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RESEARCH ARTICLE

The Mechanical Performance of Clayey Soils Reinforced with Waste PET Fibers

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INFORMATION

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ABSTRACT

Nowadays, scarcity of good land for construction which is one of important problems for engineers using land increases demand for unsuitable soils. When the mechanical qualities of unsuitable soils are lower than those required, reinforcing can be an option to improve performance, notably in enhancing its strength. Use of waste material is alternative method as low-cost material for soil reinforcing applications. Today, abundant plastic waste pollutants are widely used as reinforcing materials for this purpose. In this study, uniaxial compressive tests were done to determine the resistance behavior of clayey soils reinforced with waste plastic PET fibers. These tests were repeated for the unexposed and exposed samples to freeze-thaw cycles. The freeze-thaw tests were performed with a programmable freeze-thaw cabinet under laboratory conditions. The results obtained from experimental studies have shown that the reinforced clayey soil samples with the waste of the plastic bottle fibers have high strength when compare with the unreinforced sandy soil samples. At the same time, the waste PET fibers increase the resistance of reinforced clayey soil samples against to the freeze-thaw cycles. As a result, Consequently, it is concluded that the waste PET fiber materials can be successfully used for the reinforce of clayey soils in the geotechnical applications.

1. Introduction

The expansive soil containing rich hydrophilic minerals is a kind of clay soil formed in the natural geological process. These soils are characterized with expansion, shrinkage and consolidability, which is significantly different from general clay (Liu et al., 2019; Miao and Liu, 2001). Clayey soils are generally classified as expansive soils and these soils are known to cause severe damage to structures resting on them. However, these soils are very important in geology, construction, and for environmental applications, due to their wide usage as impermeable and containment barriers in landfill areas and other environmentally related applications (Erguler and Ulusay, 2003; Harvey and Murray, 1997; Kayabali, 1997; Keith and Murray 1994; Murray, 2000; Sabtan, 2005; Kalkan and Akbulut, 2004; Kalkan et al., 2019; Indiramma et al., 2020).

Safe and economic designs of foundations on clayey soils and performance of compacted clayey soils for geotechnical purposes require the knowledge of swelling characteristics such as swelling pressure, swelling potential and swelling index. Cyclic drying and wetting phenomena can cause progressive deformation of expansive clayey soils, which may affect building foundations, drainage channels, buffers in radioactive waste disposals, etc. (Guney et al., 2007; Nowamooz and Masrouri, 2008; Rao et al., 2001; Kalkan, 2011; Zeng et al., 2020).

Basic principles of soil reinforcement already existing in nature and are demonstrated by animals, plants and birds (Patil et al., 2016). The concept of soil reinforcement with natural fiber materials originated in ancient times. Randomly distributed fiber-reinforced soils have recently attracted increasing attention in geotechnical engineering (Yetimoglu and Salbas, 2003; Zaimoğlu and Yetimoğlu, 2012). The concept and principle of soil reinforcement was first developed by Vidal (1969). He demonstrated that the introduction of reinforcement elements in a soil mass increases the shear resistance of the medium. The primary purpose of reinforcing soil mass is to improve its stability, increase its bearing capacity and reduce settlements and lateral deformation (Hausmann, 1990; Prabakar and Sridhar, 2002; Yarbaşı et al., 2007; Zaimoğlu and Yetimoğlu, 2012; Yarbaşı and Kalkan, 2019a; Yarbaşı and Kalkan, 2019b).

Nowadays there are various alternatives available to increase the strength and stiffness of the weak soil and to improve the behavior of soil under various loading and environmental conditions (Parihar et al., 2015). Many earth structures such as liners of waste landfills, levees and dams are constructed of fine grained soils. Also, excavated fine grained soils might be reused as fill material in some earth structures. In these kind of applications, there could be a tendency for characteristics of the soils (e.g. strength, volume change and mechanical characteristics) to vary over time. One possible solution to these problems is the use of randomly distributed tensile reinforcement elements in the soil. Such elements are available as polypropylene fibers (Yetimoğlu et al., 2005; Akbulut et al., 2007; Zaimoğlu, 2010; Zaimoğlu and Yetimoğlu, 2012; Kalkan, 2013).

The use of randomly dispersed fibers in clayey soil in soil improvement applications has been an interesting research topic in geotechnical engineering in recent years. The addition of these elements to the soil has been found to increase shear strength, soil carrying capacity and reduce settlements and limit lateral deformations. Natural or synthetic fibers have significant advantages such as low costs and the production of synthetic fibers by recycling plastic waste. However, polypropylene fiber material is also resistant to chemical and biological degradation (Hassania et al., 2005; Anabal, 2007; Sevencan and Vaizoğlu, 2007; Tayyar and Üstün, 2010; Telli et al., 2012; Muntohar et al., 2013).

Plastics have become an essential material for daily use and the annual plastic consumption has been increasing steadily over the past decades, primarily driven by its inherited factors such as inexpensiveness, user friendly designs, fabrication capabilities, high durability, lightweight and strength (Siddique, 2008). Basically, there are two alternatives for PET recycling: mechanical methods and chemical methods. Trough mechanical methods, 84 % of PET is recycled by collecting, sorting, washing, and crushing the material (Ragaert et al., 2017; Shaikh, 2020).

On the other hand, by chemical recycling the polymer chains are transformed and degraded to monomers by a process known as depolymerization (Al-Sabagh et al., 2016; Scremin et al., 2019). By this method, an unsaturated polyester resin widely used by the textile industry, tissue engineering, construction, coatings and among others is obtained (Gonçalves et al., 2017; Mendivil-Escalante et al., 2017; Saha et al., 2016; Wang et al., 2017; Chinchillas-Chinchillas et al., 2020).

The effects of different types of fibers on soil properties have been studied in the past decades. Environmental and economic issues have attracted the interest of many researchers to develop alternative materials that can fulfil design specifications. Experimental researches have shown that compressive strength, failure strain, ductility and shear strength of samples is increased when discrete fibers are mixed with the soil. These investigations indicate that strength properties of fiber-stabilized soils consisting of randomly distributed fibers are a function of fiber content and fiber-surface friction along with the soil and fiber strength characteristics (Hoover et al., 1982; Gray and Maher, 1989; Maher and Gray, 1990; Ranjan et al.., 1996; Nataraja and Mcmanis, 1997; Kaniraj and Havanagi, 2001; Santoni et al. 2001; Yetimoglu and Salbas, 2003; Park and Tan, 2005; Akbulut et al., 2007; Tang et. al., 2007; Consoli et, al., 2009; Zaimoglu, 2010; Babu and Chouksey 2011; Acharyya et al. 2013; Kalumba and Chebet, 2013; Hajiannezhad et. al., 2019; Yarbaşı and Kalkan, 2019a; Yarbaşı and Kalkan, 2019b).

The main objectives of this research are to investigate the utilizability of waste PET fiber for the reinforcement of clayey soils in geotechnical applications and to test mechanical performance and freeze-thaw resistance of clayey soils reinforced with waste PET fiber. To accomplish these objectives, natural clayey soil samples were reinforced by using different contents of waste PET fibers. The reinforced clayey soils obtained by the compaction process were subjected the unconfined compression tests and freeze-thaw tests under laboratory condition.

2. Materials and Methods

2.1. Clayey soil

In this study, clayey soil, known as red clayey soil, was supplied from the deposits of Oltu Oligocene sedimentary basin, Erzurum, Northeast Turkey. This soil material was gathered from a depth of 0.50 m. After drying the red clayey soil samples at 65 ± 5 °C for 48 hours, the coarse grains were milled in the Los Angeles apparatus at 6000 rpm (Fig. 1). The laboratory studies were conducted in accordance with related ASTM standards (ASTM D 2166, ASTM D 698-78, ASTM D 560). The red clayey soil sample was determined to be of low plasticity clayey soil (CL) class according to the USCS. The engineering properties of red clayey soil are shown in Table 1.

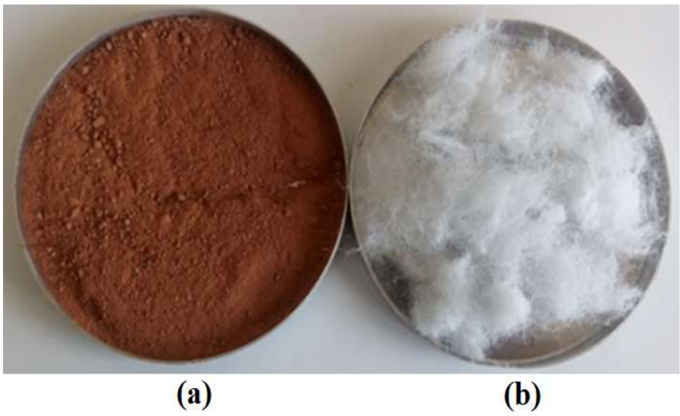

Fig. 1. The sample photos of grained clayey soil and waste PET fiber

2.2. Waste PET fiber

The other material used in this study is waste PET fibers. The waste PET fibers are polyester fibers defined as PET (Polyethylene Terephthalate). The PETs are obtained by polycondensation of a divalent organic acid and a divalent alcohol, are useful up to 175 °C and are not affected by acids (İşmal et al., 2000). The waste PET bottle fibers were supplied from Ertona Textile Factory (Nilufer-Bursa, Turkey) which provides raw materials to the textile market. The fibers were cut to sizes of 10 mm-15 mm length and 0.02 mm thick. The samples photo of waste PET fibers was shown in Fig. 1. Its physical and mechanical properties were summarized in Table 2.

Table 1. Engineering properties of clayey soil (Yarbaşı, 2018)

Parameters	Values
Specific gravity, Gs	2.62
Sand (%)	14.0
Silt (%)	52.0
Clay (%)	34.0
Liquid limit, (%)	43.5
Plastic limit, (%)	22.0
Plasticity index, (%)	21.5
Optimum water content, (%)	28.0
Maximum dry density, (kN/m^3)	13.9
Soil classification	CL

Table 2. Physical and chemical properties of PET fiber (Anabal, 2007)

Parameters	Methods	Values
Density	--	1.41 (g cm^{-3})
Melting temperature	DSC	265 (°C)
Breaking force	Tensile	50 (MPa)
Tensile strength	--	1700 (MPa)
The lowest stress value	Tensile	4 (%)
Impact strength	ASTM D 256-86	90 (J m^{-1})
Water absorption (after 24h)	--	0.5 (%)

2.3. Preparation of mixtures

The clayey soil used in this study has been dried in an oven at approximately 65 °C and then ground before using the mixtures. The required amounts of clayey soil and waste PET fiber were prepared and then blended together under dry conditions. The contents of waste PET fiber were 0.1 %, 0.2 % and 0.3 % by the total weight of mixtures. As the waste PET fibers tended to lump together, considerable care and time were spent to get a homogeneous distribution of the waste PET fibers in the mixtures. The weights of the mixtures were determined according to the formula below;

$$W_{CF} = W_C + W_F \quad (1)$$

where W_{CF}, W_C and W_F are the total dry weights of clayey soil-waste PET fiber mixtures, clayey soil and waste PET fiber, respectively. The component of the samples used in the experimental studies is summarized in Table 3.

2.4. Preparation of samples

The clayey soil and the mixtures of the clayey soil-waste PET fiber were blended with the required amount of water for optimum water content. All mixing was done manually and proper care was taken to prepare homogeneous mixtures at each stage of mixing. The unconfined compression and freeze-thaw tests were carried out on the cylindrical samples compacted at optimum water contents. The compaction processes were performed by Standard Proctor test. After compactions, cylindrical samplers were pressed into the compacted samples within the mold to obtain samples with appropriate length-to-diameter ratios. Then the cylindrical samples taken into the cylindrical samplers were extruded using a hydraulic sample extractor. The samples of unconfined compression tests had 35 mm diameter by 70 mm length (Fig. 2). In the tests, at least three samples were tried for each combination of variables. After each sample was extracted from the cylindrical samplers, it was wrapped in plastic to prevent from water loss (Kalkan, 2013).

Table 3. The clayey soil and the waste PET fiber percentage of mixture

No	Samples	Materials		Total (%)
		Clayey soil (%)	West PET fiber (%)	
1	MIX0	100.00	0.00	100.00
2	MIX1	99.90	0.10	100.00
3	MIX2	99.80	0.20	100.00
4	MIX3	99.70	0.30	100.00

Fig. 2. The compacted cylindrical samples of the unreinforced and reinforced clayey soil

2.5. Compaction tests

The unreinforced and reinforced clayey soil with waste PET fibers were compacted at their optimum water contents. The compaction processes were carried out by the Standard Proctor Test in accordance with ASTM D698-78. During the compaction process, a soil at selected water content was placed in three layers into a mold of standard dimensions, with each layer compacted by 25 blows of rammer dropped from a distance of 305 mm, subjecting the soil to total compaction effort. This procedure was repeated for six numbers of water contents to establish a relationship between the dry unit weight and the water content for the clayey soil and the mixtures. The compaction curves were plotted from the data and the values of optimum water content and maximum dry unit weight were determined from the compaction curves (Kalkan, 2013). The clayey soil and the mixtures of clayey soil and waste PET fibers were compacted at the optimum water content to prepare the samples for the unconfined compression and freeze-thaw tests.

2.6. Unconfined compression tests

The unconfined compressive strength (UCS) values of unreinforced and reinforced clayey soil samples were determined from the unconfined compressive tests in accordance with ASTMD 2166. This test is widely used as a quick and economical method of obtaining the approximate compressive strength of the cohesive soils. In this study, tests were carried out on the cylindrical samples compacted at optimum water contents. For this purpose, three cylindrical samples were prepared and tested for each combination of mixtures of clayey soil and waste PET fibers. The dimensions of cylindrical samples were 35 mm diameter and 70 mm height. The unconfined compression tests were performed at a deformation rate of 0.16 mm/min (Kalkan, 2013).

2.7. Freeze-thaw tests

The freeze-thaw tests were performed to investigate the resistance of unreinforced and reinforced clayey soil with waste PET fibers against to freeze-thaw cycles. This tests were carried out by a programmable freezing-thawing cabinet in accordance with ASTM D 560. All samples were subjected to freeze-thaw tests in accordance with ASTM C 666-92. The samples were placed in the freezing apparatus and conditioned at −21 °C for 24 hours. During the freezing process, the cylindrical samples were insulated by 50 mm polystyrene to obtain one-dimensional freezing. After the freezing was completed, the samples were transferred from the freezing apparatus into a test room at +21 °C for 24 hours (Ghazavi and Roustaie, 2010; Zaimoğlu, 2010: Kalkan, 2013). This freezing and thawing cycle was repeated 10 times for 7,14 and 28 days' cycles, and then these samples were subjected to the unconfined compression tests.

3. Result and Discussion

According to the test results, all the waste PET fiber-reinforced clayey soil samples show better strength performance than the unreinforced clayey soil samples. The clayey soil, in which randomly distributed waste PET fibers were incorporated, increases peak compressive strength and ductility of samples. The UCS increases with length of curing time and waste PET fibers rate. An increase in waste PET fibers content in the red clayey soils made more strength and more ductile as compared to the red clayey unreinforced samples. In the failure moment of unreinforced samples for the unconfined compression tests, the shapes of the sample surface are seen as flat surface (Fig. 3a).

In contrast, the samples of reinforced clayey soil exhibit bulging failure mode on the cylindrical surface of samples (Fig. 3b). With the addition of waste PET fibers, deformations as a result of bar relations or blistering of the sample mid-section occurs (Akbulut et al., 2007; Zaimoğlu and Yetimoğlu, 2012; Kalkan, 2013). In addition, the bridging effect, which is one of the important factors that increase the strength of mixture. This effect has a significant effect on strength and ductility. The waste PET fibers reinforcements, which connect the two fracture planes, thus increase the ductility (Zaimoglu and Yetimoglu, 2012).

The stress-strain curves obtained from unconfined compression tests on the unreinforced and the reinforced samples subjected to 10 times freeze-thaw cycles. These curves were prepared for the unreinforced and reinforced clayey soil samples exposed to the 7, 14 and 28 days curing period. The stress-strain curves obtained from unconfined compression tests were given in Fig. 4. When the stress-strain relationships were examined, it was seen that the waste PET fibers did not affect the clayey soil sufficiently before and after freezing-thawing after 7 and 14 days of curing. The short curing times did not make much difference as it was not sufficient to complete the reactions between the clayey soil and the PET fibers. Significant increases in strength were observed after 28 days of curing period.

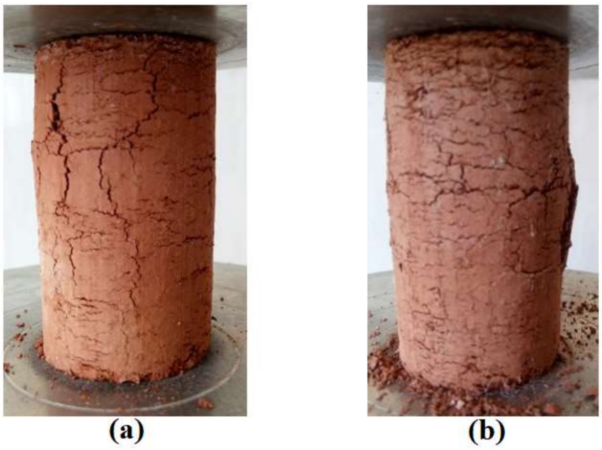

Fig. 3. The surface deformation of samples at the failure moment; (a) unreinforced clayey soil sample and (b) waste PET fiber-reinforced clayey soil sample

The increase in curing period and PET fiber rates was clearly observed at the fracture peaks gained. Furthermore, it is thought that the bridging effect of the PET fibers in the clayey ground is caused by the transition to ductility in the spreading of the peak where the fracture occurs (Fig. 4). The addition of waste PET fiber to the clay soils changes the stress-strain behavior of the samples under static load and increases the strength. However, after peak pressure, the decrease in strength decreases and the deformation energy absorption increases (Zaimoğlu, 2010; Zaimoglu and Yetimoğlu, 2012). Also, it was observed from these results that strength increases occurred in parallel with the increase in curing time and PET fiber ratio in clayey soil reinforced with waste PET fibers (Altun et al., 2009; Jafari and Esna-Ashari, 2012; Kalkan, 2013).

As compared to the unreinforced samples before freeze-thaw cycles, the UCS value of the reinforced sample content of 0.3 % waste PET fiber content (MIX3) and at 28-day curing period was the maximum level (Fig. 5). It can also be seen that the waste PET fiber-reinforced soils exhibit more ductile behavior than the unreinforced clayey soil. On the other hand, the initial stiffness of soil appears not to be affected by the addition of waste PET fiber reinforcement. Similar results were also obtained for granular soils modified with waste additives (Akbulut et al., 2007; Yarbasi et al., 2007; Zaimoğlu, 2010; Kalkan, 2013). Before and after freeze-thaw cycles, all samples were subjected to the unconfined compression tests at the end of 7-day, 14-day and 28-day curing period and obtained results illustrated on the Fig. 5. Before freeze-thaw cycles, the strength value of sample MIX3 showed a higher strength value than that of the samples MIX1 and MIX2. At the end of curing period at the 28-day, the strength values of the sample MIX1 increased in 10 %, the sample MIX2 by 37.14 % and the sample MIX3 by 67.14 % (Fig. 5). After freeze-thaw cycles, the strength value of sample MIX3 showed a higher strength value than the samples MIX 1 and MIX2. At the end of the 28-day of curing period, the strength values of sample MIX1 increased in 2.31 %, the sample MIX2 by 30.78 % and the sample MIX3 by 62.10 %. (Fig. 5). When freeze-thaw before and after strength values were compared proportionally; a decrease of 7.69 % was observed in the sample MIX1, 6.36 % decrease in the sample MIX2 and 5.04 % decrease in the sample MIX3. As a result, minimum strength reduction was occurred in the sample MIX3.

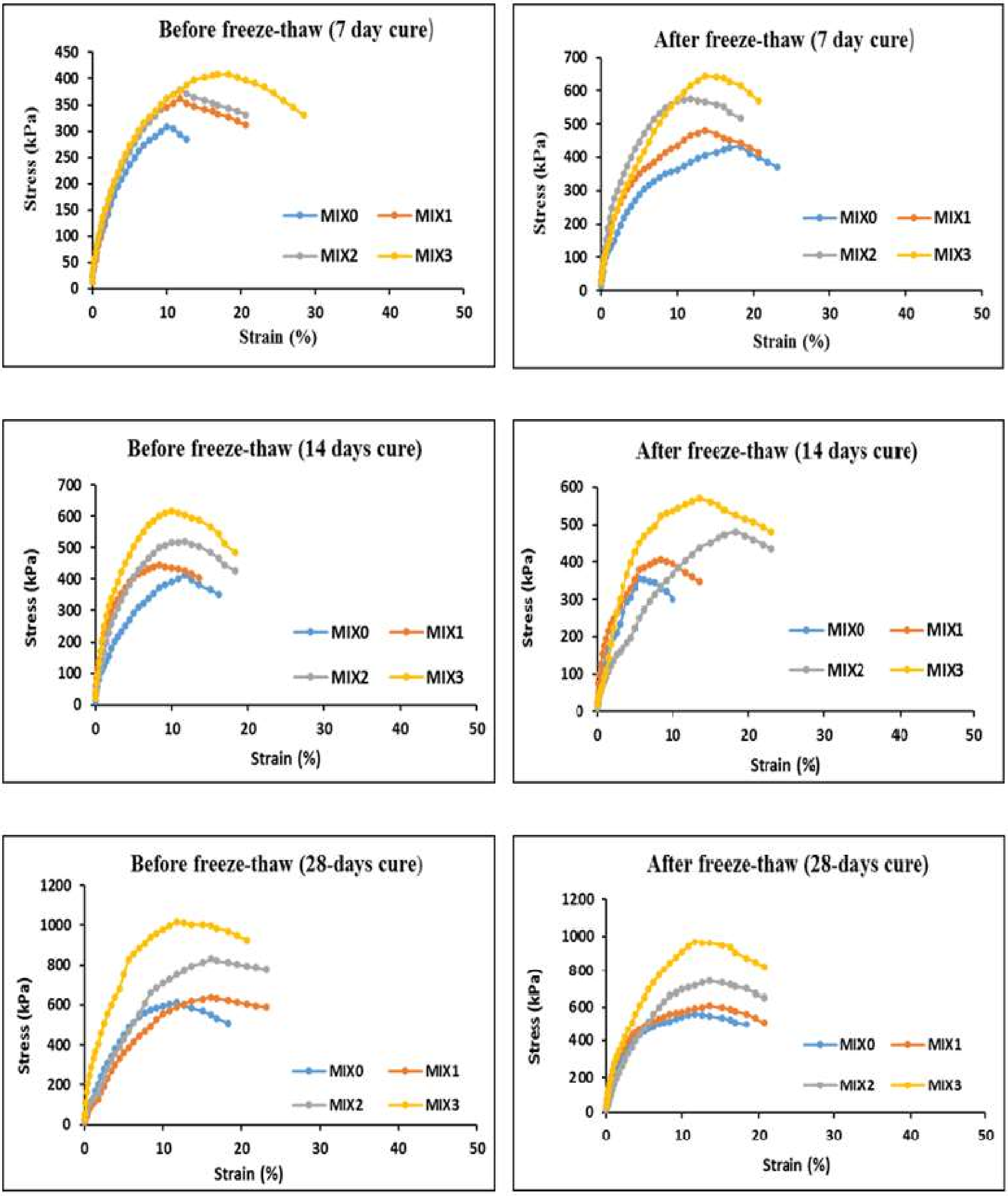

Fig. 4. Stress-strain relationship before and after freeze-thaw cycles

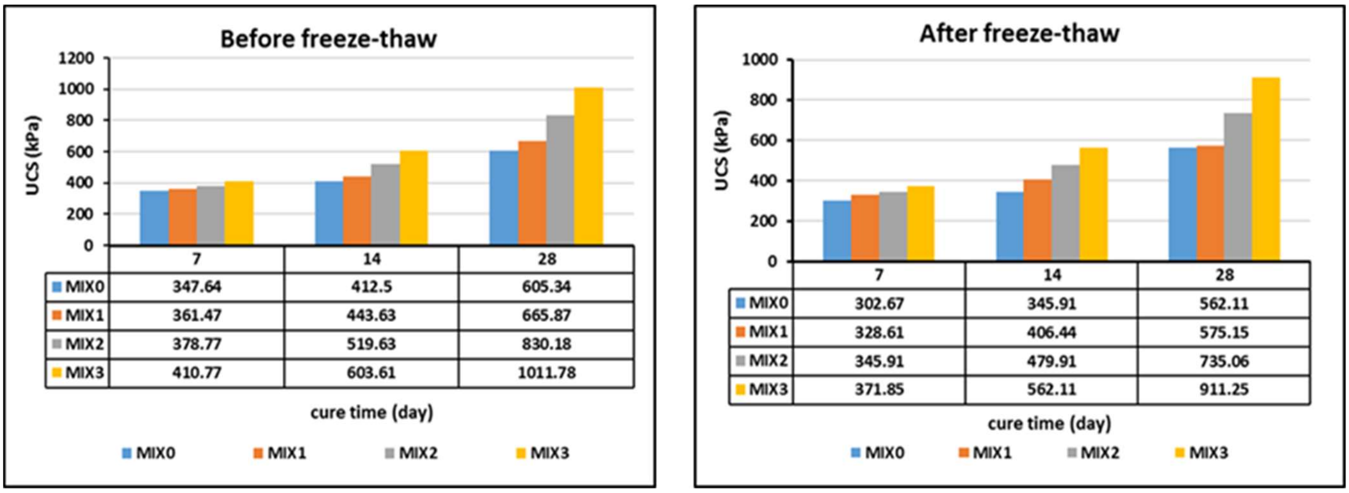

Fig. 5. Before and after freeze-thaw cycles, the UCS values of mixtures for 7-day, 14-day and 28-day curing period

4. Conclusion

In this study, it was determined that the waste PET fibers obtained by recycling increase the strength of the clayey soil. The maximum strength values were obtained in a mixture containing 0.3 % waste PET fiber and 28 days curing. In this mixture, the strength values before and after freeze-thaw increased by 67.14 % and 62.10 %, respectively. The lowest rate of change between strength values before and after freeze-thaw was also observed in this mixture with 5.04 %. As a result, the increase in strength occurred in parallel with the increases in curing period and waste PET fiber content. The addition of waste PET fiber to clayey soil increased the ductility of the soils. It was observed in the stress-strain relationship that waste PET fiber-reinforced clayey soils continue their behavior ductility, even if they are under a certain freeze-thaw effect. The unconfined compressive strengths observed with this study showed that the waste PET fibers can be successfully used to increase the strength of the clayey soils in the geotechnical applications. Also, considering that PET fiber raw material is obtained from waste plastic PET bottles, a reinforcement made using waste material is also considered as a solution that reduces stabilization costs and contributes to recycling.

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