. Geomembranes*, **28**(1), 93-99. https://doi.org/10.1016/j.geotexmem.2009.09.017

Al-Wahab, R.M. and El-Kedrah, M.A. (1995), "Using fibers to reduce tension cracks and shrink/Swell in compacted clays", *Proceedings of the Geoenvironment 2000*, New Orleans, Louisiana, U.S.A., February.

ASTM D1557-12e1 (2012), *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³))*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D1883-16 (2016), *Standard Test Method for California Bearing Ratio (CBR) of Laboratory Compacted Soils*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D2166/D2166M-16 (2016), *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D2435/D2435M-11 (2011), *Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D2487-11 (2011), *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM D4318-17e1 (2017), *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Ayyar, T.S.R., Krishnaswamy, N.R. and Viswanadham, B.V.S. (1989), "Geosynthetics for foundations on a swelling clay", *Proceedings of the International Workshop on Geotextiles*, Bangalore, India, November.

Aziz, M., Saleem, M. and Irfan, M. (2015), "Engineering behavior of expansive soils treated with rice husk ash", *Geomech. Eng.*, **8**(2), 173-186. https://doi.org/10.12989/gae.2015.8.2.173.

Cai, Y., Shi, B., Ng, C.W.W. and Tang, C.S. (2006), "Effect of polypropylene fibre and lime admixture on engineering properties of clayey soil", *Eng. Geol.*, **87**(3-4), 230-240. https://doi.org/10.1016/j.enggeo.2006.07.007.

Changizi, F. and Haddad, A. (2015), "Strength properties of soft clay treated with mixture of nano-SiO2 and recycled polyester fiber", *J. Rock Mech. Geotech. Eng.*, **7**(4), 367-378. https://doi.org/10.1016/j.jrmge.2015.03.013.

Chegenizadeh, A. and Nikraz, H (2011), "CBR test on reinforced clay", *Proceedings of the 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (PCSMGE), the 64th Canadian Geotechnical Conference (CGC)*, Toronto, Ontario, Canada, October.

Chen, F.H. (1975), *Foundations on Expansive Soils*, Elsevier Scientific Publication Company.

Consoli, N.C., Casagrande, M.D. and Coop, M.R. (2005), "Effect of fiber reinforcement on the isotropic compression behavior of a sand", *J. Geotech. Geoenviron. Eng.*, **131**(11), 1434-1436. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:11(1434).

Cutright, T., Michael, M., Keith, F. and Anil, P. (2013), "Carbon footprint assessment of polypropylene fiber reinforced concrete floors", *Int. J. Construct. Environ.*, **3**(1), 73-84. https://doi.org/10.18848/2154-8587/CGP/v03i01/37372.

Das, B.M. and Sobhan, K. (2013), *Principles of Geotechnical Engineering*, Cengage Learning.

Estabragh, A.R., Bordbar, A.T. and Javadi, A.A. (2011), "Mechanical behavior of a clay soil reinforced with nylon fibers", *Geotech. Geol. Eng.*, **29**(5), 899-908. https://doi.org/10.1007/s10706-011-9427-8.

Fatahi, B., Le, T.M., Fatahi, B. and Khabbaz, H. (2013), "Shrinkage properties of soft clay treated with cement and geofibers", *Geotech. Geol. Eng.*, **31**, 1421-1435. https://doi.org/10.1007/s10706-013-9666-y.

Garg, A., Bordoloi, S., Mondal, S., Ni, J.J. and Sreedeep, S. (2020), "Investigation of mechanical factor of soil reinforced with four types of fibers: An integrated experimental and extreme learning machine approach", *J. Nat. Fibers*, **17**(5), 650-664. https://doi.org/10.1080/15440478.2018.1521763.

Guney, Y., Sari, D., Cetin, M. and Tuncan, M. (2007), "Impact of cyclic wetting-drying on swelling behavior of lime-stabilized soil", *Build. Environ.*, **42**(2), 681-688. https://doi.org/10.1016/j.buildenv.2005.10.035.

Hejazi, S.M., Sheikhzadeh, M., Abtahi, S.M. and Zadhoush, A. (2012), "A simple review of soil reinforcement by using natural and synthetic fibers", *Constr. Build. Mater.*, **30**, 100-116. https://doi.org/10.1016/j.conbuildmat.2011.11.045.

Holtz, W.G. (1983), "The influence of vegetation on the swelling and shrinking of clays in the United States of America", *Géotechnique*, **33**(2), 159-163. https://doi.org/10.1680/geot.1983.33.2.159.

Holtz, W.G. and Gibbs H.J. (1956), "Engineering properties of expansive clays", *T. ASCE*, **121**, 641-663.

Houston, S.L., Dye, H.B., Zapata, C.E., Walsh, K.D. and Houston, W.N. (2011), "Study of expansive soils and residential foundations on expansive soils in Arizona", *J. Perform. Constr. Fac.*, **25**(1), 31-44. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000077.

Jiang, H., Cai, Y. and Liu, J. (2010), "Engineering properties of soils reinforced by short discrete polypropylene fiber", *J. Mater. Civ. Eng.*, **22**(12), 1315-1322. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000129.

Kaufmann, J., Winnefeld, F. and Hesselbarth, D. (2004), "Effect of the addition of ultrafine cement and short fiber reinforcement on shrinkage, rheological and mechanical properties of Portland cement pastes", *Cement Concrete Compos.*, **26**(5), 541-549. https://doi.org/10.1016/S0958-9465(03)00070-2.

Khan, M.I., Irfan, M., Aziz, M. and Khan, A.H. (2017), "Geotechnical characteristics of effluent contaminated cohesive soils", *J. Environ. Eng. Landscape Manage.*, **25**(1), 75-82. https://doi.org/10.3846/16486897.2016.1210155.

Li, C. (2005), "Mechanical response of fiber-reinforced soil", Ph.D. Thesis, University of Texas at Austin, Austin, Texas, U.S.A.

Loehr, J.E., Axtell, P.J. and Bowders, J.J. (2000), "Reduction of soil swell potential with fiber reinforcement", *Proceedings of the ISRM International Symposium*, Melbourne, Australia, November.

Maher, M. and Ho, Y. (1994), "Mechanical properties of kaolinite/fibre soil composite", *J. Geotech. Eng.*, **120**(8), 1381-1393. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:8(1381).

Malekzadeh, M. and Bilsel, H. (2012a), "Effect of polypropylene fiber on mechanical behavior of expansive soils", *Electron. J. Geotech. Eng.*, **17**, 55-63.

Malekzadeh, M. and Bilsel, H. (2012b), "Swell and compressibility of fiber reinforced expansive soils", *Int. J. Adv. Technol. Civ. Eng.*, **1**(2), 42-45.

Mandal, J.N. and Murthi, M.V.R. (1989), "Potential use of natural fibres in geotechnical engineering", *Proceedings of the International Workshops on Geo-Textiles*, Bangalore, India, November.

Mishra, A.K., Dhawan, S. and Rao, S.M. (2008), "Analysis of swelling and shrinkage behavior of compacted clays", *Geotech. Geol. Eng.*, **26**(3), 289-298. https://doi.org/10.1007/s10706-007-9165-0

Moghal, A.A.B., Bhaskar, C.S., Chittoori, B., Basha, M. and Al-Mahbashi, A.M. (2017), "Effect of polypropylene fibre reinforcement on the consolidation, swell and shrinkage behaviour of lime-blended expansive soil", *Int. J. Geotech. Eng.*, **12**(5), 1297002. https://doi.org/10.1080/19386362.2017.1297002.

Mohanty, S.K., Pradhan, P.K. and Mohanty, C.R. (2017), "Stabilization of expansive soil using industrial wastes", *Geomech. Eng.*, **12**(1), 111-125. https://doi.org/10.12989/gae.2017.12.1.111.

Nataraj, M.S. and McManis, K.L. (1997), "Strength and deformation properties of soils reinforced with fibrillated fibers", *Geosynth. Int.*, **4**(1), 65-79. https://doi.org/10.1680/gein.4.0089.

Obrzud, R.F. (2010), "On the use of the hardening soil small strain model in geotechnical practice", *Numerics Geotech. Struct.*

Olgun, M. (2013), "Effects of polypropylene fiber inclusion on the strength and volume change characteristics of cement-fly ash stabilized clay soil', *Geosynth. Int.*, **20**(4), 263-275. https://doi.org/10.1680/gein.13.00016.

Park, S.S. (2011), "Unconfined compressive strength and ductility of fiber-reinforced cemented sand", *Constr. Build. Mater.*, **25**(2), 1134-1138. https://doi.org/10.1016/j.conbuildmat.2010.07.017.

Pradhan, P.K., Kar, R.K. and Naik, A. (2012), "Effect of random inclusion of polypropylene fibers on strength characteristics of cohesive soil", *Geotech. Geol. Eng.*, **30**(1), 15-25. https://doi.org/10.1007/s10706-011-9445-6.

Ramasamy, S. and Arumairaj, P.D. (2013), "The effect of polypropylene fiber on index properties and compaction characteristics of clay soil", *Turkish J. Eng. Sci. Technol.*, **2**, 35-38.

Rashid, I. (2015), "Characterization and mapping of expansive soils of Punjab", M.Sc. Thesis, University of Engineering & Technology, Lahore, Pakistan.

Rivera-Gómez, C., Galán-Marín, C. and Bradley, F. (2014), "Analysis of the influence of the fiber type in polymer matrix/fiber bond using natural organic polymer stabilizer", *Polymers*, **6**(4), 977-994. https://doi.org/10.3390/polym6040977.

Shariati, M., Azar, S.M., Arjomand, M.A., Tehrani, H.S., Daei, M. and Safa, M. (2019), "Comparison of dynamic behavior of shallow foundations based on pile and geosynthetic materials in fine-grained clayey soils", *Geomech. Eng.*, **19**(6), 473-484. https://doi.org/10.12989/gae.2020.19.6.473.

Sharma, A.K. and Sivapullaiah, P.V. (2016), "Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer", *Soils Found.*, **56**(2), 205-212. https://doi.org/10.1016/j.sandf.2016.02.004

Shen, R.X. (1995), *Fibre Reinforced Concrete*, in *Concrete Practical Manual*, 881-927.

Shukla S.K. (2017), *Fundamentals of Fibre-Reinforced Soil Engineering*, Springer.

Soğancı, A.S. (2015), "The effect of polypropylene fiber in the stabilization of expansive soils", *Int. J. Environ. Chem. Ecol. Geol. Geophys. Eng.*, **9**(8), 994-997.

Sravya, G.S. and Suresh, K. (2016), "Swell and strength characteristics of expansive soil reinforced with synthetic fibers", *I-Manager J. Civ. Eng.*, **6**(4), 21-30.

Surjandari, N.S. and Dananjaya, R.H. (2018), "The effect of egg shell powder on the compression strength of fine-grained soil", *Proceedings of the 4th International Conference on Rehabilitation and Maintenance in Civil Engineering*, Solo, Indonesia, July.

Taha, M.R., Alsharef, J.M.A., Khan, T.A., Aziz, M. and Gaber, M. (2018), "Compressive and tensile strength enhancement of soft soils using nanocarbons", *Geomech. Eng.*, **16**(5), 559-567. https://doi.org/10.12989/gae.2018.16.5.559.

Tang, C.S., Shi, B., Gao, W., Chen, F. and Cai, Y.J. (2007), "Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil", *Geotext. Geomembranes*, **25**(3), 194-202. https://doi.org/10.1016/j.geotexmem.2006.11.002.

Tang, C.S., Shi, B., Cui, Y.J., Liu, C. and Gu, K. (2012), "Desiccation cracking behavior of polypropylene fiber-reinforced clayey soil", *Can. Geotech. J.*, **49**(9), 1088-1101. https://doi.org/10.1139/t2012-067.

Tang, C.S., Wang, D.Y., Cui, Y.J. and Shi, B. (2016), "Tensile strength of fiber reinforced soil", *J. Mater. Civ. Eng.*, **28**(7). https://doi.org/10.1061/(ASCE)MT.1943-5533.0001546.

The Fiber Year (2009), https://www.ptj.com.pk/Web-2010/08-10/Features-Global-fiber.htm.

Thomas, G. and Rangaswamy, K. (2020), "Strengthening of cement blended soft clay with nano-silica particles", *Geomech. Eng.*, **20**(6), 505-516. https://doi.org/10.12989/gae.2020.20.6.505.

USBR United States Bureau of Reclamation (1998), *Earth Manual*.

Vessely, M.J. and Wu, J.T.H. (2002), "Feasibility of geosynthetic inclusion for reducing swelling of expansive soils", *Transport. Res. Rec.*, **1787**(1), 42-52. http://doi.org/10.3141/1787-05.

Viswanadham, B.V.S., Phanikumar, B.R. and Mukherjee, R.V. (2009), "Swelling behaviour of a geofiber-reinforced expansive soil", *Geotext. Geomembranes*, **27**(1), 73-76. https://doi.org/10.1016/j.geotexmem.2008.06.002.

Wang, Y. (2006), *Utilization of Recycled Carpet Waste Fibers for Reinforcement of Concrete and Soil - Recycling in Textiles*, Woodhead Publishing.

Wang, Y.X., Guo, P.P., Ren, W.X. and Yuan, B.X. (2017), "Laboratory investigation on strength characteristics of expansive soil treated with jute fiber reinforcement", *Int. J. Geomech.*, **17**(11), 04017101. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000998.

Xu, G.L., Liu, F.S. and Tang, H.M. (2004), *Modern Technology Theory and Engineering Practice Concerning Reinforced-Soil*, *China University of Geosciences Press*, Wuhan, China, 2-15.

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