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ORIGINAL PAPER

The effect of polypropylene and glass fibers on strength and failure behavior of clayey sand soil

Ali M. Rajabi[1] · S. M. S. Ghorashi[2] · Meysam Mahdavi Yeganeh[3]

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Abstract

The soil reinforcement is a method to improve the soil properties using the proper additives. An example of such additives is synthetic fibers, which improve the strength parameters of the soil. In this paper, the effect of the polypropylene (PP) and the glass (GS) fibers on the strength of the clayey sand (SC) soil stabilized with different contents (0.2, 0.5, 1, and 1.5%), using the unconfined compressive strength (UCS) test, has been studied. The results showed that by increasing the fiber content for both types of fibers, the values of UCS are considerably enhanced, and for 1.5% fiber content, they all reach their maximum values. In addition, PP fibers have shown to be more effective in enhancing the UCS, elastic modulus (E), and ductility compared to the GS fibers. This can be attributed to the fact that PP fiber has higher tensile and flexural strength compared to GS fiber.

Keywords Clayey sand · PP fiber · GS fiber · UCS · Failure behavior

Introduction

The natural and synthetic materials have shown to successfully improve the soil strength (Bascetin et al. 2021; Rajabi et al. 2021; Tuylu 2022; Mohammadi et al. 2022; Bascetin et al. 2022; Eker and Bascetin 2022a, b). Among them, different types of natural and synthetic short (discontinuous) fibers have attracted much attention. The effect of both natural and synthetic fibers in different types of the soils and their various properties such as cohesion and internal friction angle, tensile and compression strength, etc. has been widely studied (Maher and Gray 1990; Li et al. 2014; Mirzababaei et al. 2017; Hao et al. 2017; Priyadarshee et al. 2019, Choobbasti et al. 2020; Langroudi et al. 2021; Khorram and Rajabi 2022; Xue and Yilmaz 2022; Xue et al. 2022).

So far, numerous studies have been separately conducted for each of the polypropylene (PP) and glass (GS) fibers in different types of the soils. In the area of the PP fiber studies, Zaimoglu and Yetimoglu (2012) conducted a series of unconfined compressive strength (UCS), direct shear, and California bearing ratio (CBR) tests to explore the effect of random distribution of PP fibers on fine-grained soil strength. The results of the UCS test indicated that compressive strength increased by increasing the fiber content to a certain extent. Verma et al. (2015) conducted triaxial tests to study variations of cohesion and internal friction angle following addition of PP fibers to clay soil. Their findings revealed that cohesion escalated with an increase in the PP fiber content. In addition, linear growth of fiber length improved cohesion, whereas the increase in fiber length and content did not considerably alter the internal friction angle. Correia et al. (2015) investigated the effect of PP fibers on the stabilization and improvement of the mechanical behavior of the soft soil by UCS, tensile strength, and flexural strength tests. The results showed that in addition to soil stabilization, addition of fibers to the soil reduced the hardness while increasing the tensile and compressive strength leading to a change in behavior of the soil from

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✉ Ali M. Rajabi
amrajabi@ut.ac.ir; amrajabi@ymail.com

[1] Engineering Geology Department, School of Geology, College of Science, University of Tehran, Tehran, Iran

[2] Civil Engineering Department, Faculty of Engineering, University of Qom, Qom, Iran

[3] Graduated From Civil Engineering Department, University of Qom, Qom, Iran

brittle to flexible. Han et al. (2021) performed a series of direct shear tests for measuring the reinforcing capability of PP fibers on clay, with varied lengths and contents of fiber. Results showed that the PP fibers can enhance the soil shear strength significantly, so that the internal friction angle of the fiber-reinforced soil increased slightly while its cohesion was increased substantially. Also, the experimental results indicated that 0.3% fiber with a length of 9 mm is the optimum mix ratio. Also, about GS fiber studies, Patel and Singh (2017) carried out a series of proctor compaction and CBR tests to investigate the behavior of a GS fiber-reinforced cohesive soil by the varying fiber content, fiber length, compacted moisture content, and soaking period on CBR and secant modulus. Test results showed that both CBR value and secant modulus increased with fiber content and fiber length at any compacted state and they decreased with increasing soaking period. In another research, Patel and Singh (2019) conducted proctor compaction and consolidated undrained triaxial tests to investigate the effects of GS fiber varying in length and content on the deviator stress response, pore water pressure response, deformation mode, stiffness, and shear strength of the samples. Test results depicted that at any molding dry unit weight and confining pressure, the failure deviator stress of the reinforced samples increases only up to limiting magnitudes of fiber content or fiber length. Sujatha et al. (2021) examined the use of two different types of GS fibers — alkali resistant GS fiber and electronic grade GS fiber as reinforcement in soils to improve its strength. The results of this study showed that random inclusion of fibers improve the UCS of the reinforced soil and its energy absorption capacity. Also, alkali resistant GS fiber performed better than electronic grade GS fiber for all proportions of fiber inclusion. Rabab'ah et al. (2021) conducted a series of free swell, UCS, indirect tensile strength (ITS), and CBR tests on unreinforced and GS fiber-reinforced expansive soil samples by the varying fiber content. The results showed that the inclusion of GS fibers in subgrade soil significantly increases the UCS, ITS, and CBR, and decreases the free swell values.

As mentioned above, the studies about PP and GS fibers have been mainly individually carried out. Accordingly, in this paper, the unconfined compressive strength (UCS) tests were conducted on the soil samples to investigate the effect of different contents of PP and GS fibers (0.2, 0.5, 1.0, and 1.5%) on the strength and failure behavior of clayey sand soil samples. In this case, the strength and failure behavior of the non-reinforced (with no fiber) soil samples, PP, and GS fiber-reinforced soil samples (FRSS) were compared together. Since these fibers are widely applied in soil improvement projects, especially in subgrades and pavements (Madhkhan et al. 2012; Patel and Singh 2017; Rabab'ah et al. 2021; Sujatha et al. 2021; Tiwari and Satyam 2022; and others), simultaneous studies on PP and GS FRSS, and comparison of their strength and failure behavior, can help to select better type of fiber (PP or GS).

Materials and methods

In this paper, the clayey sand (SC according to unified soil classification system) soil has been used to study, because the SC soils are widely used in subgrade and pavement of roads and it has been used in other studies as an important material (Shams et al. 2020; Muthu Lakshmi et al. 2021a, b). To apply the same conditions, SC soil samples were created by mixing 70% sand and 30% kaolin clay in laboratory. Table 1 indicates the specification of SC soil mixture used in this study, including, physical and chemical properties. Note that the SC soil used in this study had no plasticity index.

In this study, the UCS tests were conducted and their results were compared for the non-reinforced samples and PP and GS FRSS with different fiber contents (0.2, 0.5, 1, and 1.5% by dry weight of the soil). Table 2 presents the specifications of the fibers which are used in this paper. Figure 1 depicts a representative example of these fibers.

The UCS tests were conducted on the compacted samples with a maximum dry density of 1.92 g/cm^3 and an optimal moisture content of 10.78%. The samples with a diameter of

Table 1 The specifications of the soil mixture used in this study

Physical Properties								
Soil	Color	Specific gravity	Percentage finer than 0.075 mm (no. 200 sieve)		Particle-size distribution (mm)		Fine aggregate angularity (FAA)	
Sand	white	2.7	< 1		0.075–0.42		< 1.3	
Kaolin clay	White	-	100		> 0.04 (< 0.5%) < 0.02 (> 99%) < 0.002 (47 ± 3%)		-	
Chemical properties (%)								
SiO_2	L.O.I	MgO	CaO	K_2O	Na_2O	Al_2O_3	Fe_2O_3	SiO_2
97.5	0	0.24	0.27	0.19	-	0.95	0.85	97.5
63 ± 1	9 ± 1	0.55 ± 0.06	1.2 ± 0.2	0.3 ± 0.1	0.4 ± 0.1	24 ± 1	0.55 ± 0.1	63 ± 1

Table 2 Specifications of the PP and GS fibers

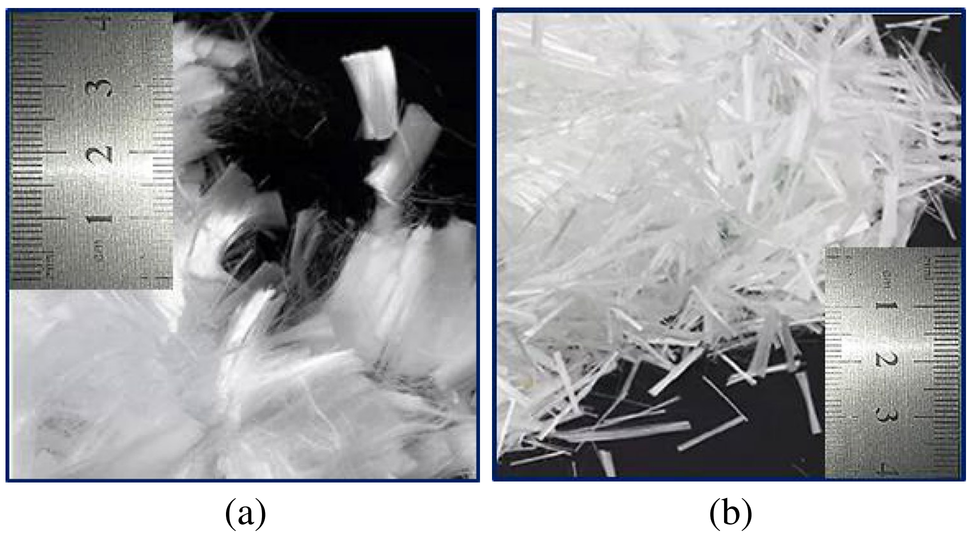
Fiber	Color	Length (mm)	Specific gravity	Tensile strength (MPa)	Flexural strength) GPa)
PP	White	12	0.91	400	3
GS	White	12	0.8	Tensile strength (MPa)	1.5

50 cm and height of 100 mm were selected for all the tests. The reinforced and unreinforced compacted soil samples were prepared by mixing of dry soil (oven dried), fibers, and water. For proper mixing, randomly distributed fiber-reinforced method has been used. Accordingly, the fibers were first mixed manually with dry soil and then water was gradually added to the samples to achieve an integrated mixture. Then, the mixture was divided into three equal parts and compacted in the molds to achieve the desired density according to ASTM D698-07 (2007). Afterwards, the UCS test was carried out on each sample according to ASTM D 2166 (2013). It should be mentioned that according to the standards, the loading type for UCS test is a displacement control with the rates of 1 mm/min.

Results and discussion

Figure 2 shows the stress–strain curves of the non-reinforced samples, PP, and GS FRSS. According to Fig. 2, the samples with no fiber completely failed following the maximum strength point, while the fiber-reinforced samples (both the

Fig. 1 Sample of fibers used in this study; **a** PP and **b** GS



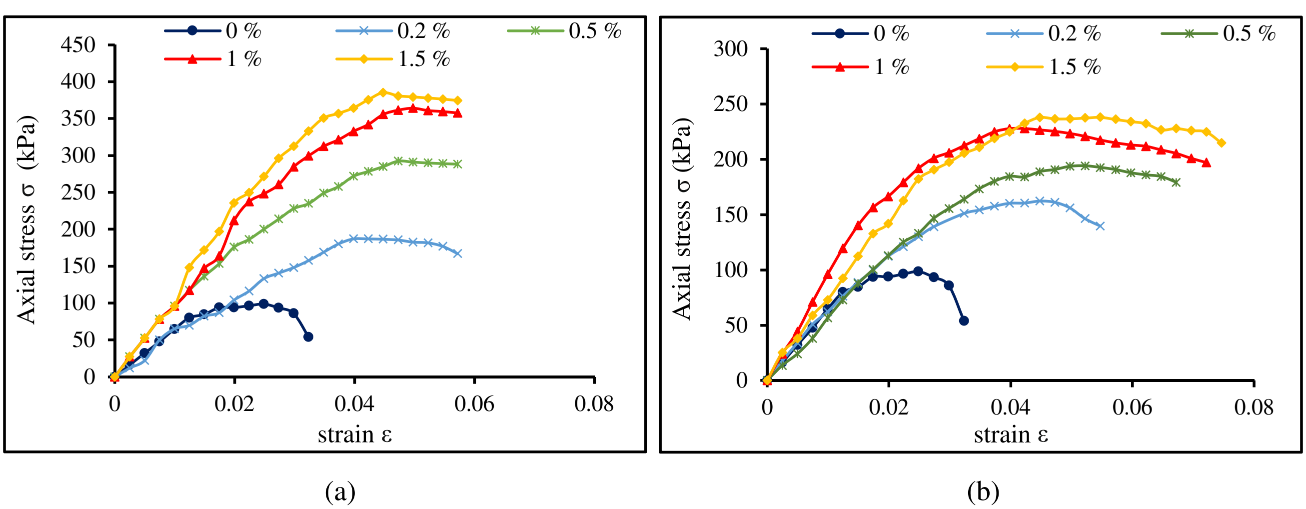


Fig. 2 The axial stress–strain curves in soil samples with different fiber contents; **a** PP and **b** GS

PP and GS fibers) failed after a delay, i.e., the samples reinforced with fibers (either PP or GS fiber) are more ductile compared to samples with no fiber and so, they have more failure strain (FS). According to Yao et al. (2021), adding fiber to the samples influences the post-cracking performance and consequently, it restrains the further propagation of crack due to the fiber-bridging effect that relies on the bonding and frictional resistance between fiber and the soil. So, the strength, ductility, and energy absorption capacity of the reinforced soil samples are enhanced with increasing fiber addition, and the effect of fiber reinforcement loses its efficacy with the completely pull out of fibers (Yao et al. 2021). The FS in this study is defined the axial strain at peak stress according to Fig. 2. Moreover, after reaching the maximum soil strength point, the rate of decrease in the strength of fiber-reinforced samples was lower compared to the samples with no fiber. This behavior can be attributed to the interlocking between soil mass and fibers.

Figure 3 depicts the FS values of PP and GS FRSS for different fiber contents. As can be seen, the reinforced samples have more FS compared to the samples with no fiber. But, PP and GS FRSS show distinct behavior. For the fiber content of 0 to 0.5%, the FS values increase for both PP and GS fibers, but these values for GS FRSS are greater than PP FRSS. Also, the FS reaches the maximum value at 0.5% for GS FRSS (maximum ductility for GS FRSS). From 0.5 to 1% of fiber content, the FS values of PP FRSS increase and reach their maximum value at 1% (maximum ductility for PP FRSS) while, for GS FRSS, the FS values decrease. From 1 to 1.5% of fiber content, the FS values for PP and GS FRSS decreases and increases, respectively. Finally, at 1.5% of fiber content, both the PP and GS FRSS reach the same value of FS. Therefore, it can be concluded that the ductility behavior of PP FRSS increases with increasing of fiber content up to a peak at 1% of fiber content which then the behavior of samples changes to brittle. But for GS FRSS,

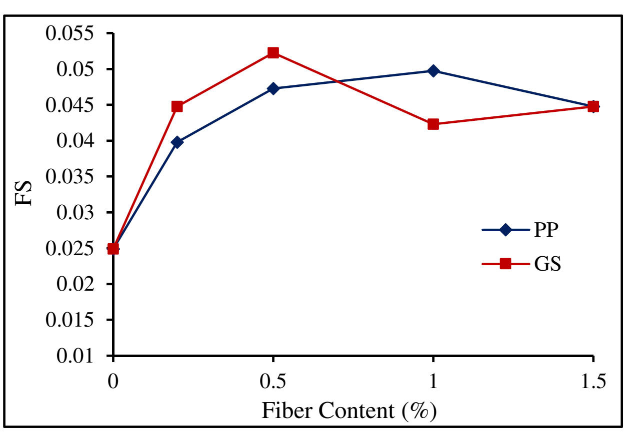


Fig. 3 FS values of samples reinforced with PP and GS fibers contents

the trend of ductility behavior is periodic and as a result, it shows an unpredictable behavior.

Figure 4 shows the diagram of variations of UCS values versus fiber contents. For both PP and GS fibers, the UCS values increase as the fibers content increases, but the increment rate decreases, i.e., the effect of fibers on improvement of the strength decreases gradually as fiber content increases. According to Fig. 4, the PP FRSS display a higher UCS than GS FRSS, which can be attributed to the higher tensile and flexural strength of PP fibers compared to the GS fibers. According to Table 2, the tensile and flexural strength values for PP are 2 times greater than GS fiber. Moreover, by increasing the fiber content, the difference of UCS values between the PP and GS fiber increases. Table 3 shows the UCS values of the PP and GS FRSS for different fiber contents to compare them with each other. As it is clear, both mentioned samples reach their maximum value at 1.5% of fiber. Also at 1.5% fiber, they have the maximum difference in UCS value, so that the ratio of UCS of PP FRSS to the GS FRSS reaches to 1.616. The results are in good agreement with Li et al. (2022) which is coincident with the present study.

For evaluation of strength behavior of the SC soil samples reinforced with PP and GS, the elastic modulus (E) is the

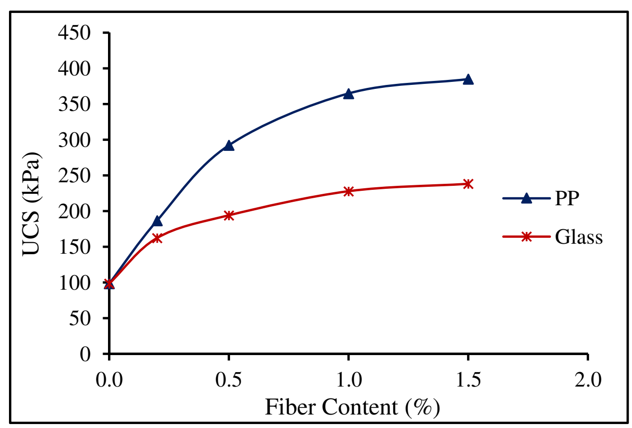


Fig. 4 The change of UCS values versus PP and GS fibers contents

Table 3 The UCS values of GS and PP fiber-reinforced samples for different fiber contents

Fiber content (%)	UCS (kPa)	
0	GS fiber-reinforced samples	PP fiber-reinforced samples
0.2	98.463	98.463
0.5	162.350	186.719
1	194.132	292.238
1.5	227.848	364.803
0	238.155	384.916

other important parameter that should be attained. The E values can be calculated from the stress–strain curves (Fig. 2) using an appropriate relation as follows (Lee et al. 1995);

$$E = \frac{\sigma_{0.01}}{0.01} \tag{1}$$

where $\sigma_{0.01}$ is the stress corresponding to strain of 0.01.

As shown in Fig. 5, the E values of PP FRSS are greater than the GS FRSS at different fiber contents. For PP FRSS, at first, by increasing the fiber contents up to 0.5%, the E value increases. Next, the maximum and constant values of E for fiber contents greater than 0.5% can be seen. But for the GS FRSS, an unknown trend of decreasing and increasing in E values is seen at different fiber contents, i.e., it is observed an oscillatory trend in elasticity behavior of the GS FRSS. As it is seen in Fig. 5, from 0 to 0.5% of fiber, the E values decrease, and then increase from 0.5 to 1%, and finally from 1 to 1.5% of fiber content, the E values increase again. In fact, the decrease in E values despite the addition of fiber leads to this unknown trend. The E value such as UCS is a strength property of the soil, so like UCS, it is expected that the E values of the GS FRSS increase with increasing of fiber content. But, at 0.5 and 1.5% of fiber, a decrease in E values is seen which leads to an unknown and oscillatory trend in curve of E values versus fiber content (Fig. 5).

Some reasons can be attributed to the decreasing in E value of the GS FRSS at mentioned fiber contents (0.5 and 1.5%). At first, it should be regarded that the E values are corresponded to the elastic behavior of the samples before the failure state which is calculated based on the samples stresses corresponding to strain of 1% (Eq. (1)). Therefore, the capacity of fiber reinforcement is not completely activated. On the other hand, lower fiber content (such as 0.5% of fiber) cannot play its role to increase in E value and so the addition of the fiber causes that the void ratio of the sample increases and consequently, E value decreases. With increasing of fiber contents (at 1% of fiber), the property of the fiber

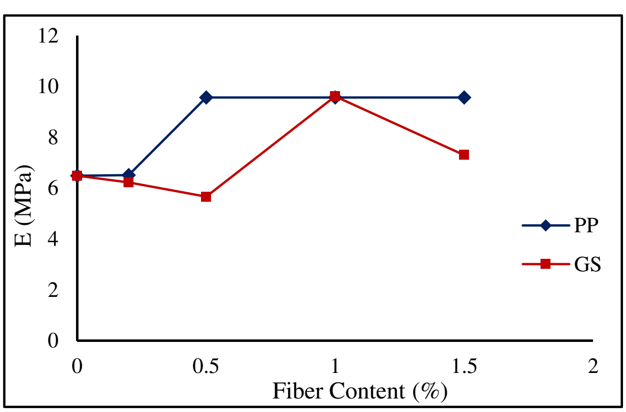


Fig. 5 The change of E values versus PP and GS fibers contents

reinforcement is activated to improve the elastic behavior of the GS FRSS. But at higher fiber content (e.g., at 1.5% of fiber), instead of fiber-soil interaction, the fiber–fiber contact may be constituted which results in a decrease in fiber reinforcement effect (Rabab'ah et al. 2021) and causes to decrease in strength parameters such as E or UCS values of the samples. The other reason is that when the content of the fiber is rather high (such as 1.5% of fiber), many fiber filaments can gather in clusters inside the soil sample because of the electrostatic interaction, which causes uniform distribution of fibers be difficult. It leads to the formation of the weak area of stress, which is not appropriate to transfer the stress. Therefore, further increase in content of fibers can reduce the effect of fiber reinforcement (Gao et al. 2015) and consequently, it can decrease the E or UCS values.

As it is clear in Fig. 3 and Fig. 5, the elasticity and ductility behaviors of the GS FRSS are inversely dependent to each other, which means as the E values (as the representation of elastic behavior) increase, the FS values (as the representation of ductility behavior) decrease and vice versa, while a different behavior was observed for PP FRSS. In other words, from 0 to 0.5% of fiber, both elasticity and ductility behavior of the samples increase and then the elastic behavior remains constant up to 1.5%, but the increase in ductility behavior of the samples continues up to 1% of fiber. Next, from 1 to 1.5% of fiber, the ductility behavior of the samples decreases. Therefore, it can be concluded that just in lower fiber contents (0 to 0.5%), the elastic behavior of the PP FRSS is directly dependent on their ductility behavior, and in higher fiber contents (0.5 to 1.5%), it is observed that the elastic behavior is independent to ductility behavior of the samples.

Figure 6 shows the variations of the sample failure planes in the soil sample with no fiber and samples reinforced with different contents of PP fiber. According to Fig. 6, the fibers changed the failure planes and mechanism. This is due to the extensive distribution of fibers in the reinforced samples (which depends on the fiber content). Therefore, fibers prevent formation as well as rapid growth of weak surfaces. Hence, the sample resists until fiber failure and slipping occur, but it fails after a certain plasticity point (which increases with an increase in fiber content).

Based on Fig. 6, when the sample is under loading, the bridge effect of fibers prevents further spread of tensile cracks and deformations. As it is clear, non-reinforced SC soil sample fails with distinct, diagonal shear plane while reinforced SC samples show multi-shear failure and bulging with a network of minor cracks. This is in a good agreement with some of the previous studies. For example, Freilich et al. (2010) conducted a study on a clay soil by triaxial testing and found that the axial deformation of the unreinforced clay samples caused a failure plane, but PP-reinforced samples tended to form a bulge and so, they are more ductile.

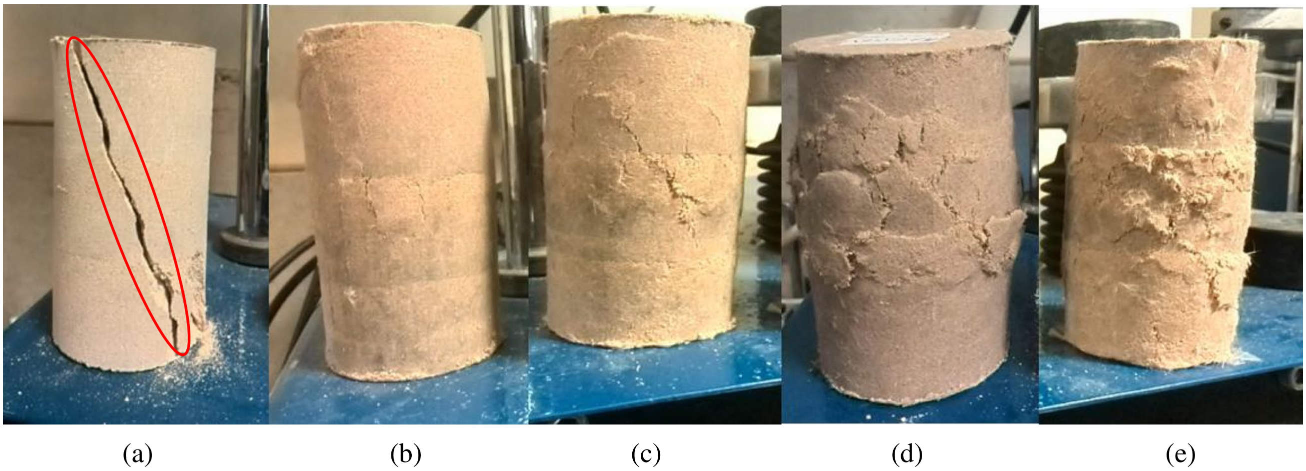


Fig. 6 Variations of the failure plane by increasing the PP fiber contents; **a** without fiber, **b** 0.2%, **c** 0.5%, **d** 1%, and **e** 1.5%

This is also approved for samples reinforced with GS fiber. Gul and Mir (2022) found that the soil sample reaches its failure state at a low strain and then fails rather suddenly along a well-defined vertical failure plane which proves a brittle failure condition. However, the addition of fibers to the soil prevents the progress of the development of cracks by intersecting the failure plane, so the prominent cracks are not occurred. The appearance of hair line cracks (micro cracks) with sample bulging demonstrates that a transformation into plastic failure state is performed.

Conclusion

The synthetic fibers have been used extensively as a reinforcement method in soil improvement operations. In this paper, the feasibility of stabilization of SC soil with PP and GS fibers was studied. To this end, various contents of the aforementioned fibers were added to the soil samples and the effect of the changing fiber content on soil strength parameters was studied using the UCS tests. The results of this study are summarized in the following:

- For both PP and GS fibers, the UCS values increase as the fibers' content increases, but the effect of fibers on improvement of strength decreases gradually as fiber content increases.
- The PP FRSSs have greater UCS and E than GS FRSS, which can be attributed to the higher tensile and flexural strength (2 times greater) of PP fibers as compared to GS fibers.
- Both the SC soil samples reinforced with PP and GS fibers reached their maximum UCS value at 1.5% fiber. Also in the 1.5% fiber, they had maximum difference in UCS value, so that the ratio of UCS of PP FRSS to the GS FRSS was about 1.62.
- Addition of fibers to the soil samples changed the failure mechanism and direction of slip surface as well as soil failure behavior. The fiber-reinforced sample became more ductile and displayed lateral buckling.
- The ductility behavior of PP FRSS increased up to 1% of fiber and decreased from 1 to 1.5%, which means at 1% of fiber, the samples had maximum ductility, while the GS FRSS reached their maximum ductility at 0.5% of fiber.

However, this study was conducted on the laboratory scale, and since the achievement of uniform and homogenous soil and fiber mixture are difficult on larger scales, these findings must be used with precaution in local conditions.

Declarations

Conflict of interest The authors declare no competing interests.

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