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RESEARCH PAPER

Influence of adding waste polyethylene terephthalate plastic strips on uniaxial compressive and tensile strength of cohesive soil

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Abstract
Unconfined compressive strength and tensile strength are important geotechnical characteristics which are used for performance prediction and mix design in civil engineering projects. In recent years, the use of waste materials as reinforcement elements such as glass, rubber and plastic waste increased significantly. Nowadays, the use of polyethylene terephthalate (PET) has grown substantially for drink bottles which is one of the most important environmental hazards. In the current study, the effect of adding PET strips as reinforcement elements to a clayey soil has been studied by unconfined compressive strength and tensile strength tests. The compressive and tensile strengths of reinforced specimens with different PET contents (0%, 0.4%, 0.6%, 0.8% and 1% by the soil weight), lengths (12 mm to 21 mm) and widths (3 mm and 6 mm) have been investigated. It was found that addition of the PET strips to the clay resulted in an increase in both the compressive and tensile strengths. The optimum PET content was dependent on the both width and length of the PET strips. The maximum UCS was 321 kPa which observed in the specimen containing 0.8 % PET strips with 3 mm width and 18 mm length. The maximum tensile strength was 33 kPa which observed in the specimen containing 0.6 % of PET strips with 6 mm width and 15 mm length. The reinforced specimens containing I-shape PET elements exhibited a higher UCS value than that of the reinforced specimens with PET strips in most cases which is may be due to increase of friction between the soil particles and the PET elements.

Keywords: Clayey soil, Stabilization, Polyethylene terephthalate, Unconfined compressive strength, Tensile strength.

Introduction

Polyethylene terephthalate (PET) is a polymer of the polyester family which was first patented by two British scholars in 1941. Polyester materials are synthetic fabric that are usually derived from petroleum (Wei & Zimmermann, 2017). Today, PET is the most produced thermoplastic in the world which is used in various modes such as PET film, PET sheets, and plastic bottles. Today, PET plastic bottles are profusely and widely produced due to the excellent relationship between mechanical and thermal properties and production cost (Thiounn & Smith, 2020). The production of this material exceeded 40 million tons in Iran in the year 2014 and is expected to grow to 70 million tons by the year 2020 (Fathi et al., 2021). Recycling of plastic material, particularly those made of PET (e.g. disposable bottles and utensils) is a challenge which is more important than that of other materials due to their longer biodegradation period. Because of this, during the recent years, many studies have been concentrated to find as efficient as

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possible solutions for using recycled PET waste in other fields, so as to lessen the prejudices brought to the environment. Notwithstanding, waste PET bottles have been used little for construction projects, and most of these materials have been placed in storage or disposal sites. The most present application of PET waste in the civil engineering construction includes its use as resin for polymer concrete (Cabalar et al., 2014; Karabash & Cabalar, 2015; Rebeiz & Fowler, 1996; Tawfik & Eskander, 2006) and as fiber for reinforced concrete (Ochi et al., 2007). Few studies have attempted to invest the properties of PET waste being non-degradable and highly tensile strength in its use as steel bars replacement in civil engineering construction (Falih et al., 2020; Foti, 2013).

Investigation of mechanical behavior of reinforced or stabilized soil has been the subject of numerous researches within the past decades. The reinforcement and stabilization of soft soil using various additives such as fibers (Eshaghzadeh et al., 2021; Gao et al., 2017; Hejazi et al., 2012; Jassem & Tabarsa, 2015; Wei et al., 2018), cement (Asgari et al., 2015; Bayat et al., 2013; Salehi et al., 2021; ShahriarKian et al., 2021; Yin et al., 2019; Yong and Ouhadi, 2007) and lime (Bayat et al., 2013; Guney et al., 2007; He & Zhang, 2005; Yong & Ouhadi, 2007) or a mixture of them (Arabani & Haghsheno, 2020; Chen et al., 2015; Gupta and Kumar, 2016; Kutanaei and Choobbasti, 2016; Park, 2011; Pincus et al., 1993; Xiao et al., 2013; Zhang et al., 2010; Zheng et al., 2019) has been considered by researchers. From the recent studies it could be conducted that solid waste materials such as flyash, rice husk ash, waste crushed stone, waste ceramic, carpet waste fibers, waste plastic and waste tires were used for enhancing the engineering properties of soft and weak soils with or without lime or cement (Abbaspour et al., 2019; Cabalar et al., 2017; Choobbasti et al., 2019; Consoli et al., 2002; Dhoble and Ahmed, 2018; Edincliler et al., 2013; Fırat et al., 2012; Hameed & Hamza, 2019; Jafar, 2016; Jafer et al., 2018; James & Kasinatha Pandian, 2014; James & Pandian, 2016; Riyad & Shoaib, 2020; Roustaei et al., 2016; Sabat, 2012). Most of the produced waste was collected to be sent to landfills which could be reused with additional processes or directly without transformation (Botero et al., 2015). PET with additional industrial processes, can be transformed in recycled PET fibers. Some of previous studies focused on the reinforced concrete by recycled PET waste fibers (Arulrajah et al., 2020; Falih et al., 2020; Foti, 2013, 2013; Hosseini, 2020; Kim et al., 2010; Mahdi et al., 2013; Thomas & Moosvi, 2020; Tonet & Gorninski, 2013). Utilization of waste materials such as rubber, wire wastes and PET as reinforcement elements to improve the mechanical behavior of soils has also been emerged into a popular topic in the scope of geotechnical research. Babu and Chouksey (2011) studied the effect of plastic waste on the mechanical behaviour of sand using triaxial and uniaxial compression tests. The results of triaxial tests showed that the inclusion of the plastic waste resulted in an increase and decrease of the strength and compressibility of the soil, respectively. The results of unconfined compression tests indicated that the inclusion of the plastic waste results in a significant improvement in the unconfined compressive strength (UCS). Consoli et al. (2002) carried out a series of unconfined compression, splitting tensile, and saturated drained triaxial compression tests on the cemented and uncemented specimens. The results indicated that the PET fiber reinforcement increased the peak and ultimate strength and reduced the brittleness of the cemented specimens. Arulrajah et al. (2020) studied strength of cement stabilized PET blends with construction waste as a pavement construction material using UCS test. The results indicated that the cemented specimen blends of 5% PET with recycled concrete aggregate and crushed brick can be utilized in constructing pavement bases and subbases. Botero et al. (2015) a series of unconfined undrained triaxial tests were performed to study the behavior of a reinforced soil with PET. The test results showed that the strength and deformation capacity of reinforced specimens increased due to the increasing quantities of the PET fiber. Fathi et al., (2020) conducted a series of shaking table tests to evaluate the dynamic properties of a reinforced sand with PET. The results indicated that addition of the PET strips to the soil results in a reduction of the soil brittleness and shear modulus and an increase in the damping ratio. Louzada et al. (2019) performed a series of triaxial tests to obtain the strength parameters of the soil-PET mixtures. Based on the tests results, it could be conducted that the addition of the PET results in an increase of the friction angle and a reduction of the cohesion.

Despite mentioned studies, there are limited studies on the effects of PET strips as reinforcement elements in increasing the compressive and tensile strengths of clayey soils. In the current study, UCS and Brazilian tensile strength tests were performed to investigate the effect of PET strips on the mechanical properties of the clayey specimens. The novelty of the current study in considering the effects of PET strips and I-shape PET elements on the compressive and tensile strengths of the compacted soil specimens.

Materials and methods

Materials

In the present work, a clayey soil obtained from Abyek Area in Qazvin Province of Iran was used which classified as CL according to the USCS (ASTM D2487). PET strips are also used as a product of one of the polyethylene terephthalate manufacturer which is the primary supplier of plastic bottles. Fig. 1 and Table 1 show grading distribution curve and geotechnical properties of Abyek clay, respectively. Table 2 also presents the physical and mechanical properties of the PET material.

Specimens preparation

In the current study, the UCS and Brazilian tensile strength tests were conducted on the cylindrical specimens with a diameter of 70mm and a height of 140mm. Asgari et al. (2015) indicated that the initial water content has an important effect on the UCS of untreated clay and stabilized clay specimens. In the current study, for preparing the specimens, the soil was mixed with optimum moisture content and stored in plastic bags for 24 hours to achieve uniform distribution of moisture content. As shown in Fig. 2, waste plastic is used as strip or I-shape.

Waste plastic strips were cut into 3 or 6mm width and lengths of 12, 15, 18, or 21mm which mixed with the soil at various contents (0%, 0.4%, 0.6%, 0.8% and 1%) by dry weight of soil (see Table 3).

Table 1. Geotechnical properties of Abyek clay

Specimen type	Ultimate tensile strength (kPa)	
	b=9 mm	b=6 mm
0.6% PET	33.1	36.4
0.8% PET	29.9	31.8

Table 2. Physical and mechanical properties of PET strips

Property	Value
Specific gravity (G_s)	2.66
Liquid limit (LL) (%)	36
Plastic limit (PL) (%)	20
Plasticity index (PI) (%)	16
Maximum dry unit weight ($\gamma_{d\text{-}max}$) (gr/cm^3)	1.82
Optimum moisture content (%)	18.5

Table 3. Details related to the preparation of the reinforcement PET elements

Property	Value
Density (gr/cm^3)	1.37
Tensile Strength (MPa)	400
Elongation at break (%)	200
Elasticity Modules (MPa)	2.81×10^3

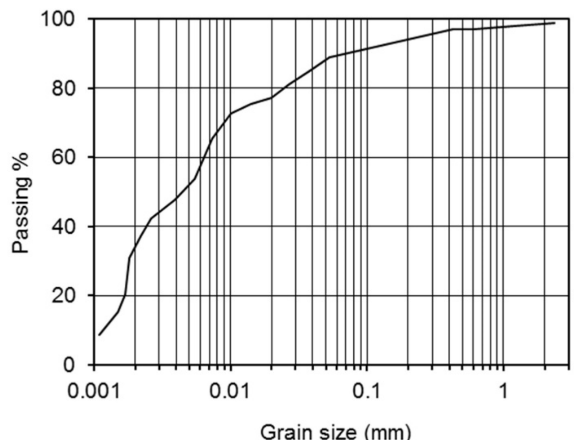

Figure 1. Grading distribution curve of Abyek clay

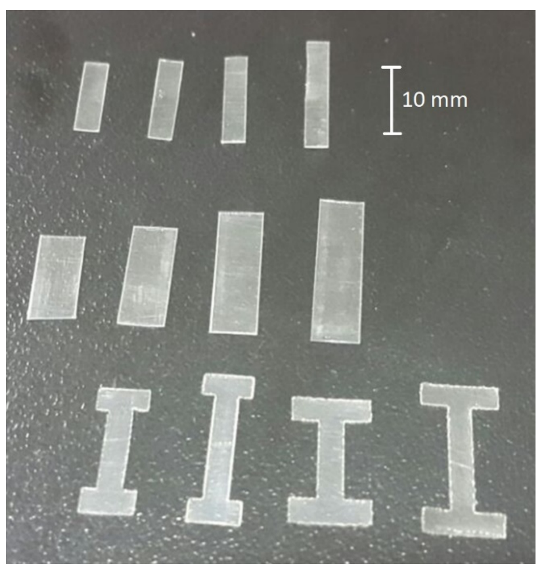

Figure 2. Reinforcement PET elements

As shown in Table 3, I-shape waste plastics were cut into 3mm width and lengths of 15 mm or 18 mm which mixed with the soil at various content of (0%, 0.6% and 0.8%) by dry weight of soil. A mixer was used to thoroughly mix the soil and PET. The soil and PET mixed until the mixture appeared visually homogeneous. The soil and waste plastic strips were compacted into four layers by the static compaction method at the maximum dry density.

UCS and tensile strength tests

As shown from Fig. 3, the UCS and Brazilian tensile strength tests were conducted in the current study to examine the behavior of PET-reinforced specimens.

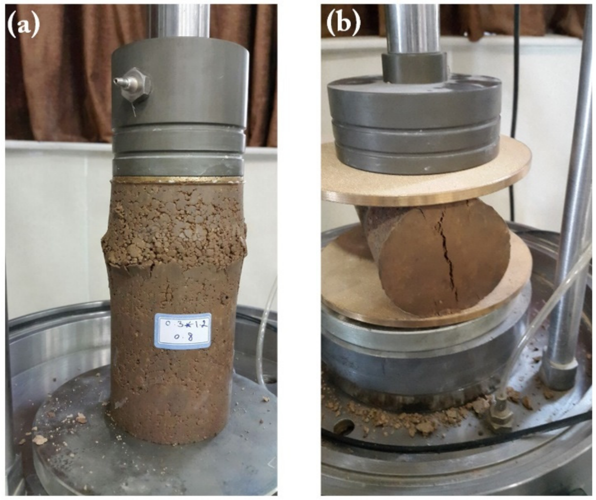

Figure 3. Cylindrical specimen tested under (a) UCS and (b) Brazilian tensile strength

The UCS tests can be used to estimate the strength of stabilized or reinforced soil specimens and also as a resistance index. The UCS tests were conducted with a strain rate of 1% per minute following the procedure in ASTM D2166. Further, in order to determine tensile strength of the specimens, the Brazilian tensile strength tests were conducted according ASTM C496. The Brazilian tensile strength test is an indirect technique commonly used to determine the tensile strength of rock, cemented materials and cohesive soils (Anggraini et al., 2015; Frydman, 1964; Karimian et al., 2021; Li et al., 2014; Maher & Ho, 1994; Muntohar, 2009; Stirling et al., 2015; Tang et al., 2015). To measure the tensile deformation of the horizontal diameter due to compressive loading in an orthogonal direction. In this study, the split-tensile strength test equipment was modified from triaxial test apparatus.

Results and discussion

UCS results

The stress-strain curves for the unreinforced specimen as well as the reinforced specimen with PET strips of 3 mm in width and various lengths and contents are presented in Fig. 4. As shown in Fig. 4, the results show that the PET reinforcement improved the UCS of specimens and somewhat reduced the brittleness of the soil. As shown from the results, UCS and failure strain of the reinforced specimens exhibited an increase with increasing the length of PET strips. In other words, increasing length of the PET strips results in changing soil behavior toward further brittleness. This could be related to the creation of a larger mass of brittle material (PET strips) is soil-PET mixtures. Fig. 5 present the variation in UCS versus PET content and length of PET strips for the reinforced specimens with PET strips with width of 3 mm. As shown from Fig. 5, the addition of PET strips results in an increase of UCS. The value of UCS of the specimens increased as the PET strips content increased up to 0.8% and then decreased. The specimens containing 0.8% PET strips content recorded the highest UCS at a given PET length. The reason behind the reduction in strength in specimens containing PET with 1% can be the increase in the volume of the reinforcing elements, thereby creating discontinuities within the soil body. The UCS of the reinforced specimens increases as the length of the strips increased from 12 mm to 18 mm and then decreased as the length of the strips increased from 18 mm to 21 mm. The increasing of the length of the strips from 12 mm to 18 mm could be a result of more interaction between PET strips and soil particles. Maximum increase in UCS was 117% which observed in the specimen containing 0.8 % PET strips with 18 mm length. The effects of PET content and length of PET strips on unconfined compressive stress-strain curve of the reinforced specimens containing PET strips with width of 6 mm are shown in Fig. 6. Similar to the reinforced specimens containing PET strips with width of 3 mm, the addition of PET strips results in increasing UCS. Furthermore, with increasing the PET content, further increase was observed in strength compared to the unreinforced specimen. Fig. 7 present the variation in UCS versus PET content and length of PET strips for the reinforced specimens with PET strips with width of 6 mm.

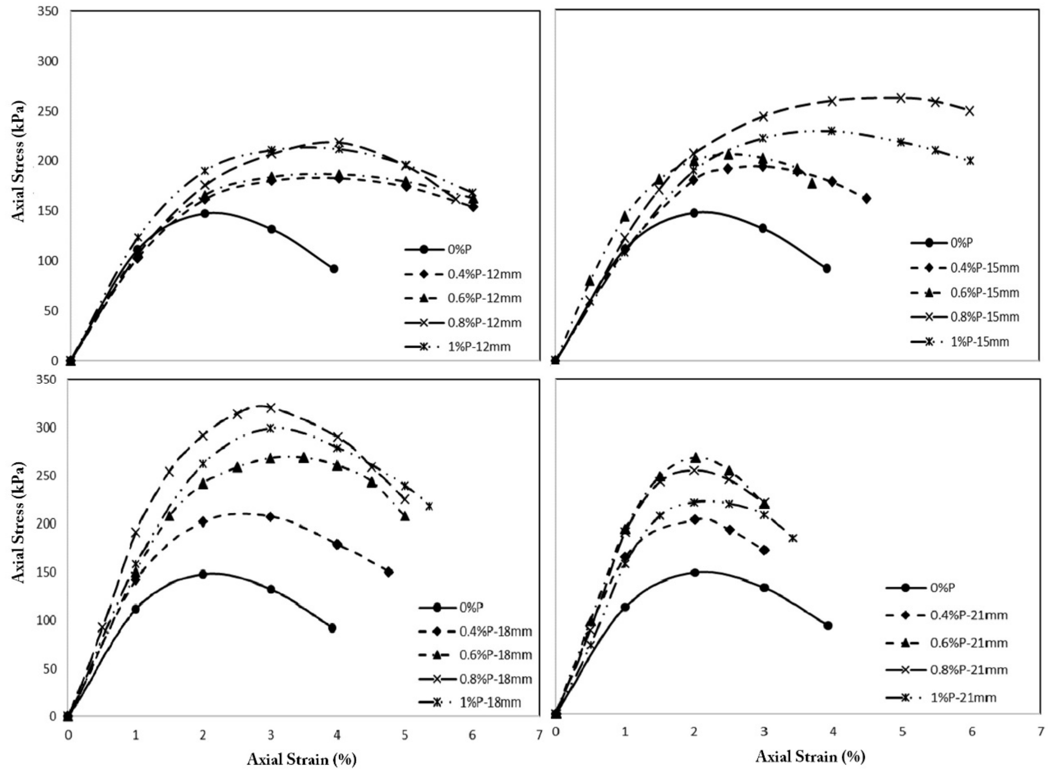

Figure 4. Stress-strain curves of reinforced specimens with PET strips with width of 3 mm and length of 12, 15, 18 or 21 mm

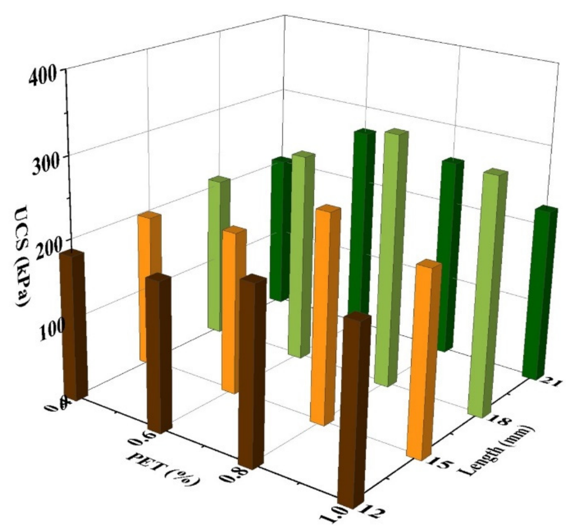

Figure 5. Effect of PET content and length of PET strips on the UCS of reinforced specimens with PET strips with width of 3 mm

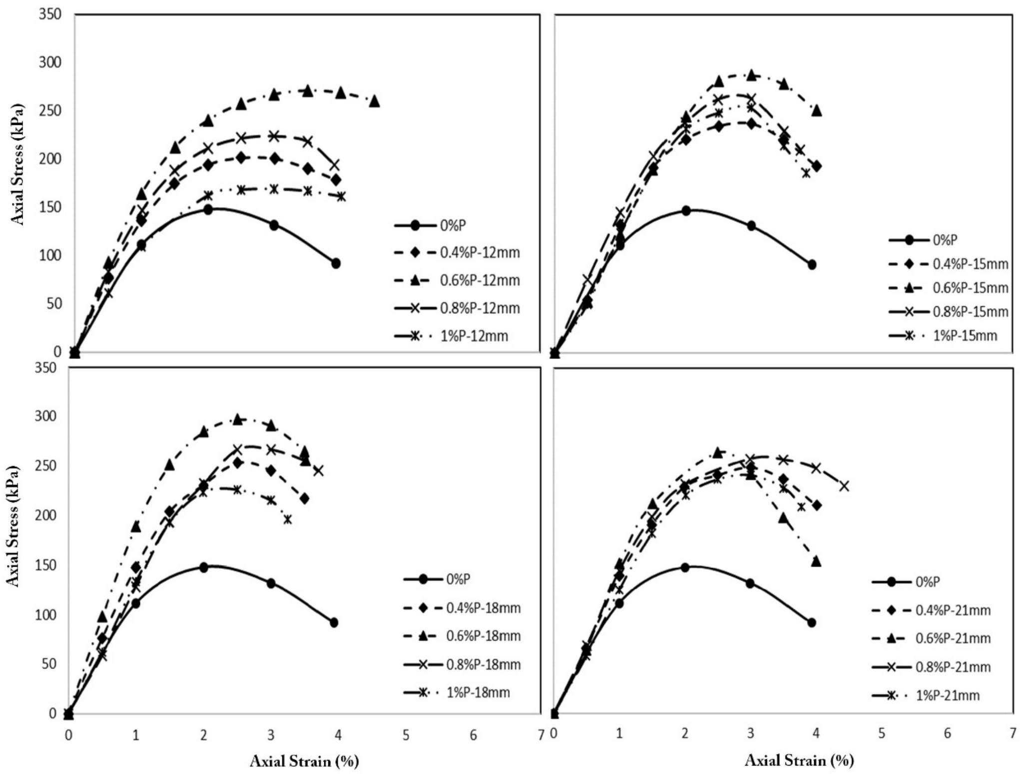

Figure 6. Stress-strain curves of reinforced specimens with PET strips with width of 6 mm and length of 12, 15, 18 or 21 mm

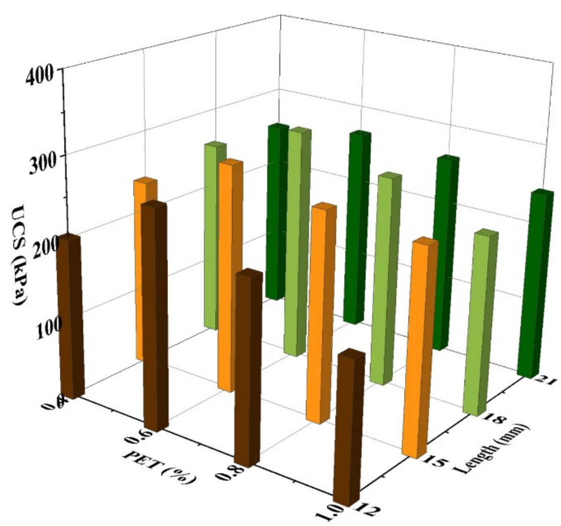

Figure 7. Effect of PET content and length of PET strips on the UCS of reinforced specimens with PET strips with width of 6 mm

The maximum strength was observed in the specimens containing 0.6% of PET strips with width of 6 mm. The value of UCS of the specimens increased as the PET strips content increased up to 0.6% and then decreased with increasing of the PET content from 0.6% to 1%. As perceived from the results, the strength of specimens increases gradually as the PET content increases from 0% to 0.6% which is in good agreement with previous studies (Acharyya & Raghu, 2013; Botero et al., 2015; Fathi et al., 2021). As shown in Fig. 6, the UCS of the reinforced specimens increased and deformability and failure strain decreased with increasing the length of PET stripes from 12mm to 18mm and then the UCS decreased as the length of the strips increased from 18mm to 21mm similar to the reinforced specimens with PET strips with width of 3 mm. Maximum increase in UCS is about 101% which observed in case of the specimen containing 0.6% PET strips with length of 18 mm. Comparing Figs. 5 and 7 shows that increasing the width of the strips from 3 mm to 6 mm increases the UCS for a given PET content and length of PET strips.

In order to investigate the effect of the shape of PET elements on the UCS of reinforced specimens, I-shape PET elements were used as shown in Fig. 8. Fig. 9 shows stress-strain curves of the specimens containing 6% and 8% I-shape PET elements. In Fig. 9, the flange width of the PET is indicated by *b*. The specimens are named based on flange width, PET content, and height of the strips. As shown in the results, the reinforced specimens containing I-shape PET elements exhibit more UCS than the reinforced specimens with PET strips which is due to the increasing friction between the soil particles and the PET elements. However, the increase in UCS followed a decreasing trend with increasing PET content from 6% to 8%. In addition, a decreasing trend has been almost observed in the UCS with increasing the height of I-shape element from 15mm to 18 mm.

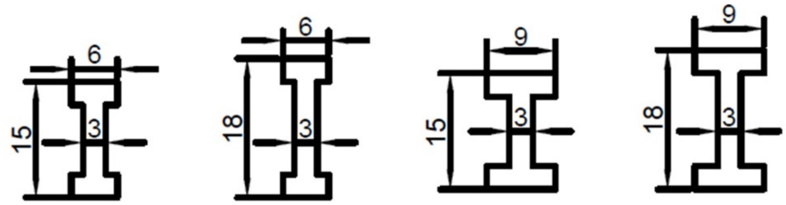

Figure 8. Details of the I-shape PET elements (All dimension in mm)

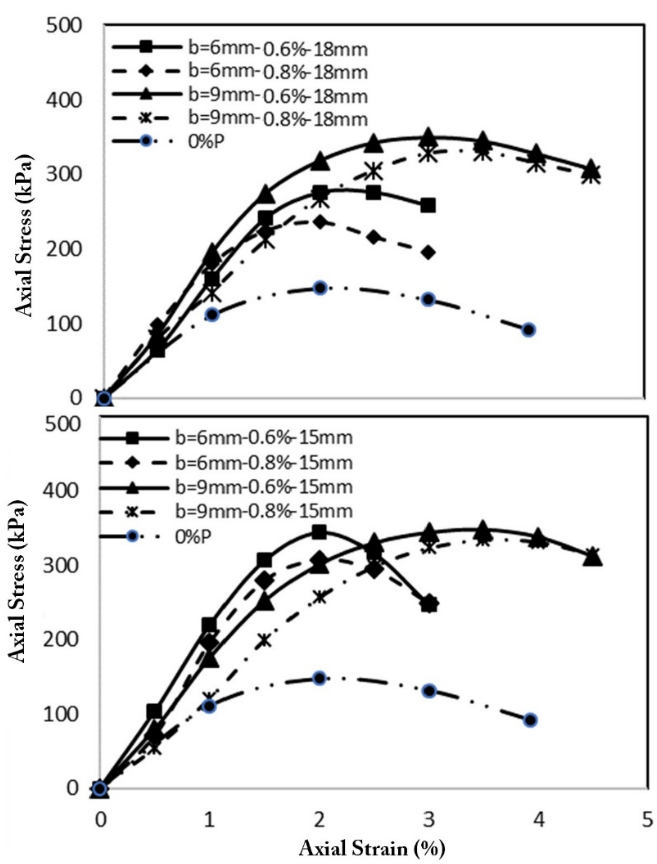

Figure 9. Stress-strain curves of reinforcement specimens with I-shape PET elements

Fig. 3(a) shows a picture of the typical failure mode of samples which is drum-expansion failure. The failure models for all specimens were almost the same; the samples all crouch to break at the weak cross section to demonstrate a petal-model.

Result of tensile strength tests

Fig. 10 shows the results of tensile strength test on unreinforced specimens as well as the specimens reinforced with PET strips with width of 3 mm, lengths of 12, 15, and 18 mm, with PET contents of 0, 0.4, 0.6, 0.8, and 1%. It should be noted that the tensile strength of the unreinforced specimen was about 16.5 kPa. As shown from the results, addition of PET strips in the soil specimens improved the tensile strength of the soil. Furthermore, the tensile strength of the reinforced specimens increases with increasing the content of the PET from 0.4% to 0.6%. However, the tensile strength of the reinforced specimens containing more than 6% PET is almost lower than that of the reinforced specimen with 6% PET for a given length of PET strips. Maximum tensile strength is about 30 kPa which is related to the reinforced specimen containing 0.6% PET strips with the length of 15 mm.

Fig. 11 shows the results of the tensile strength tests on reinforced specimens with PET strips with a width of 6 mm at various PET contents and PET strip lengths. The results show that the tensile strength of soil increased by adding PET strips. Maximum tensile strength is about 33 kPa for the specimen containing 0.6% of PET strips with the length of 15 mm. Increasing the PET content more than 6% has almost reduced the tensile strength of the reinforced specimen.

The effect of soil reinforcement with I-shape PET elements on the tensile strength has been also investigated using the specimens containing I-shape PET elements with length of 15 mm and flange widths of 6 mm and 9 mm. Table 4 shows the tensile strength test results of the reinforced specimens with I-shape PET elements. As shown form the results, addition of I-shape PET elements in the soil specimens increases the tensile strength remarkably. Maximum tensile strength observed in the specimen containing 0.6% of I-shape PET elements with a flange width of 6mm. As shown from the results, increasing PET content or flange size results in a decrease of the tensile strength of the reinforced specimens.

Table 4. Results of the tensile strength tests on the reinforced specimen with I-shape PET elements with a width of 3 mm

Type	Length (mm)	Width (mm)	Content (%)
Strip	12, 15, 18, 21	3 , 6	0, 0.4, 0.6, 0.8, 1
I-shape	15, 18	3	0, 0.6, 0.8

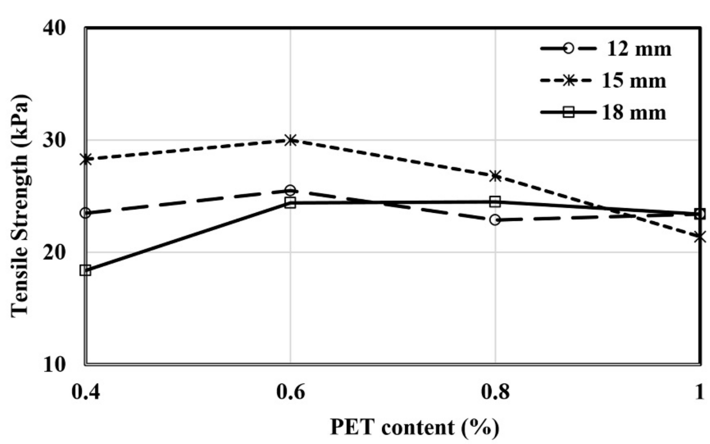

Figure 10. Ultimate tensile strength changes of reinforced specimens with PET strips with a width of 3 mm

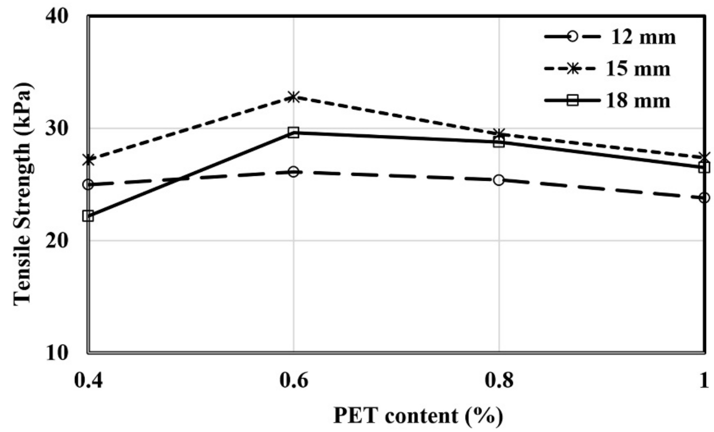

Figure 11. Ultimate tensile strength changes of reinforced specimens with PET strips with a width of 6 mm

Conclusions

Application of industrial wastes in geotechnical engineering has gained popularity which can be useful in waste management. In this study, the effect of polyethylene terephthalate strips on unconfined compressive strength and tensile strength of clayey soil was investigated. For this purpose, clayey soil specimens containing PET strips with widths of 3 and 6 mm, lengths 12, 15, 18 and 21 mm for various PET contents 0, 0.4, 0.6, 0.8 and 1% were prepared in optimum moisture content and maximum dry density. The reinforced specimens were subjected to unconfined compressive strength and Brazilian tensile strength tests. Based on the results, the following conclusions are reached:

Addition of PET strips leads to an increase of the unconfined compressive strength. Based on the results, it can be conducted that for the PET strips with widths of 3 and 6 mm, 0.8% and 0.6% are the optimum PET contents for the selected soil, respectively. Increasing the lengths of PET strips results in increasing the UCS values. This phenomenon attributed to an increase in the interaction between the reinforcement elements and the soil particles. The results indicate that there is an optimum length of PET strips (about 18 mm) above which increasing the PET strips length was not effective. The reinforced specimens containing 0.8% of PET strips with 3 mm in width and 18 mm in length exhibit the highest UCS value which is about 2.17 times more than that of the unreinforced specimen. The reinforced specimens containing I-shape PET elements have more UCS than the reinforced specimens with PET strips which is due to the increasing friction between the soil particles and the PET elements. Based on the results, it seems that when the PETs are added randomly and have an irregular shape results in a more increase of strength than when the shape of plastics is regular. The tensile strength of the specimens has also increased due to addition of PET strips. Based on the tensile strength tests, the optimum PET content was found to be 0.6% independent of width and length of PET strips. The highest tensile strength is about 1.81 times more than that of the unreinforced specimen which was observed in reinforced specimen containing 0.6% PET strips with 3 mm width and 15 mm length.

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