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Modification of clayey soils using scrap tire rubber and synthetic fibers

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Abstract

A number of studies have been conducted recently to investigate the influence of randomly oriented fibers on the geotechnical behavior of grained soils. However, very few studies have been carried out on fiber-reinforced clayey soils. Therefore, this experimental work has been performed to investigate the influence of randomly oriented fiber inclusion on the geotechnical behavior of clayey soils. This research evaluates the use of waste fiber materials such as scrap tire rubber, polyethylene, and polypropylene fiber for the modification of clayey soils. This investigation focuses on the strength and dynamic behavior of the reinforced soils with randomly included waste fiber materials. The unreinforced and reinforced samples were subjected to unconfined compression, shear box, and resonant frequency tests to determine their strength and dynamic properties. These waste fibers improve the strength properties and dynamic behavior of clayey soils. The scrap tire rubber, polyethylene, and polypropylene fibers can be successfully used as reinforcement materials for the modification of clayey soils.

Keywords: Fibers; Scrap tire rubber; Polyethylene; Polypropylene; Compressive strength; Soil

1. Introduction

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). 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).

Several reinforcement methods are available for stabilizing expansive soils. These methods include stabilization with chemical additives, rewetting, soil replacement, compaction control, moisture control, surcharge loading, and thermal methods (Chen, 1988; Nelson and Miller, 1992; Steinberg, 1998). All these methods may have the disadvantages of being ineffective and expensive. Therefore, new methods are still being researched to increase the strength properties and to reduce the swell behaviors of expansive soils (Puppala and Musenda, 2002). Many investigators

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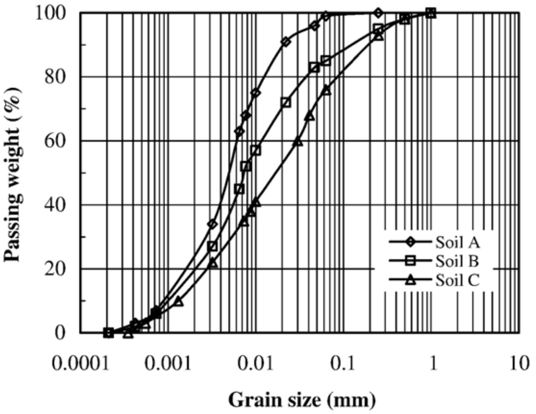

Fig. 1. Grain-size distributions of clayey soil samples.

have experienced on natural, fabricated, and by-product materials to use them as stabilizers for the modification of clayey soils (Aitcin et al., 1984; Sandra and Jeffrey, 1992; Kayabali, 1997; Asavasipit et al., 2001; Prabakar et al., 2003; Kalkan and Akbulut, 2004; Akbulut et al., 2004; Cetin et al., 2006; Kalkan, 2006).

Recently, there have been many experimental researches on the reinforcement of soils with randomly disturbed natural and synthetic fiber materials (Hoare, 1979; Hoover et al., 1982; Gray and Ohashi, 1983; Setty and Rao, 1987; Maher, 1988; Gray and Maher, 1989; Maher and Gray, 1990; Charan, 1995; Ranjan et al., 1996; Nataraj and McManis, 1997; Atom and Al-Sharif, 1998; Abu-Zreig et al., 2001; Makiuchi and Minegishi, 2001; Kaniraj and Havanagi, 2001; Santoni et al., 2001; Park and Tan, 2005; Terzano et al., 2005; Cetin et al., 2006). These previous investigations indicate that strength properties of fiber-reinforced soils consisting of randomly distributed fibers are a function of fiber content and fiber-surface friction along with the soil and fiber strength characteristics. The use of fibers in geotechnical design and application is a major focus of several research studies because fiber materials are cost-competitive with other materials (Crockford et al., 1993; Gregory and Chill, 1998; Puppala and Musenda, 1998; Musenda, 1999). In addition, these fiber materials can be recycled from plastic waste materials, so the fiber-stabilization of soils method can potentially reduce.

In this study, scrap tire rubber, polyethylene, and polypropylene fibers were used to modify the clayey soils. These fibers were obtained from wastes of tire rubber, polyethylene, and polypropylene materials. The clayey soils were investigated in terms of a number of properties of the clayey soil–waste fiber mixtures such as unconfined compressive strength (*UCS*), strength parameters, and the dynamic behavior.

Table 1
Chemical composition of clayey soils used in the study

Property	Clayey soils		
	Soil A	Soil B	Soil C
Compound			
Al_2O_3, (%)	13.94	13.24	17.82
CaO_3, (%)	57.29	44.35	51.04
CaO, (%)	11.02	8.26	9.55
Fe_2O_3, (%)	6.21	7.56	8.03
MgO, (%)	3.48	6.15	2.38
SO_3, (%)	0.12	0.44	0.15
SiO_2, (%)	41.59	44.69	44.27
LOI, (%)	12.45	13.19	10.10

LOI: loss in ignition.

The main objectives of this research were to investigate the use of waste fiber materials in geotechnical applications and to evaluate the effects of scrap tire rubber and synthetic fibers on the *UCS*, strength parameters, and dynamic behavior of clayey soils. The data of *UCS* were obtained from the compression tests, strength parameters from the shear box tests, and

Table 2
Engineering properties of clayey soils used in the study

Property	Clayey soils		
	Soil A	Soil B	Soil C
Density			
Density, (Mg/m^3)	2.63	2.68	2.60
Grain size			
Gravel (>2000 µm), (%)	0	0	0
Sand (75–2000 µm), (%)	2	15	25
Silt (2–75 µm), (%)	73	65	59
Clay (<2 µm), (%)	25	20	16
Atterberg limits			
Liquid limit, (%)	65	62	65
Plastic limit, (%)	35	35	42
Plasticity index, (%)	30	27	23
Clay activity			
Activity	1.25	1.22	1.15
Compaction parameters			
Optimum moisture content, (%)	26	25	26
Maximum dry unit weight, (Mg/m^3)	1.36	1.37	1.38
Soil classification			
Unified Soil Classification (*USCS*)	*CH*	*CH*	*CH*
Mineralogy			
Clay minerals			
Montmorillonite	x	x	x
Nontronite	x	–	–
Halloysite	x	x	x
Palygorskite	x	–	–
Hydrobiotite	x	x	x
Non-clay minerals			
Quartz	x	x	x
Anortite	–	–	x
Calcite	x	x	x

dynamic parameters from the resonant frequency tests under laboratory conditions.

2. Materials

2.1. Clayey soils

Three clayey soils were supplied from the clay deposits of Oltu Oligocene sedimentary basin, Erzurum, Northeast Turkey. They consist of montmorillonite, nontronite, halloysite, palygorskite, and hydrobiotite. These clayey soils are over consolidated and have clayey-rock characteristics in natural conditions. They are defined as high plasticity soil (*CH*) according to the Unified Soil Classification System (Akbulut, 1999; Kalkan, 2003). The grain-size distribution, chemical analysis, and index properties are given in Fig. 1, Tables 1, and 2, respectively.

2.2. Scrap tire rubber fibers

The scrap tire rubber fibers were supplied by local recapping truck tires producer in Erzurum, Northeast Turkey. When the tread on truck tires down, it is more economical to stave off the old tread and replace it than to purchase brand new tires. The tire is shaved off into 150 mm and smaller strips using a sharp rotating disc. These strips are then ground into scrap rubber (Pierce and Blackwell, 2003). The rubber fibers used in this study have three different lengths ranging from 2 to 5 mm, from 5 to 10 mm, and from 10 to 15 mm (Table 3).

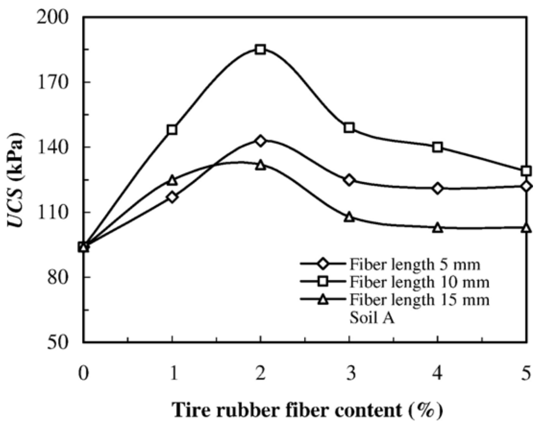

Fig. 2. The effect of scrap tire rubber fiber on *UCS* of the samples for Soil A.

Table 3
Properties of reinforcement materials used in the study (Celik, 1996; Park et al., 1997; Hernandez-Olivares et al., 2002; Sacan, 2002)

Property and component	Reinforcement materials		
	Tire rubber fiber	Synthetic fibers	
		Polyethylene	Polypropylene
Property			
Density (Mg/m^3)	1.153–1.198	0.92–0.96	0.90
Elastic modulus, (MPa)	1.97–22.96	–	3000–4500 (wet, 23 °C)
Tensile strength, (MPa)	28,1	200–400 (wet, 23 °C)	500–900 (wet, 23 °C)
Extent at failure, (%)	44–55	20–40 (23 °C)	15–30 (23 °C)
Softening temperature, (°C)	175	–	–
Melting temperature, (°C)	–	167	115–138
Component			
Sryrene–butadiene-copolymer, (%)	62	–	–
Carbon block, (%)	31	–	–
Extender oil, (%)	1.9	–	–
Zinc oxide, (%)	1.9	–	–
Stearic acid, (%)	1.2	–	–
Sulphur, (%)	1.1	–	–
Accelerator, (%)	0.7	–	–

2.3. Polyethylene fibers

The polyethylene fibers were obtained from polyethylene waste materials. The waste woven polyethylene fibers were dismantled as long fibers and then they were cut into required lengths. Their thickness was 0.25 mm and their width was 2.5 mm. Polyethylene fiber lengths were considered as 5, 10, 15, 30, 40, and 60 mm (Table 3).

2.4. Polypropylene fibers

The polypropylene fibers were produced from long fibers of polypropylene waste materials by cutting into required lengths. The polypropylene fibers were 1 mm in diameter. Six different fiber lengths were considered as reinforcement fiber material. Fiber lengths were selected as 5, 10, 15, 30, 40, and 60 mm (Table 3).

3. Testing programme

3.1. Preparation of clayey soil–fiber mixtures

The clayey soils were dried in an oven at approximately 105 °C and then ground before using in the mixtures. First, the required amounts of clayey soils and waste reinforcement fibers were blended together under dry conditions. The contents of scrap tire rubber fiber were chosen as 1, 2, 3, 4, and 5% by total weight of reinforced samples. The contents of synthetic polyethylene and the polyethylene fibers were 0.1, 0.2, 0.3, 0.4, and 0.5% by the total weight of reinforced samples. As the

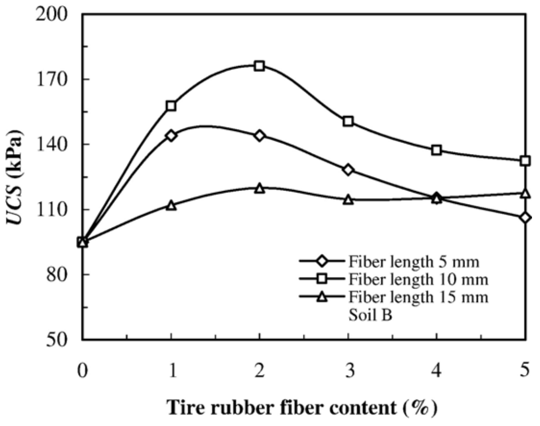

Fig. 3. The effect of scrap tire rubber fiber on *UCS* of the samples for Soil B.

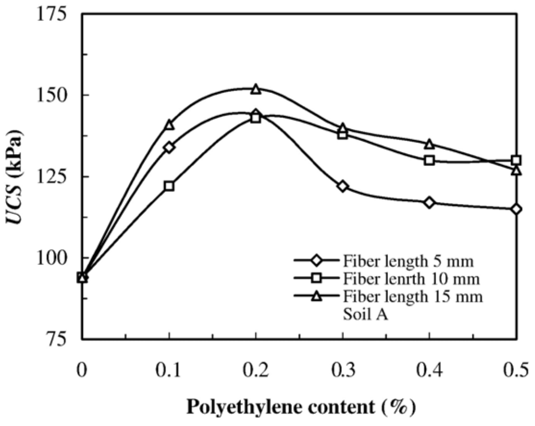

Fig. 5. The effect of polyethylene fiber on *UCS* of the samples for Soil A.

fibers tended to lump together, considerable care and time were spent to get a homogeneous distribution of the fibers in the mixtures. Then the clayey soil–fiber mixtures were mixed with the required amount of water according to the optimum moisture content.

3.2. Preparation of reinforced soil samples

The unconfined compression, the shear box, and the resonant frequency tests were carried out on the cylindrical unreinforced and reinforced samples compacted at optimum water contents. The compaction processes were performed by Standard Proctor test (ASTM D 698). To ensure uniform compaction, the entire required quantity of the moist clayey soil–fiber mixture was placed inside the mould-collars assembly and compacted in three steps alternately from the two ends till the samples reached the dimensions of the mould. After compactions of the natural clayey soils and the clayey soil–fiber mixtures, cylindrical samplers were pressed into the compacted samples within the mould to obtain samples with appropriate length-to-diameter ratios for unconfined compressive, shear box, and the resonant frequency tests. Then the cylindrical unreinforced and reinforced samples taken into the cylindrical samplers were extruded from the cylindrical samplers using a hydraulic jack. The unreinforced and reinforced samples of unconfined compression tests had three different dimensions: 35 mm in diameter by 70 mm in length, 50 mm in diameter by 100 mm in length, and 80 mm in diameter by 160 mm in length. 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. The unreinforced and reinforced samples with 60-mm diameter and 35-mm length were

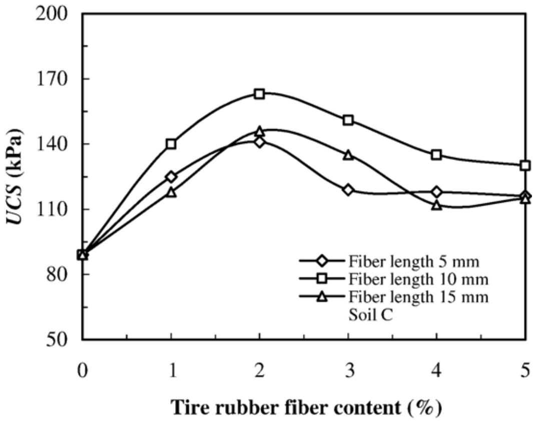

Fig. 4. The effect of scrap tire rubber fiber on *UCS* of the samples for Soil C.

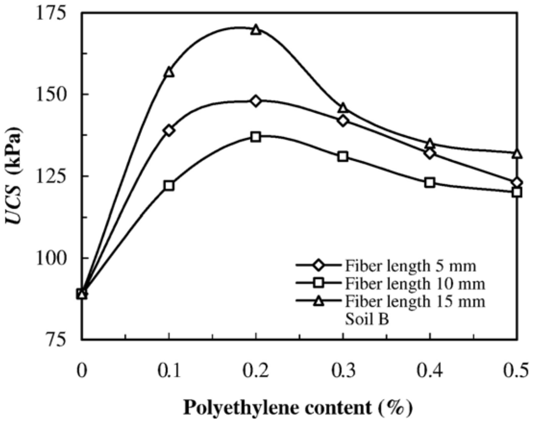

Fig. 6. The effect of polyethylene fiber on *UCS* of the samples for Soil B.

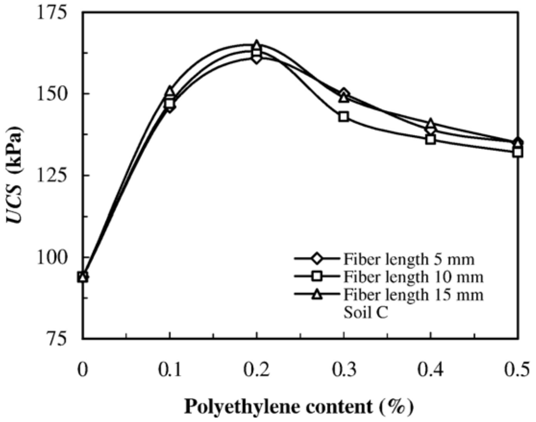

Fig. 7. The effect of polyethylene fiber on *UCS* of the samples for Soil C.

used for the shear box tests. For the resonant frequency tests, the unreinforced and reinforced samples with a length/diameter ratio 3 were prepared (*L*: 14.25 mm and *D*: 4.75 mm).

3.3. Unconfined compression tests

The *UCS* values of unreinforced and reinforced samples were determined from the unconfined compressive tests in accordance with ASTM D 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, three cylindrical samples were prepared and tested for each combination of clayey soil–waste fiber mixtures. The unconfined compressive tests were performed at a deformation rate of 0.16 mm/min.

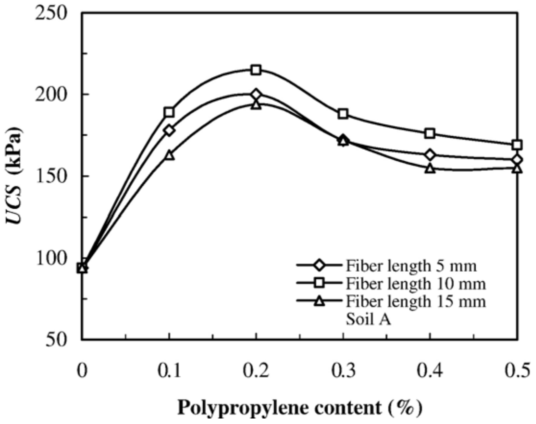

Fig. 8. The effect of polypropylene fiber on *UCS* of the samples for Soil A.

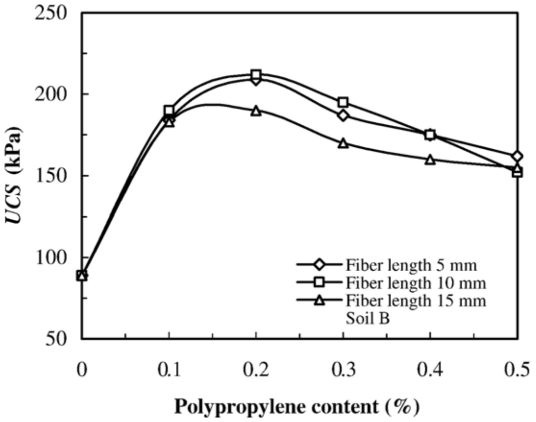

Fig. 9. The effect of polypropylene fiber on *UCS* of the samples for Soil B.

3.4. Shear box tests

In order to determine the shear strength parameters of unreinforced and reinforced samples, a series of shear box tests was carried out in accordance with ASTM D 3080. All samples were initially compacted in a Standard Proctor mould by Standard Proctor tests (ASTM D 698) and then extruded using a cutting ring before shear box tests. For these tests, samples were placed in the standard shear box apparatus with 60 mm in diameter and 35 mm in length. To obtain the shear strength parameters such as cohesion and internal friction angle, the values of shear stress versus the value of normal stress were plotted to construct a best fit straight line through the plotted points. The cohesion values were obtained from the intercept with the ordinate axis and the slops of the internal fraction angles from the slope.

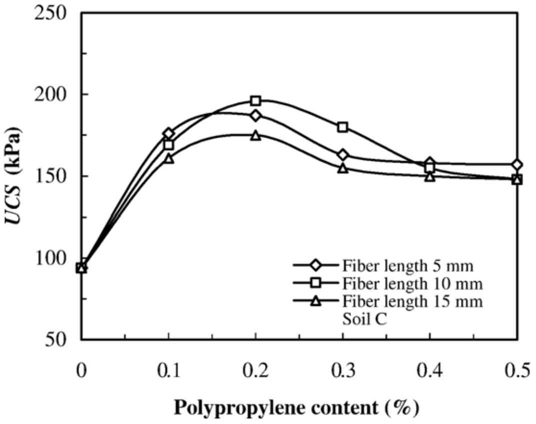

Fig. 10. The effect of polypropylene fiber on *UCS* of the samples for Soil C.

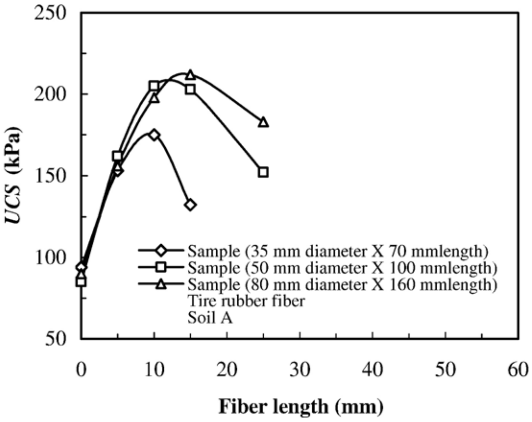

Fig. 11. The effect of fiber lengths and sample dimensions on *UCS* of Soil A for the scrap tire rubber fiber.

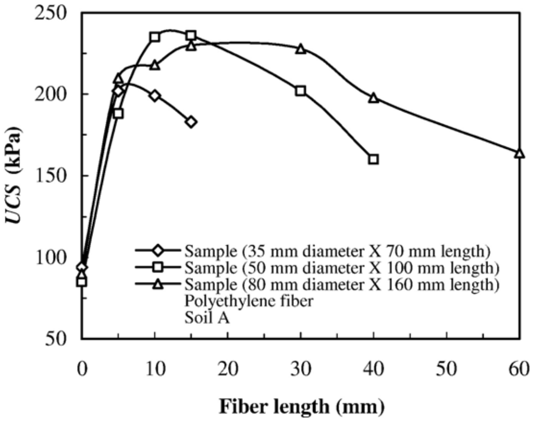

Fig. 12. The effect of fiber lengths and sample dimensions on *UCS* of Soil A for the polyethylene fiber.

3.5. Resonant frequency tests

The resonant frequency tests were carried out with an E-meter instrument produced by James Instruments Inc. A supported sample is forced to vibrate by an electromechanical driving unit. The sample response is monitored by a lightweight pickup unit on the sample. The driving frequency is varied until the measured sample response reaches the maximum amplitude. The value of the frequency causing maximum response is the resonant frequency of the sample. These tests were carried out on unreinforced and reinforced samples with 47.5-mm diameter and 14.25-mm length in accordance with ASTM C 215.

4. Results and discussion

4.1. Effects of scrap tire rubber fibers on the UCS

The effects of scrap tire rubber fibers on *UCS* values of clayey soils are given in Figs. 2–4 for soils A, B, and C, respectively. Both the lengths and contents of the scrap tire rubber fibers played an important role in the development of *UCS*. Figs. 2–4 indicate that the *UCS* values of clayey soil–fiber mixtures have a tendency to increase first, after a peak value, the *UCS* values of these mixtures decrease. It was found that the *UCS* values of unreinforced samples increased due to the rise of 2% tire rubber fiber content with 10-mm length from 94 to 185 kPa, from 94 to 176 kPa, and from 89 to 163 kPa for the clayey soils A, B, and C, respectively. The maximum *UCS* value of soil A being 185 kPa is 1.97 times higher than that of unreinforced sample. These findings indicated that the optimum tire rubber fiber content based on *UCS* values depends on fiber dimensions. According to the test results, the optimum tire rubber fiber length is 10 mm and optimum tire rubber fiber content is 2%.

4.2. Effects of synthetic fibers on the UCS

The effects of polyethylene fibers on the *UCS* of clayey soils are given in Figs. 5–7. The effects of polypropylene fibers on the *UCS* of clayey soils are presented in Figs. 8–10. The polyethylene and polypropylene fibers increased the *UCS* values of the reinforced samples. Both the length and content of the polyethylene and polypropylene fibers improve the *UCS* values of the reinforced samples. The maximum *UCS* values of reinforced samples were obtained at 0.2% polyethylene fibers of 15-mm length and at 0.2% polypropylene fibers of 10-mm length. As compared to the unreinforced samples, the *UCS* values of the

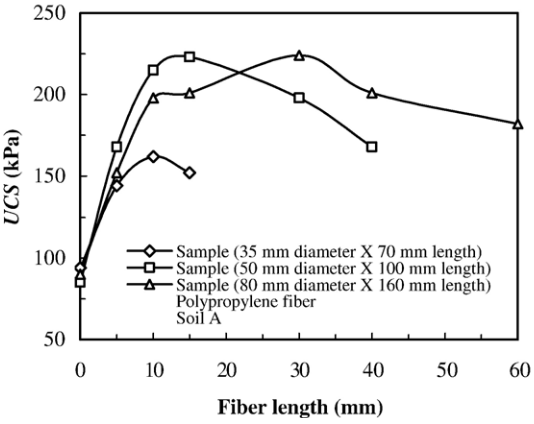

Fig. 13. The effect of fiber lengths and sample dimensions on *UCS* of Soil A for the polypropylene fiber.

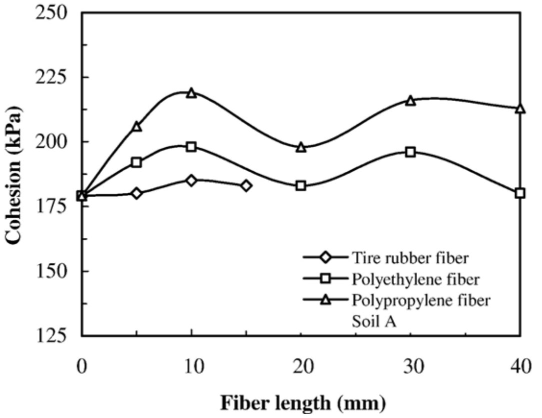

Fig. 14. Variation of the cohesion with fiber length of tire rubber, polyethylene, and polypropylene.

reinforced samples at 0.2% content with 15-mm polyethylene fibers increased from 94 to 152 kPa, from 94 to 170 kPa, and from 94 to 165 kPa for the clayey soils A, B, and C, respectively, and those of the reinforced samples at 0.2% content with 15-mm polypropylene fibers increased from 94 to 215 kPa, from 94 to 212 kPa, and from 94 to 196 kPa for the clayey soils A, B, and C, respectively.

4.3. Effects of fiber lengths and sample dimensions on the UCS

The samples with different dimensions were subjected to the unconfined compressive tests. These samples were prepared by adding 2% rubber fibers and 0.2% polyethylene and polypropylene fibers to the clayey soils. To obtain the maximum reinforcements from reinforced samples, it was necessary to increase sample dimensions depending on increasing fiber lengths in the reinforced samples (Figs. 11–13).

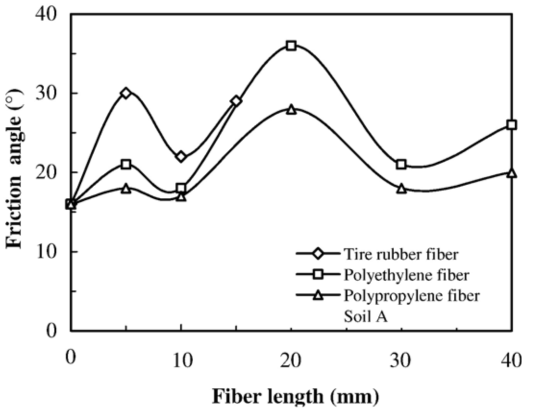

Fig. 15. Variation of the internal friction angle with fiber length of tire rubber, polyethylene, and polypropylene.

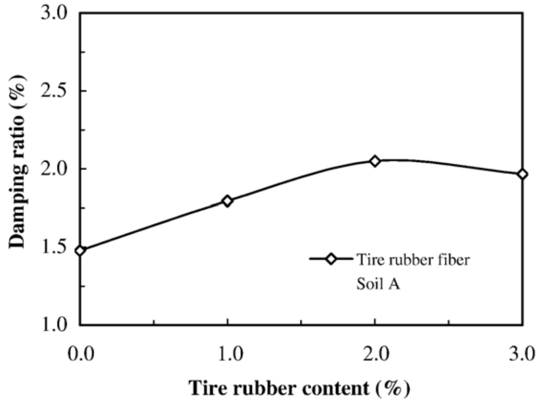

Fig. 16. The effect of scrap tire rubber fibers on the damping ratio.

The maximum *UCS* values were obtained for 0.2% samples reinforced with polypropylene fibers as 236 kPa, which is 2.78 times higher than that of reinforced samples with 50-mm diameter and 100-mm length. As seen in Figs. 11–13, the increase in the *UCS* values of reinforced samples carried on with increase in the fiber length up to 10-, 15-, and 30-mm fiber length for reinforced samples with 35-, 50-, and 80-mm diameters, respectively. In addition, the *UCS* value of each sample dimension decreased at the longer fibers than these fiber lengths. The decrease in the *UCS* value for each sample dimension might be due to the increase in the amount of fiber particles that are associated with the top of the cylindrical sampler because of the longer fibers and the smaller cylindrical sampler. A problem

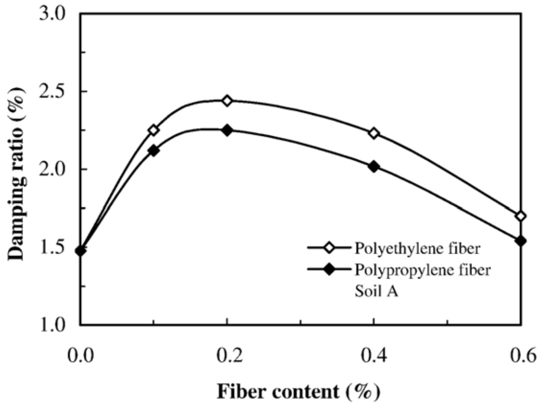

Fig. 17. The effect of polyethylene and polypropylene fibers on the damping ratio.

arose during pushing the cylindrical sampler into the compacted reinforced soil samples because the fibers along the advancing edge of the cylindrical sampler were dragged through the reinforced samples. Therefore, the voids and striations arising from fibers occurred on the sample surface. Because of these voids and striations, the *UCS* values of the reinforced samples may have been decreased.

4.4. Effect of scrap tire rubber and synthetic fibers on the shear strength parameters

The shear box tests showed that the cohesion and internal friction angle values increased by the addition of tire rubber, polyethylene, and polypropylene fibers (Figs. 14 and 15). The maximum cohesion values of reinforced samples were observed for 30-mm fibers as 219 kPa, which is 1.2 times more than that of the unreinforced samples. The increase in the cohesion of reinforced samples might be due to the increase in the confining pressure due to the development of tension in the fiber, and the moisture content in the fiber favors formation of absorbed water layer on the clay particles, which enables the reinforced soil to act as a single coherent matrix of soil–fiber mass (Prabakar and Sridhar, 2002). As seen in Fig. 15, the variation of internal friction angle with tire rubber, polyethylene, and polypropylene fiber contents showed a non-linear variation. In general, the internal friction angle value of each reinforced sample increased, and these values ranged from 17° to 36°. The variation of cohesion and internal friction angle with tire rubber, polyethylene, and polypropylene fiber contents was a non-linear variation because the reinforcement materials exhibited a distribution with horizontal and vertical directions to the shear surface.

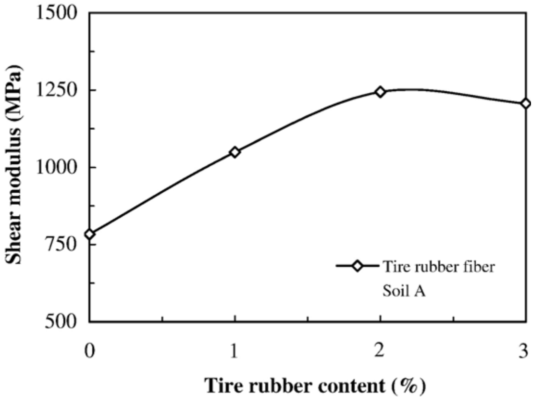

Fig. 18. The effect of scrap tire rubber fibers on the shear modulus.

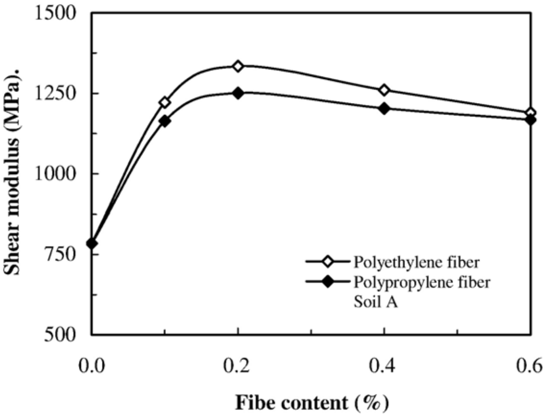

Fig. 19. The effect of polyethylene and polypropylene fibers on the shear modulus.

4.5. Effect of scrap tire rubber and synthetic fibers on the dynamic behaviors of soils

The damping ratio values of unreinforced and reinforced samples were calculated from the resonant frequency tests. Both the tire rubber and synthetic (polyethylene and polypropylene) fibers increased the damping ratio of reinforced samples. The damping ratio of each reinforced sample increased when compared to those of unreinforced sample (Figs. 16 and 17). The damping ratio of reinforced samples with tire rubber fiber increased with increasing scrap tire rubber fiber contents up to 2% and then decreased slightly. The maximum damping ratio was observed for 2% tire rubber content of 10-mm fibers as 2.05%, which was 1.4 times more than that of unreinforced sample (Fig. 16). Both the polyethylene and polypropylene fibers increased damping ratio of reinforced samples. The damping ratio of reinforced samples with polyethylene and polypropylene fiber increased with the fiber content up to 0.2% and then decreased slightly. The maximum damping ratio values of reinforced samples with polyethylene and polypropylene fibers were obtained for 0.2% fiber content of 10-mm fibers as 2.43% and 2.25%, which were 1.6 and 1.5 times higher than that of the unreinforced sample.

The shear modulus values of unreinforced and reinforced samples were also calculated from the resonant frequency tests. The shear modulus of the reinforced samples increased due to the adding waste fibers (Figs. 18 and 19). It was observed that by increasing the tire rubber fiber content, the shear modulus value of reinforced sample increased up to 2% 10-mm fibers and then decreased slightly. The shear modulus of the polyethylene and polypropylene reinforced samples had a maximum at 0.2%. The maximum shear modulus values of reinforced samples with tire rubber, polyethylene and polypropylene fibers were obtained in 2% fiber content of 10-mm fiber, in 0.2% fiber content of 15-mm fiber, and in 0.2% fiber content of 15-mm fiber as 1243, 1334, and 1251 MPa, which are 1.6, 1.7 and 1.6 times higher than that of unreinforced samples for reinforced samples with tire rubber, polyethylene, and polypropylene fibers, respectively.

The design of geotechnical engineering problems that involve dynamic loading of soils and soil-structure interaction systems requires the determination of two important parameters, the damping and the shear modulus of the soils. Dynamic analyses to evaluate the response of earth structures to dynamic stress applications produced by earthquakes or machine vibrations are conducted to assess and mitigate the risk of possible earthquake hazards in geotechnical practice (Lo Presti et al., 1997; Amini, 1999; Assimaki et al., 2000; Sitharam et al., 2004). The resonant frequency tests in this paper indicate that the use of randomly distributed waste fibers at optimum fiber levels improves the damping and the shear modulus of clayey soils. The modification of clayey soils by the scrap tire rubber and synthetic fibers can be a viable and innovative method to raise the response of earth structures to dynamic stress applications. These observations can be useful for soil scientists in order to mitigate possible earthquake hazards in the geotechnical applications.

5. Conclusions

- Both lengths and contents of the rubber fibers played an important role in the development of the *UCS* of the reinforced samples. In general, the *UCS* values increased with increasing tire rubber fiber contents up to 2% and then decreased. Both the length and the content of synthetic fibers improved the *UCS* values. The polyethylene and polypropylene fibers increased the *UCS* values for all contents with a maximum at 0.2%.
- For maximum improvement of the *UCS* values, the fiber length has to be increased with the sample dimension. The *UCS* values of all samples significantly increased with fiber contents at optimum fiber length.
- In general, tire rubber and synthetic fibers increased the cohesion values. The maximum cohesion values were observed for 10-mm long fibers. The internal friction angle value of each reinforced sample increased in a non-linear way.
- The tire rubber, polyethylene, and polypropylene fibers increased damping ratio and shear modulus. The maximum values were observed for 2% tire rubber fibers of 10-mm length and 0.2% polyethylene and polypropylene fibers of 15 mm.
- The *UCS* values of all reinforced samples obtained from the tests may have been underestimated. The real improvement in the *UCS* may be higher.
- The waste fibers such as scrap tire rubber, polyethylene, and polypropylene fibers can be used to improve the strength and dynamic behavior of clayey soils in geotechnical applications. In addition, these reinforcement fibers are waste materials, so the soil stabilization with waste fiber can potentially reduce stabilization costs.

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References

Abu-Zreig, M.M., Al-Akhras, N.M., Atom, M.F., 2001. Influence of heat treatment on the behavior of clayey soils. Applied Clay Science 20 (3), 129–135.

Aitcin, P.C., Ballivy, G., Parizeau, R., 1984. The use of condensed silica fume in grouting. Innovative cement grouting. Publication SP-83, ACI Detroit MI, USA, pp. 1–18.

Akbulut, 1999. Improvement of geotechnical properties of granular soils by grouting. PhD Thesis (in Turkish), The Institute of The Technical University of Istanbul, Turkey.

Akbulut, S., Hasiloglu, A.S., Pamukcu, S., 2004. Data generation for shear modulus and damping ratio in reinforced sands using adaptive neuro-fuzzy inference system. Soil Dynamics and Earthquake Engineering 24, 805–814.

Amini, F., 1999. Effect of time on dynamic properties of cohesive soils using improved transfer function estimators. Soil Dynamics and Earthquake Engineering 18, 457–461.

Asavasipit, S., Nanthamontry, W., Polprasert, C., 2001. Influence of condensed silica fume on the properties of cement based solidified wastes. Cement and Concrete Research 31, 1147–1152.

Assimaki, D., Kausel, E., Whittle, A., 2000. Model of dynamic shear modulus and damping for granular soils. Journal of Geotechnical and Geoenvironmental Engineering 126 (10), 859–869.

Atom, M.F., Al-Sharif, M.M., 1998. Soil stabilization with burned olive waste. Applied Clay Science 13 (3), 219–230.

Celik, O.N., 1996. The engineering properties and fatigue behavior of asphaltic concrete made with waste thread tire rubber modified binders. PhD. Dissertation, the University of Leeds, London.

Cetin, H., Fener, M., Gunaydin, O., 2006. Geotechnical properties of tire-cohesive clayey soil mixtures as a fill material. Engineering Geology 88 (1–2), 110–120.

Charan, H.D., 1995. Probabilistic analysis of randomly distributed fiber reinforced soil. Ph. D. Thesis, Department of Civil Engineering, University of Roorkee, Roorkee, India.

Chen, F.H., 1988. Foundations on Expansive Soils. Elsevier.

Crockford, W.W., Grogan, W.P., Chill, D.S., 1993. Strength and life of stabilized layers containing fibrillated polypropylene. Transformation Research Record 1418, TRB. National Research Council, Washington, C. C., pp. 60–66.

Gray, D.H., Maher, M.H., 1989. Admixture stabilization of sand with discrete randomly distributed fibers. Proceedings of XII International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil, vol. 2, pp. 1363–1366.

Gray, D.H., Ohashi, H., 1983. Mechanics of fiber reinforcing in sand. Journal of Geotechnical Engineering Division, ASCE 109 (3), 335–353.

Gregory, G.H., Chill, D.S., 1998. Stabilization of earth slope with fiber reinforcement. Proceedings 6th International Conference on Geosynthetics, Atlanta.

Hausmann, M.R., 1990. Engineering Principles of Ground Modification. McGraw-Hill, New York.

Hernandez-Olivares, F., Barluenga, G., Bollati, M., Witoszek, B., 2002. Static and dynamic behaviour of recycled tire rubber-filled concrete. Cement and Concrete Research 32, 1587–1596.

Hoare, D.J., 1979. Laboratory study of granular soils reinforced with randomly oriented discrete fibers. Proceedings of International Conference on Soil Reinforcement, Paris, France, vol. 1, pp. 47–52.

Hoover, J.M., Moeller, D.T., Pıtt, J.M., Smıth, S.G., Wainaina, N.W., 1982. Performance of randomly oriented fiber reinforced roadway soils. Iowa DOT Project-HR-211. Department of Transportation.

Kalkan, E., 2003. The improvement of geotechnical properties of Oltu (Erzurum) clayey deposits for using them as barriers. PhD Thesis (in Turkish), Ataturk University, Graduate School of Natural and Applied Science, Erzurum, Turkey.

Kalkan, E., 2006. Utilization of red mud as a stabilization material for preparation of clay liners. Engineering Geology 87 (3–4), 220–229.

Kalkan, E., Akbulut, S., 2004. The positive effects of silica fume on the permeability, swelling pressure and compressive strength of natural clay liners. Engineering Geology 73, 145–156.

Kaniraj, S.R., Havanagi, V.G., 2001. Behavior of cement-stabilized fiber-reinforced fly ash–soil mixtures. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 127 (7), 574–584.

Kayabali, K., 1997. Engineering aspects of a novel landfill liner material: bentonite-amended natural zeolite. Engineering Geology 46, 105–114.

Lo Presti, D.C.F., Jamiolkovski, M., Pallara, O., Cavallaro, A., Pedroni, S., 1997. Shear modulus and damping of soils. Geotechnique 47, 603–617.

Maher, M.H., 1988. Static and dynamic response of sands reinforced with discrete randomly distributed fibers. Ph. D. Thesis, University of Michigan, Arbor, USA.

Maher, M.H., Gray, D.H., 1990. Static response of sands reinforced with randomly distributed fibers. Journals of Geotechnical Engineering Division, ASCE 116 (11), 1661–1667.

Makiuchi, K., Minegishi, K., 2001. Strain-induced toughness and shearing characteristics of short-fiber reinforced soils. Landmarks in earth reinforcement. In: Ochiai, H., et al. (Ed.), Proceedings of the International Symposium on Earth Reinforcement, vol. 1. Balkema Publishers, Fukuoka, Japan, pp. 83–88.

Musenda, C., 1999. Investigation of the effects of using discrete randomly distributed fiber reinforcement in expansive foundation soils. Master's Thesis University of Texas at Arlington.

Nataraj, M.S., McManis, K.L., 1997. Strength and deformation properties of soils reinforced with fibrillated fibers. Geosynthetics International 4 (1), 65–79.

Nelson, J.D., Miller, D.J., 1992. Expansive Soils: Problems and Practice in Foundation and Pavement Engineering. John Wiley and Sons, Inc., New York.

Park, T., Tan, S.A., 2005. Enhanced performance of reinforced soil walls by the inclusion of short fiber. Geotextiles and Geomembranes 23 (4), 348–361.

Park, J.K., Kim, Y.J., Madsen, C.D., Edil, T.B., 1997. Retardation of volatile organic compound movement by a soil-bentonite slurry cutoff wall amended with ground tires. Water Environment Research 69 (5), 1022–1031.

Pierce, C.E., Blackwell, M.C., 2003. Potential of scrap tire rubber as lightweight aggregate in flowable fill. Waste Management 23, 197–208.

Prabakar, J., Sridhar, R.S., 2002. Effect of random inclusion of sisal fibre on strength behavior of soil. Construction and Building Materials 16, 123–131.

Prabakar, J., Dendorkar, N., Morchhale, R.K., 2003. Influence of fly ash on strength behavior of typical soils. Construction and Building Materials.

Puppala, A.J., Musenda, C., 1998. Investigation of geofiber reinforcement method on strength, swell, and shrinkage characteristic of soils. Presented at Fifth International Conference on Composites Engineering, Las Vegas.

Puppala, A.J., Musenda, C., 2002. Effects of fiber reinforcement on strength and volume change in expansive soils. Transportation Research Record, Paper No: 00–0716, pp. 134–140.

Ranjan, G., Vasan, R.M., Charan, H.D., 1996. Probabilistic analysis of randomly distributed fiber-reinforced soil. Journals of Geotechnical Engineering Division, ASCE 122 (6), 419–426.

Sacan, M., 2002. Fibers Chemistry. Gazi Publication, Ankara, Turkey.

Sandra, T., Jeffrey, C.E., 1992. The effects of filler and admixtures on grout performance. Grouting, Soil Improvement, and Geosynthetics, vol. 1. Geotechnical Engineering Division of ASCE, USA, pp. 337–349.

Santoni, R.L., Tingle, J.S., Webster, S.L., 2001. Engineering properties of sand–fiber mixtures for road construction. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 127 (3), 258–268.

Setty, K.R.N.S., Rao, S.V.G., 1987. Characteristics of fiber reinforced lateritic soils. Proceedings of the Indian Geotechnical Conference, Bangalore, India, vol. 1, pp. 329–333.

Sitharam, T.G., GovindaRaju, L., Sridharan, A., 2004. Dynamic properties and liquefaction potential. Geotechnics and Earthquake Hazards 87, 1370–1378.

Steinberg, M., 1998. Geomembranes and the Control of Expansive Soils in Construction. McGraw-Hill, New York.

Terzano, R., Spagnuolo, S., Medici, L., Tateo, F., Ruggiero, P., 2005. Zeolite synthesis from pre-treated coal fly ash in presence of soil as a tool for soil remediation. Applied Clay Science 29 (2), 99–110.

Vidal, H., 1969. The principle of reinforced earth. Highway Research Record No: 282, 1–16.

Yarbaşı, N., Kalkan, E., Akbulut, S., 2007. Modification of freezing–thawing properties of granular soils with waste additives. Cold Regions Science and Technology 48, 44–54.

Yetimoglu, T., Salbas, O., 2003. A study on shear strength of sands reinforced with randomly distributed discrete fibers. Geotextiles and Geomembranes 21, 103–110.