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Effect of silica fume on the undrained strength parameters of dispersive soils

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Treatment
Strength

ABSTRACT

Dispersive soils are one of the problematic soils such as swelling and collapsible soils and they are common in many countries of the world. Due to dispersive soils, significant problems arise in road embankments and earth dams. Therefore, the use of such soils is possible with treatment. Silica fume (SF) as a waste material has been used in concrete production instead of partially cement, in the stabilization of expansive soils and in many civil engineering applications for different purposes. Within the scope of this study, to determine the dispersibility behavior of the soil sample, crumb test was performed. SF additive was used to improve the soil sample, which was determined to have high dispersibility. The compaction properties of the soil specimens mixed with SF in different proportions (0, 5, 10, 15, 20, 25 and 30%) were determined by the standard Proctor test. Crumb tests were performed to assess the dispersibility potential of the prepared specimens, and also unconsolidated and undrained (UU) triaxial tests were carried out to evaluate the strength parameters. UU experiments were performed under 20 kPa, 40 kPa and 60 kPa effective cell pressures on specimens cured for 1, 7 and 28 days because stabilization occurred at shallow depths in field applications. As a result, it was determined that the dispersibility feature of the soil sample was treated and the strength properties were improved depending on the SF content.

1. INTRODUCTION

Dispersive soils, which are not structurally stable, can be easily dispersed and eroded in the presence of water. When dispersive clay soils are used as building material in hydraulic structures, embankment dams and road embankments, they can cause serious problems and structural damage. Treatment of dispersive soils is usually done with chemical additives having different properties. This process eliminates the costs of transportation and material procurement that would occur when replacing problematic soil with quality material. Extensive studies have been carried out for many years to improve dispersive clay soils. Bhuvaneshwari et al. (2007) stated that dispersive soils can be improved by 5% lime or 2% lime and 15% fly ash additive. Savaş et al. (2018) showed that the use of 10% C class fly ash is sufficient for the improvement of dispersive soils. Using waste materials for the treatment of problematic soils can result in less pollution of nature and provide economic benefits. Many researches have been conducted on the use of silica fume (SF), which is an industrial waste material, as a substitute for cement in concrete production, especially in civil engineering applications. Liu et al. (2019) showed that the strength and freeze-thaw resistance of a pervious concrete lining material containing different amounts of SF (3%, 6%, 9% and 12%) instead of cement significantly increased. The positive effects of SF on concrete properties have been reported by many researchers (Zivica 2000; Wu et al. 2018; Sezer 2012). From the literature studies on the use of SF for soil stabilization, it is understood that the SF is used as an additive either alone or in combination with different additives such as lime and cement to improve the engineering properties of swelling soils (Kalkan and Akbulut 2004; Goodarzi et al. 2016; Türköz et al. 2018. For instance, Fattah et al. (2015) found that the bearing capacity of the square foundation built on a

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soft clay soil mixed with lime-silica fume increased, Al-Soudany (2017) stated that the expansive soil treated with SF showed low plasticity and low swelling pressure, Goodarzi et al. (2016) found that the additive of cement and SF caused a significant effect in the treatment of swelling soils., and Kalkan (2009) determined that SF admixture effectively reduced desiccation cracks of expansive clays. In the study conducted by Kalkan (2011), the effect of wetting-drying cycles on the swelling behavior of a clay soil modified with different percentages of SF (10%, 20%, 25%, and 30%) was investigated. The positive effect on the swelling percentage and swelling pressure of modified soil was observed in the samples prepared at 25% to 30% SF additive level. Topçu and Kaval (2001) also conducted a study on the economic analysis of the use of silica fume in concrete.

The use of industrial wastes as an engineering material for the improvement of problematic soils can lead to less pollution of the nature and also provides economic benefits. Although SF is used in many industries, there is not enough study about its potential effect on the treatment of dispersive soils. It is obvious that the performance of the silica fume additive used for shallow stabilization in engineering applications should also be addressed in dispersible soils.

2. MATERIAL and METHOD

Soil samples used in the tests were excavated from a depth close to the surface from Afyon province in Turkey. ASTM's (2007) standard methods were followed in sampling and sample preparation stages. Atterberg limits, sieve analysis, hydrometer, and specific gravity tests were carried out for the identification of the soil. From the results of the sieve analysis, it was determined that the soil contains 0% gravel, 23% sand, 46% silt and 31% clay. The soil sample having 51% liquid limit and 24% plasticity index values was classified as high plasticity clay (CH) according to the Unified Soil Classification System.

Silica fume was obtained from Antalya Electrometallurgy Corporation. The specific gravity of SF used in the study is 2.32. The chemical properties of the soil sample and silica fume used in the study are presented in Table 1. Chemical analyses presented within the scope of the study were performed at Eskişehir Osmangazi University Central Research Laboratory.

Table 1. Chemical properties of the soil and silica fume

Property	Silica Fume (%)	Soil (%)
SiO_2	66.92	52.27
MgO	9.52	1.68
K_2O	4.66	3.42
Na_2O	4.52	1.61
Cr_2O_3	3.48	-
Fe_2O_3	1.27	6.47
Al_2O_3	1.22	16.58
CaO	0.98	5.13
Loss of ignition	4.77	11.76

2.1. Preparation of Soil Specimens

The soil sample, which was taken from the field and brought to the laboratory, was dried in an oven at 105 ° C for 24 hours since it was in lump form due to its natural water content. Oven drying was preferred because air drying would take a long time due to the high fines content of the samples and because it was easy to represent the same initial state in the ongoing experiments. In order to obtain a uniform distribution of the samples coming out of the oven drying, the samples were crushed with a plastic mallet and passed through sieve no 4. The sieved samples were blended in a large container and transferred to sacks. Due to the humidity of the laboratory environment, they were kept in sacks for about 2 weeks to maintain constant water content. Samples with fixed initial water content were homogeneously mixed separately in 6 different SF contents at the rate of 0, 5, 10, 15, 20, 25, and 30 % of their dry weight.

Compaction characteristics of the soil samples mixed with different silica fume (SF) additive percentages were determined by Standard Proctor test.

2.2. Crumb Test

The crumb test was developed to determine the behavior of dispersive clays in the field. Later, this experiment became used in laboratories as well. For the test, either cube samples with 15 mm side lengths are prepared in the natural water content or samples prepared by compression with compaction characteristics are used. The sample is carefully placed in a 250 ml porcelain bowl filled with distilled water. With the reaction of the soil with water, the particles of colloidal size begin to separate and turn into suspension in the water. Classification is made by observations at certain time intervals. Crumb test was carried out by considering the US Corps of Water Affairs standard methods USBR 5400 (1989).

No reaction – The soil sample may melt and move towards the bottom of the porcelain bowl. However, the turbidity caused by the colloids in the suspension is not seen.

Low-Moderate reaction – There are obvious clues to the presence of colloids in the suspension. The colloids may be on the very surface of the sample or may be found as a very thin imprint on the bottom of the porcelain bowl.

Strong reaction - The colloidal cloud covers the bottom of the bowl, usually in a thin layer. In extreme cases, the water in the porcelain bowl becomes completely cloudy.

2.3. Unconsolidated-Undranied (UU) Triaxial Test

In general, UU test results are used for rapid loading on clay soils or post-construction stability analyzes of embankment dams. Theoretically, it is accepted that the shear strength (c) value found as a result of the unconfined compression test performed on saturated soils is the same as the shear strength found as a result of the UU test. Although the unconfined compression test is widely used to determine the cohesion resistance of soils, it gives lower values due to the cracks in the sample and the absence of lateral stress. For these reasons, the UU test, which reflects the land stress state, was preferred in the evaluation of the strength parameters.

The specimens used in the experiments were prepared by compressing the ratio of height to diameter of 2 (H = 14 cm and D = 7 cm) in stainless steel tubes in the compaction characteristics. The samples taken out of the tubes were placed in plastic bags and exposed to the cure in the desiccator under suitable conditions for 1, 7, and 28 days. Thus, the effect of both silica fume additive and curing time on the strength was evaluated. The UU experiments were performed at low effective cell pressures (20, 40 and 60 kPa) because stabilization occurred at shallow depths in field applications.

3. RESULTS and DISCUSSION

In this section, each test result is divided into sub-headings and evaluated separately and the results are discussed based on the obtained results.

3.1. Compaction Test Results

The compaction characteristics obtained from the standard Proctor test on different percentages of silica fume-soil mixtures are presented in Fig. 1.

As seen in Fig. 1, there was a decrease in maximum dry density (MDD) values and an increase in optimum water content (OWC) values with increasing SF percentage. While the decrease in MDD value was significantly effective up to 15% SF content, the decrease was limited in increasing SF contents. The MDD value, which was 1.584 Mg/m³ at 0% SF, decreased to 1.559 Mg/m³ and 1.553 Mg/m³ at 15% SF and 20% SF contents, respectively.

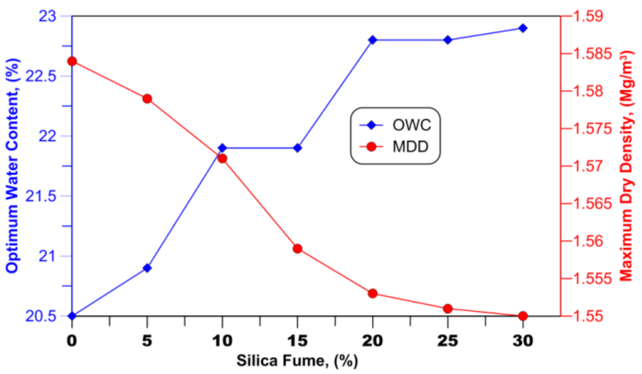

Figure 1. Variation of compaction characteristics with silica fume additive

OWC values showed a gradual increase up to 20% SF level and the increase in increasing SF percentages was limited. The increase in optimum water content (OWC) was relatively limited after 20% SF content. This is due to the lower specific gravity of the silica fume compared to soil and therefore the additional void volume due to the low specific gravity (Gs) and particle sizes of the SF additive samples. As stated in the study by Al-Azzawi et al. (2012), as a result of the replacement of sodium cations in dispersed soil with silicon cations in silica fume, the double layer thickness decreased, resulting in agglomeration of the grains.

3.2. Crumb Test Results

In this study, crumb tests were carried out to show the effect of silica fume on dispersibility. For the experiment, samples were prepared at the maximum dry density and optimum water content determined at each additive ratio. According to the degree of turbidity formed in the dispersion test, the samples were defined as "K1: non-dispersive", "K2: intermediate", "K3 and K4: dispersive".

Fig. 2 is presented in order to show the effect of a one-day curing period on the dispersive soil used in this study. As it can be seen at the end of the crumb tests, SF has been quite effective on the stabilization of the dispersive soil in one-day curing condition. Colloidal clouding, indicative of the dispersive behavior in the soil sample, made the water in the porcelain bowl completely cloudy. At 5% and 10% SF contents, the colloidal cloud covered the porcelain bowl bottom in a thin layer. Colloidal turbidity is relatively reduced in 5% and 10% silica fume additives and the dispersion class is determined as K2. At 15% SF, the soil sample melted and moved towards the bottom of the porcelain bowl, but no turbidity caused by the colloids in suspension. Therefore, the dispersion class at 15% SF was evaluated as K1. The dispersion test class did not change with increasing additive percentages.

3.3. UU Triaxial Test Results

UU experiments were performed on samples prepared by compression in compaction characteristics at 20 kPa, 40 kPa and 60 kPa confining pressures. In order to evaluate the effect of the curing time, the prepared samples were cured for 1, 7 and 28 days.

An example of the deviator stress-strain relationship is presented in Fig. 3 to illustrate the effect of the 15% SF additive on the UU test results. Similar relationships were obtained for all other SF percentages, and the deviator stress and strain values at the moment of failure from the peak point of the curves were determined.

All the results found are presented in Table 2. It can be seen from Table 2 that the greatest deviator stress is obtained at 15% SF content after 1 day of curing. Depending on the increasing curing time, the increase in deviator stress was found at lower unit deformation values. In other words, while there was no significant difference in deviator stresses at SF contents greater than 15% SF content, there was a decrease in failure unit deformations.

The failure envelopes drawn using the strength parameters determined on the basis of the Mohr-Coulomb failure criterion are presented in Figs. 4-9.

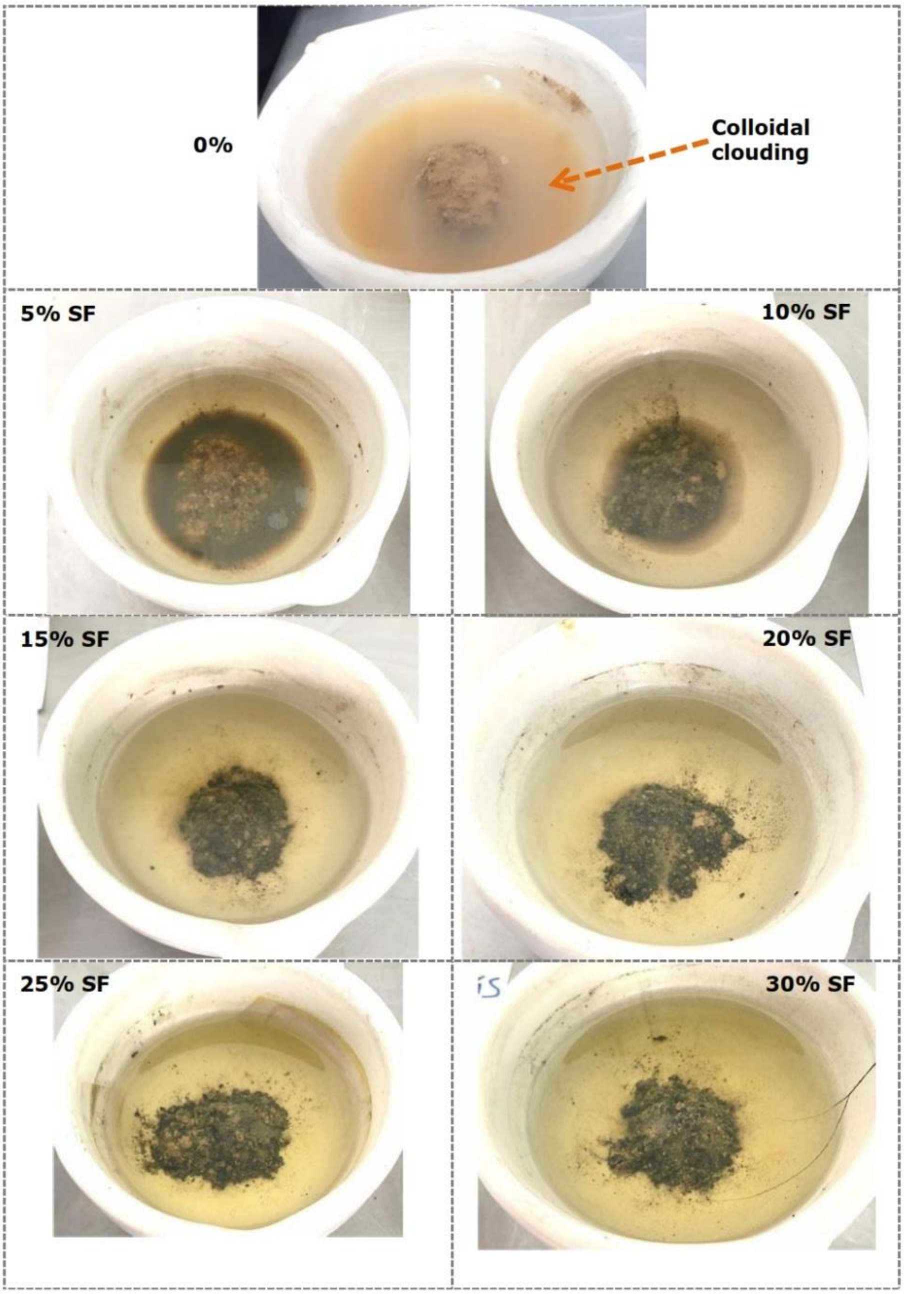

Figure 2. Images of the crumb test results

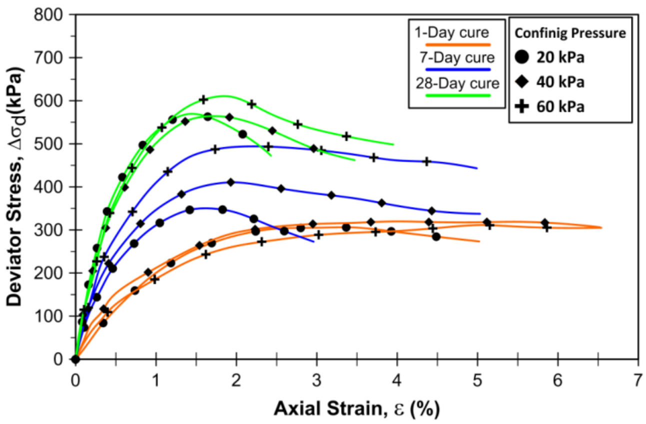

Figure 3. Stress-strain relationship for soil with 15% SF additive content

Samples did not have full saturation since the experiments were performed on samples prepared by compression at their compaction characteristics. For this reason, the envelopes of failure have been inclined. As a result of the UU tests, both cohesion and internal friction angles were determined as shear strength parameters. Especially in clay soils, the cohesion of the soils on the strength is important and has priority in the evaluations. The curing time is also important on the strength in order for the necessary chemical reactions to take place, especially in studies using additives. As seen in Figures 4-9, there was an increase in cohesion values depending on the increasing curing time. Especially after 28 days of cure, the increase in cohesion values was more pronounced.

The final results of the shear strength parameters obtained in the failure envelopes are presented in Table 3.

Table 2. Influence of SF additive contents and curing time on the UU test results

SF (%)	1-Day cure			7-Day cure			28-Day cure		
	σ_3 (kPa)	$\Delta\sigma_d$ (kPa)	ε_u (%)	σ_3 (kPa)	$\Delta\sigma_d$ (kPa)	ε_u (%)	σ_3 (kPa)	$\Delta\sigma_d$ (kPa)	ε_u (%)
0	20	281.9	5.01						
	40	301.7	5.02						
	60	310.2	5.00						
5	20	235.0	5.52	20	335.0	1.80	20	460.0	1.80
	40	286.8	5.53	40	372.0	2.30	40	474.0	2.10
	60	341.5	6.00	60	435.0	2.10	60	493.0	2.35
10	20	268.5	3.46	20	345.0	1.70	20	527.0	1.55
	40	300.6	3.99	40	415.0	2.20	40	545.0	1.67
	60	325.1	4.99	60	450.5	2.94	60	565.0	2.00
15	20	305.7	3.48	20	350.0	1.57	20	570.0	1.42
	40	319.9	3.97	40	410.6	1.96	40	585.0	1.63
	60	348.0	5.03	60	492.2	1.94	60	602.0	1.72
20	20	250.9	3.95	20	380.0	2.20	20	574.0	1.80
	40	288.7	5.51	40	425.0	2.23	40	587.0	1.84
	60	324.4	6.55	60	485.0	2.50	60	602.0	1.90
25	20	231.0	2.99	20	410.5	1.99	20	650.0	1.65
	40	258.0	3.52	40	480.0	2.00	40	680.0	1.85
	60	303.7	5.47	60	519.0	2.30	60	690.0	1.60
30	20	253.5	3.02	20	390.0	2.30	20	654.0	1.80
	40	297.5	5.00	40	454.0	2.10	40	680.0	1.95
	60	310.0	6.53	60	562.0	2.00	60	710.0	1.92

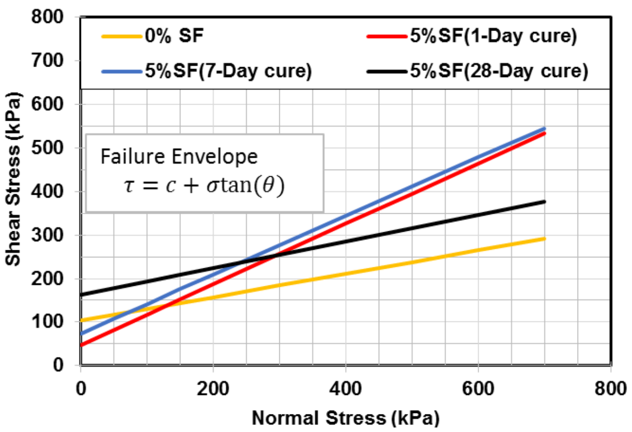

Figure 4. Effect of curing and 5% SF on failure envelope

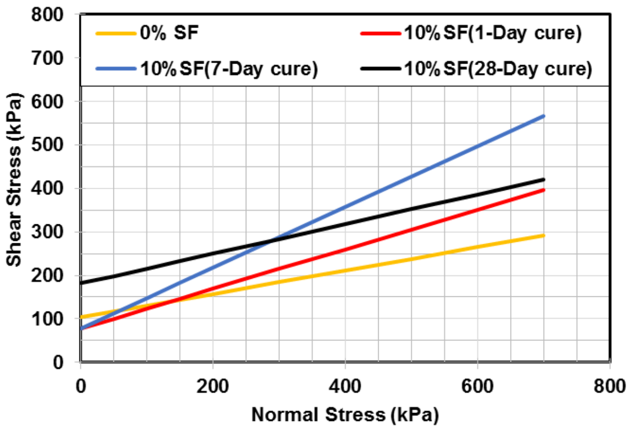

Figure 5. Effect of curing and 10% SF on failure envelope

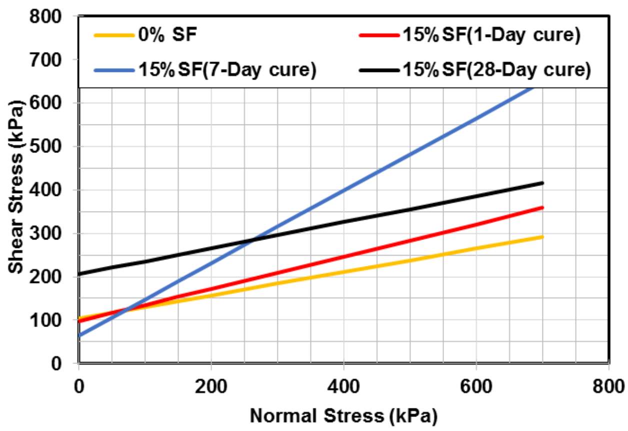

Figure 6. Effect of curing and 15%SF on failure envelope

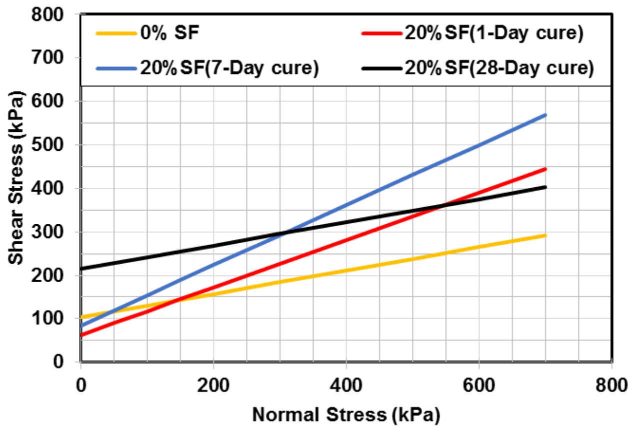

Figure 7. Effect of curing and 20% SF on failure envelope

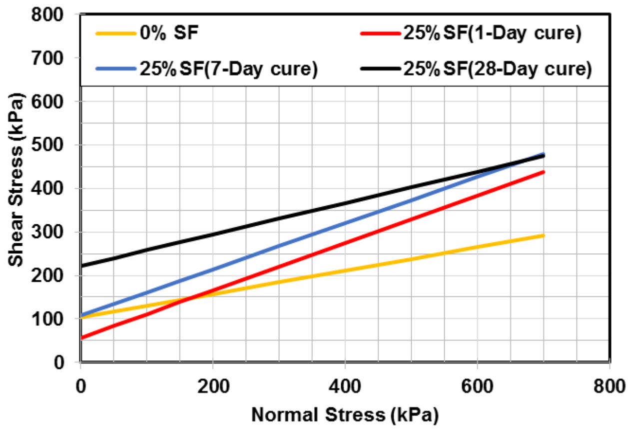

Figure 8. Effect of curing and 25% SF on failure envelope

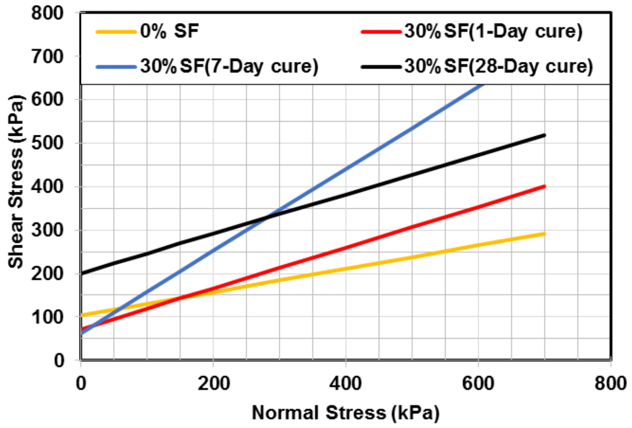

Figure 9. Effect of curing and 30% SF on failure envelope

Table 3. Effect of curing time and SF on shear strength parameters obtained UU tests

SF (%)	1-Day cure		7-Day cure		28-Day cure	
	c (kPa)	Φ (°)	c (kPa)	Φ (°)	c (kPa)	Φ (°)
0	103.29	15.11	103.29	15.11	103.29	15.11
5	47.35	34.83	74.34	33.96	163.73	17.01
10	77.59	24.52	77.00	35.01	181.76	18.79
15	97.88	20.41	64.27	39.87	206.31	16.61
20	63.66	28.61	85.12	34.65	214.60	15.03
25	56.63	28.60	108.03	27.95	221.99	19.84
30	72.52	25.10	63.49	43.29	201.23	24.33

When Table 3 is evaluated in general, an increase in cohesion values and a decrease in internal friction angle values were obtained depending on the increased curing time and SF additive. It has been observed that at 15% SF content, cohesion of the soil increases from 97.88 kPa to 206.31 kPa at 28 days of curing period.

4. CONCLUSION

In this study, the stabilization of the dispersive soil with silica fume, which is a waste material, and its effect on the strength properties of the soil were investigated. As a result of this experimental study, it was seen that silica fume could be used in the stabilization of dispersive soil. In addition, significant increases in strength were observed depending on the curing time, thanks to the silica fume with high silica content. Although performed under low confining pressures, the UU test results showed a significant improvement in failure envelopes, especially at 15-20% SF content. In future studies, it is recommended to evaluate the effect of SF on strength by performing UU tests under higher confining pressures.

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Author contributions

Ogan Öztürk: Investigation, Experimental, Writing. **Murat Türköz:** Conceptualization, Design, Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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