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Experimental Investigation on the Variation in Shear Strength of Clayey Soil Reinforced with Randomly Distributed Alkali-Resistant Glass Fiber

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Abstract

Geotechnical investigations are one of the most crucial parts of the construction to save the time and effort spent on the projects. Particularly, in the case of the clays with high plasticity are encountered, the analysis of bearing capacity and settlement of structures such as buildings, roads, and dams governs the design. The possible solutions can be leaving the land, reaching a strong soil bypassing the weak one, removing the weak soil by replacing it with a higher strength of the material, and applying soil improvement methods. Glass fibers are one of the synthetic additives which may be used to address improving the weak soil properties. In this study, the effect of alkaline-resistant glass fiber additive on the undrained shear strength of the clayey soils was investigated. Fibers with distinct lengths were added to the natural soil at increasing rates, and the mixtures were prepared in the optimum water content. The prepared mixtures were compacted in a compaction mold with a diameter of 50 mm and a height of 100 mm with standard energy. Unconfined compression test (UC) were conducted on a total of 210 cylindrical samples, 10 of natural clay and 200 of fiber-reinforced. The maximum increase was at 0.5% of a fiber blend of 40 mm length. As a result of 210 UC tests, it was observed that the alkaline-resistant glass fiber additive increased the shear strength of the clay soil.

Keywords: Alkaline-resistant glass fiber, soil improvement, undrained shear strength, Unconfined compression test.

1. INTRODUCTION

The desired situation in soil stabilization is to increase the strength by reducing the void ratio in the existing soil with the necessary equipment and closing these voids with additives. Soil improvement and stabilization methods can be divided into three groups. These are temporarily effective, permanent effective without additive to the soil, and permanent effective with additives [1]. In the solution of stability problems such as soil liquefaction, settlement problem, bearing capacity problem, different shallow soil improving methods are used instead of deep stabilization methods due to economic requirement and application difficulty. Among these methods, the most widely used method is adding natural and artificial substances as

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external additives. We can distinguish synthetic fibers as glass and polymer fibers used in the petrochemical industry among these additives. Fibers are substances that can be bent and obtained from natural resources with strength or produced industrially by human hands with desired properties [2]. The production of glass fiber and various products dates back to ancient times. Although Rene Ferchault de Reaumur produced glass fiber in 1734, its fabrication took place in the late 18th century. The reason for this is that Reaumur had difficulty in weaving these fine glass fibers such as silk [3]. Glass material, which is the main product in the manufacture of glass fibers, is in the form of lime or soda silicate, or borax silicate. Glasses are complex mixtures of alkali and alkaline earth silicates containing borate and aluminate. Since the ratio of the additives added to the glass changes, the chemical structure of the glass fibers becomes uncertain. As a general rule, the ratios of sodium carbonate, calcium carbonate, aluminum-hydroxide, magnesium-silicon, and boric acid can be counted.

Although the elongation ability and friction resistance of glass, which is a fiber type, is not high, it is used as an additional product in plastic products as an insulating material for heat and electricity. It shows that it is important to use glass fibers in X-ray and radiation isolation, protective materials against fires such as awnings and curtains, oil tanker ships, filtration, impermeability of chemical substance pipes, coating of various boilers and cables, underground insulation, coating of building elements in dust and smoke filters, packaging papers, the automotive industry, in parts of boats, tanks and planes, in rocket and aerospace industries. With the Covid-19 pandemic, a separate bracket can be opened to use glass fiber in surgical masks.

It is known that glass powders and fibers have positive effects when used in concrete applications and cement-based composites [4]. It is known that the water-retaining fibers when the concrete is wet prevent shrinkage cracks as a result of curing as the concrete begins to set, and thus prolongs the life of the concrete by protecting it against chemicals. Due to the disadvantage of alkalinity, additional studies of glass fiber with high alkali resistance were carried out to prevent segregation in concrete. Although it is seen that glass powder studies are carried out in soil stabilization, it is seen that the number of works with alkali-resistant (ACR) glass fiber is not sufficient.

In this paper, the effect of glass fiber additive on the undrained shear strength of clay soil was investigated. In this experimental study, the physical properties of the clay soil obtained from Sapanca district of Sakarya province were determined. Fibers were cut into 10 mm, 20 mm, 30 mm, and 40 mm lengths. Fibers with different lengths were added to the natural soil at the rates of 0.25%, 0.5%, 1%, 1.5%, and 2% by dry weight, and the mixture was prepared in the optimum water content of the soil. The prepared mixtures were compacted in a compaction mold with standard energy. The compacted cylindrical samples with a diameter of 50 mm, a height of 100 mm were obtained. A total of 210 cylindrical samples, 10 of them formed from natural clay and 200 produced by mixing soil with glass fiber, were tested in Unconfined Compression (UCS) device to simulate rapid loading conditions.

2. LITERATURE REVIEW

When soil reinforcement with natural and artificial additives is examined in the literature, it is seen that there are sufficient studies [5]. Among the studies with different reinforcement materials, Diallo and Ünsever [6] determined that the strength of the soil can be increased while construction debris waste and lime were used as reinforcement materials in different percentages. Reinforcement was applied by adding 2% lime and construction debris at rates ranging from 5% to 35% with increasing rates of 5% to the soil. In the study, sieve analysis and Atterberg limit tests were carried out, and optimum water content was calculated as a result of compaction. Soil samples with 38 mm x 76 mm dimensions were prepared in the optimum water content and subjected to unconfined compression tests after curing for 3, 7, and 28 days. It was determined that the best stabilization was obtained for the samples mixed with 2% lime and 20% construction debris.

On the other hand, Bilgen [9] examined the behavior of bentonite clay reinforced with 3, 5, 10, 20, and 25% of glass powder by dry weight of the soil through modified Proctor, unconfined compression and California bearing ratio (CBR) tests. While the strength of the natural bentonite clay cured for 28 days was 178 kPa, the 28-day strength of the 25% of glass powder added sample strength increased by 450% and became 795 kPa. It was observed that the CBR is increased by 400%. It has been reported that with the addition of glass powder, the water content decreased, the dry unit weight increased, and the CBR and unconfined compression values significantly increased.

In a study conducted by Maraşlı [4], 0, 1, 2, and 3% glass fiber reinforced concretes were prepared to form the estimation model of flexural and compressive strength using the maturity index method. The temperature sensors were placed in the compressive and flexural strength test samples, and by using the temperature measurements at 0.5, 1, 1.5, 2, 3, 5, 7, 14, 28, and 56 days, the maturity index values were found. Although it was observed that the concretes with 2% glass fiber added reached the maximum compressive strength, decreases were detected in the compressive strength of the concretes with 3% glass fiber addition. The maximum flexural strength was obtained in the case of the soil mixed with 3% glass fiber. The flexural strength of the 28-day fiber-concrete mixture increased by 55% compared to the fiberless concrete. As the concrete age progressed, the flexural strength values increased. Through the results obtained in the study, the necessary correlations were derived.

3. MATERIALS AND METHODS

3.1. Clayey Soil

Soil samples used in the study were obtained from the Sapanca district of Sakarya province (Figure 1). The physical properties of the soil given in Table 1 were determined as a result of the index and mechanical tests on the soil. The grain size distribution curve of the soil, in which the maximum grain size is 2 mm, is shown in Figure 2. The class of clayey soil was determined as CH (high plasticity clay) according to both TS 1500/2000 [10] and USCS [11] standards.

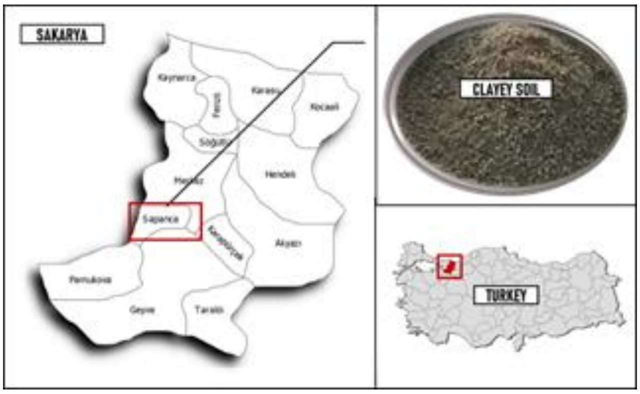

Figure 1 The sampling area and clayey soil used in the study

Table 1
Physical properties of the soil

Property	Value	Unit
-No 200	99.98	%
Liquid limit (LL)	72.00	%
Plastic limit (PL)	30.49	%
Plasticity index (PI)	41.51	%
Maximum dry unit weight ($\rho_{k,maks}$)	14.80	kN/m^3
Optimum water content (w_{opt})	25.00	%
Specific gravity (G_s)	2.65	-
Soil class: CH (according to TS 1500/2000 and the USCS) [10, 11]		

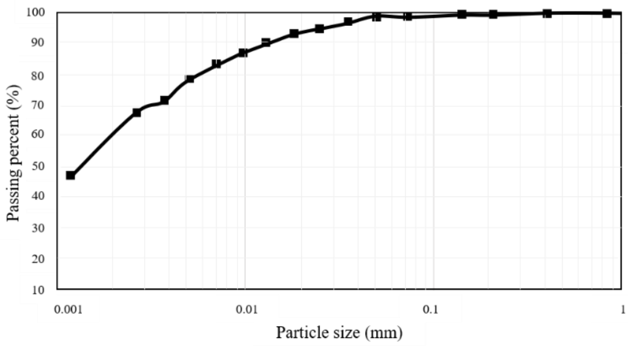

Figure 2 Particle size distribution of the soil

3.2. Glass Fiber

The high alkali-resistant glass fiber used in the study are produced by Nippon Electric Glass firm and was taken from Fibrobeton Structural Element company. Glass fiber samples and SEM images are presented in Figure 3. The properties of glass fiber are presented in Table 2. The glass fiber was cut into 10 mm - 20 mm - 30 mm, and 40 mm lengths. Filament diameters are 13.5 μm [12].

3.3. Sample Preparation and Test Process

In the experimental study, tests were carried out on natural clay and glass fiber reinforced clay samples. The fiber length, ratio, and weights used for a sample prepared in accordance with the geotechnical parameters are shown in Table 3.

To determine the shear strength of the high plasticity clay soil mixtures, they were prepared at the optimum water content obtained by the compaction test. The samples were kept in the refrigerator with nylon bags to avoid losing their water content. Compacted soil-fiber mixtures were hydraulically driven into thin-walled steel tubes with a diameter of 50 mm and a height of 100 mm. Due to the thickness and rigidity of the fiber, disturbances and ruptures occurred while the soil-fiber mixture was inserted into the steel tubes [13]. In other words, the fibers collected at the end of the thin-walled steel tube caused cracks in the sample. Decreases were observed in the unconfined compressive strength of the samples prepared without adding fiber. To get rid of this disadvantage, a specially made mold was used. The natural clay sample was mixed with the fiber ratios specified in Table 3, followed by the fiber amount. 25% of water was added to the mixture, and the mixture was compacted in special molds with an energy equivalent to twice the standard Proctor energy. In our special mold, to remove the cold joint disadvantage, which is in three stages, and allow it to behave as a whole in a monolithic structure, the compaction process was carried out by making equal numbers of drops from the lower and upper heads.

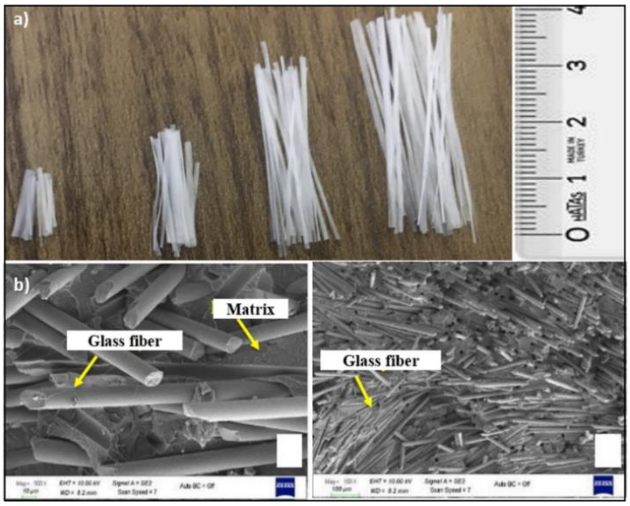

Figure 3 Glass fiber a) In different lengths used in this study b) SEM images [14]

Table 2
Physical and chemical properties of the glass fiber [4]

ACR Glass Fiber		
Physical Properties	Appearance	White – solid
	Smell	Odorless
	Melting point	820 °C
	Solubility in water	Unsoluble
	Specific density	2.8 kg/lt
	Stability	Stable in normal conditions
	Number of tex	2543
	Moisture content	%0.04
	Tensile strength	0.494 N/tex (min 0.245)
	Loss of glow	%1.22
	ZrO_2 content	%17.2
Chemical Properties	Component	Content (%)
	SiO_2	54-65
	ZrO2	16-2
	RO (MgO+Cao)	0-10
	MgO	-
	CaO	-
	TiO_2	1-7
	Al_2O_3	0-2
	R_2O ($LiO+Na_2O+K_2O$)	10-30
	Li_2O	-
	Na_2O	-
	K_2O	-

Table 3
Sample properties

No	Description of the sample	Diameter (mm)	Soil (g)	Fiber (g)	Fiber length (mm)	Fiber content (%)
1	Natural soil	50	300	0	0	0
2	%0.25 ACR fiber reinforced clay	50	300	0.75	10	0.25
3	%0.5 ACR Fiber reinforced clay	50	300	1.5		0.5
4	%1 ACR Fiber reinforced clay	50	300	3		1
5	%1.5 ACR Fiber reinforced clay	50	300	4.5		1.5
6	%2 ACR Fiber reinforced clay	50	300	6		2
7	%0.25 ACR Fiber reinforced clay	50	300	0.75	20	0.25
8	%0.5 ACR Fiber reinforced clay	50	300	1.5		0.5
9	%1 ACR Fiber reinforced clay	50	300	3		1
10	%1.5 ACR Fiber reinforced clay	50	300	4.5		1.5
11	%2 ACR Fiber reinforced clay	50	300	6		2
12	%0.25 ACR Fiber reinforced clay	50	300	0.75	30	0.25
13	%0.5 ACR Fiber reinforced clay	50	300	1.5		0.5
14	%1 ACR Fiber reinforced clay	50	300	3		1
15	%1.5 ACR Fiber reinforced clay	50	300	4.5		1.5
16	%2 ACR Fiber reinforced clay	50	300	6		2
17	%0.25 ACR fiber reinforced clay	50	300	0.75	40	0.25
18	%0.5 ACR Fiber reinforced clay	50	300	1.5		0.5
19	%1 ACR Fiber reinforced clay	50	300	3		1
20	%1.5 ACR Fiber reinforced clay	50	300	4.5		1.5
21	%2 ACR Fiber reinforced clay	50	300	6		2

Considering the ram weight and fall height data used in the Standard Proctor test, sixteen drops of the ram were calculated from the same formula for a mold volume of 196.35 cm^3. A total of thirty-two drops of ram were made by making sixteen drops from the upper and lower heads of the mold.

Unconfined compression tests were carried out after measuring the sample dimensions removed from the molds. To increase the reliability of the test results conducted on natural and glass fiber added mixtures, ten identical samples were prepared, and each of them was tested. The series was completed by mixing 10 mm - 20 mm - 30 mm and 40 mm long ACR glass fibers into the natural soil at 0.25, 0.5, 1, 1.5 and 2% by weight. The gap between the force bar and the upper plate was taken by placing the sample so that the top and bottom parts of the sample were in the center of the unconfined compression device. The maximum shear strength measurement was obtained by taking the readings until 14% strain or until the failure occurred. The failed sample was kept in an oven for 24 hours and recorded by weighing.

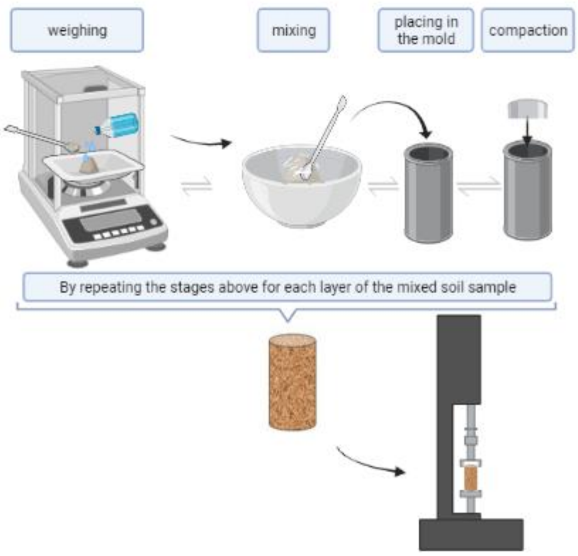

Figure 4 The test procedures followed

4. RESULTS AND DISCUSSIONS

The appearance of the natural and alkali-resistant glass fiber added samples after the unconfined compression test is given in Figure 5. While brittle failure and diagonal failure planes were observed in the natural samples as the fiber ratio and length increased, a significant decrease was observed in the failure surface and the increase in strength.

As shown in Figure 5, local disintegration was prevented in all reinforced samples, and fiber's adherence-increasing effect became more profound. Although there are local cracks, diagonal failure surfaces were not observed in the fiber-reinforced soils.

The results obtained from 210 unconfined compression tests (Figure 6) are shown in the graphs. The strength of 50 mm x100 mm samples increased in all lengths and ratios, and this increase was 135.47% on average. It was determined that the highest increase in strength was in 0.5% fiber reinforced samples with 40 mm length. With the fiber additive, it is easy for the soils to come out of the mold, and it is seen that the diagonal failure surface disappears.

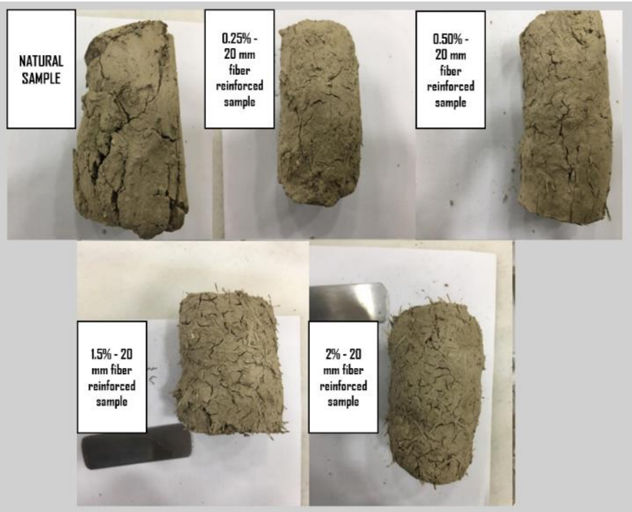

Figure 5 The failure of natural and fiber reinforced samples

Figure 6 The oven dried samples after the tests

In Table 4, the average maximum axial stresses and average strength increases of the 50 mm ×100 mm sample series obtained with different lengths of ACR glass fiber and the percentage prepared are shown. An increase in the maximum stress up to 351.95% and an average increase of 135.47% in the undrained shear strength were measured for the fiber-reinforced samples.

As seen in Figure 7, the strain value of the natural clay was found constant at 14%, while the stress value was around 20 kPa. Since it is soft clay, it was much more tiring to take shape compared to fiber-reinforced samples. It was observed from Figure 7 that the failures were evident in the natural clay and local separations took place in the clay. In addition, the significant increase in strength at the rate of 0.25% fiber was obtained with its maximum value at 12% strain, and there was an increase of approximately two times in the stress value. In 0.5% fiber reinforced soil, the axial stress increased by about 1.80% with displacement in the 12% band, approximately 2.5 times against 10-12% deformation in 1.5% fiber reinforced samples, it progresses steadily in the same displacement band in 2% fiber soil, and the stress increases approximately 2.14 times. Likewise, it was observed that the highest stress was observed in 1% fiber soil with an increase of roughly three times, and the strain value corresponding to the most significant stress was in the range of 12%.

Table 4
Strength increases with glass fiber reinforcement

Fiber length (mm)	Fiber Content (%)	$\sigma_{d\ max.avg.}$ (kPa)	Strength increase (%)	Fiber length (mm)	Fiber Content (%)	$\sigma_{d\ max.avg.}$ (kPa)	Strength increase (%)
-	-	16.88	-	30	0.25	31.20	84.83
10	0.25	25.23	49.47	30	0.50	41.30	144.67
10	0.50	36.33	115.23	30	1.00	60.03	255.63
10	1.00	30.64	81.52	30	1.50	51.07	202.55
10	1.50	26.94	59.60	30	2.00	46.33	174.47
10	2.00	25.64	51.90	40	0.25	43.76	159.24
20	0.25	34.46	104.15	40	0.50	76.29	351.95
20	0.50	31.20	84.83	40	1.00	39.14	131.87
20	1.00	51.24	203.55	40	1.50	26.85	59.06
20	1.50	41.28	144.55	40	2.00	39.88	136.26
20	2.00	36.15	114.16				

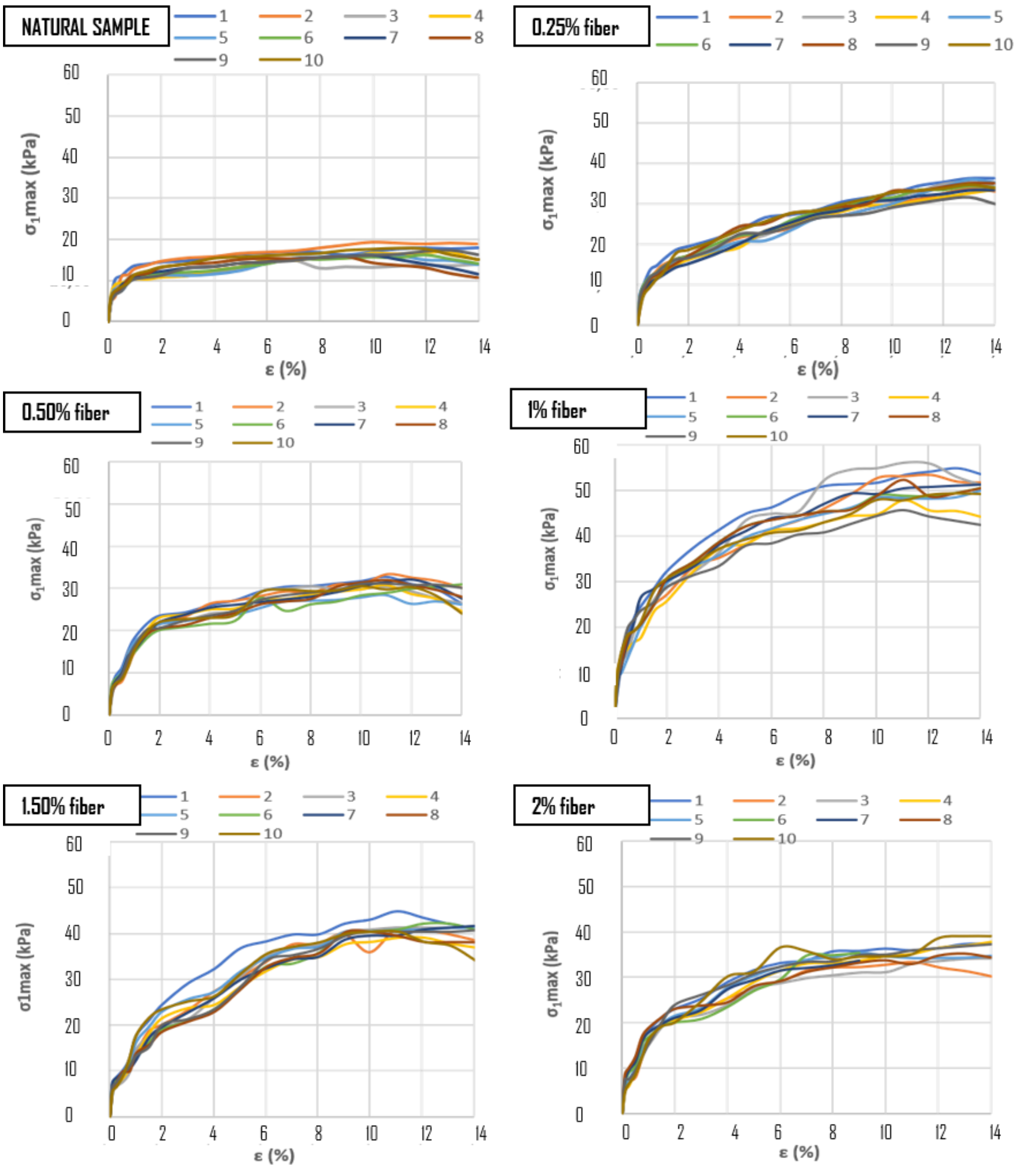

Figure 7 Test results of natural and 20 mm length fiber-reinforced soil samples

Figure 8 (a) shows the relationships between the maximum axial stresses and the strength increase ratios, depending on the glass fiber length and ratio. As reported, clay samples with 1% fiber added show the highest tensile and strength increases at 10 mm, 20 mm, and 30 mm fiber lengths, while the lowest values at 0.25% fiber lengths were obtained. In 40 mm fiber, unlike the others, at 0.5% fiber content, maximum stress, and at 1.5% fiber content, minimum stress was achieved. If we consider 50 mm diameter samples, in general, the ideal length of 30 mm can be selected in all proportions.

If the stresses shown in Figure 8 (b), depending on the fiber ratio, are examined, it is seen that the most significant stress increases were obtained at 1% fiber content in all lengths of fiber except 40 mm. After this ratio, it was seen that there is a decrease in strength as the amount of fiber increases. When the soils subjected to the test are examined, it is seen that the maximum strength was achieved with the increase in fiber length. It has been observed that samples with 20 mm fiber length behave like 30 mm samples.

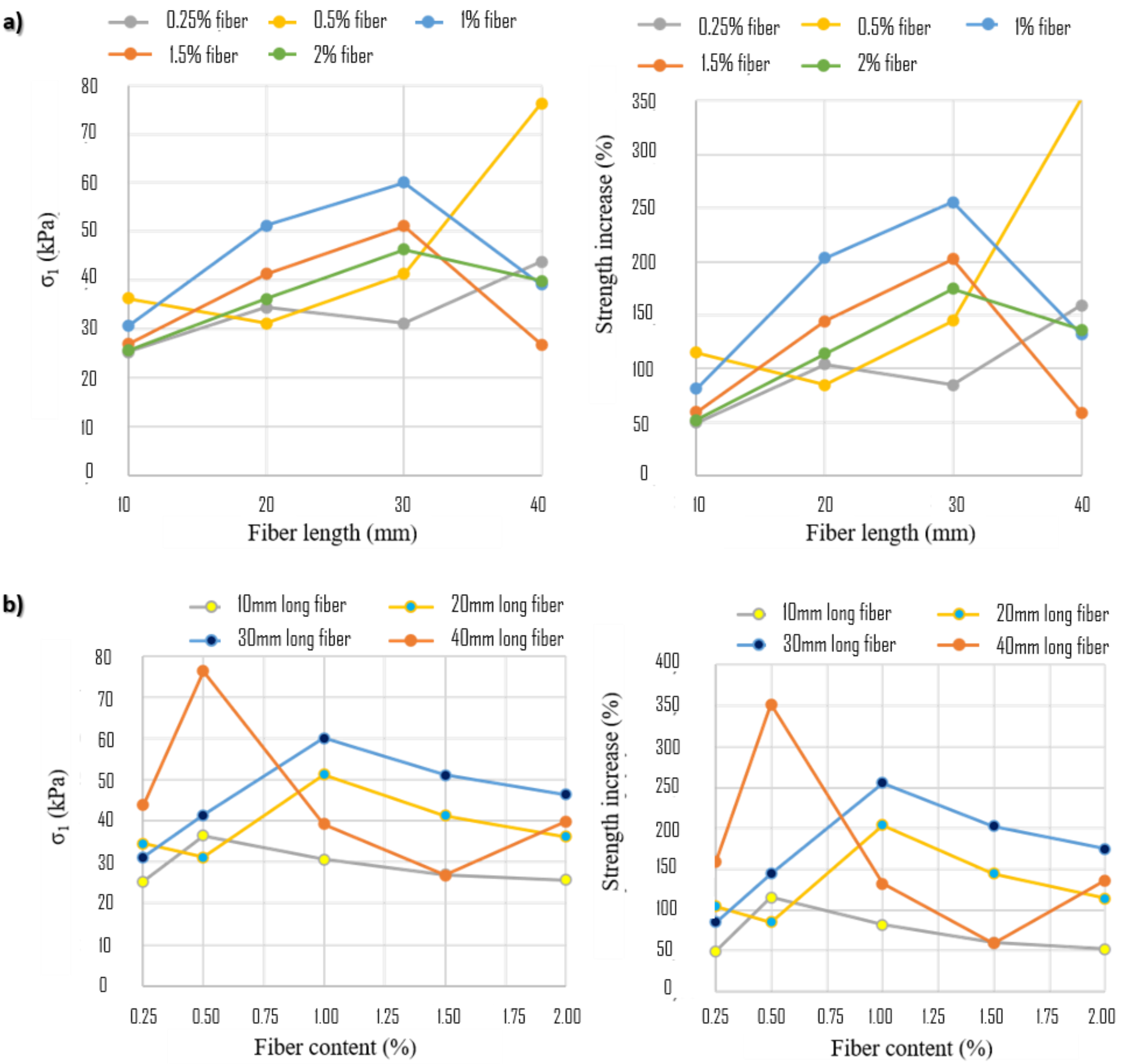

Figure 8 Test results of natural and 20 mm length fiber reinforced soil sample

5. CONCLUSIONS

In the experimental study, cylindrical samples with a diameter of 50 mm and height of 100 mm were prepared by adding 0.25, 0.5, 1, 1.5, 2 weight percent of 10, 20, 30, and 40 mm long glass fiber of high alkali resistant. The specimens were not prepared with the standard compaction mold but were prepared using a special compaction mold. A total of 210 samples, 10 of which are natural and 200 of which are glass fiber reinforced, were tested in an unconfined compression device to find the undrained shear strength of the samples. It has been observed that adding glass fiber to the soil in different lengths and proportions can increase the shear resistance of the clayey soils.

It was concluded that glass fiber increases the ductility and undrained shear strength of clay soil. According to the test data, the highest increase in unconfined compressive strength was observed in samples with 50 mm ×100 mm dimensions, 40 mm in length, and 0.5% fiber added soil samples. Due to the small diameter of the compaction mold, the monolithic structure of the sample was destroyed in case of compaction in 3 layers. That's why two-sided compaction was applied at once in the study. While the failure was evident in the natural clay soil, this surface started to disappear with the increase in the fiber ratio. In other words, it has been determined that the glass fiber holds the soil samples by providing adherence.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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