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Expansive Soil Stabilization Using Steel Factory Dust

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ABSTRACT

One of the geotechnical-engineering roles is soil stabilization, because it affects the long-term strength and functionality of structures. For suitability and durability of expansive soils for construction projects, shear strength, bearing capacity and other characteristics can be enhanced through the stabilization process. This study is focused on the effects of steel factory dust (SFD) as an additive on the improvement of the undesired geotechnical properties of expansive soil (CH soil). A series of laboratory tests were conducted on intact and treated samples. SFD was added by 0, 2, 4, 6, 8 and 10% to the dry soil. The conducted tests are consistency, specific-gravity, modified Proctor compaction, swelling-pressure and -percent and unconfined compression tests. The addition of SFD reduced the values of liquid and plastic limits, plasticity index, modulus of elasticity and allowable bearing capacity. Significantly, the 10% SFD addition significantly reduced swelling percent and pressure by 26.8% and 25.4%, respectively while notably increasing the unconfined compressive strength (UCS) from 475 MPa to 629 MPa. SFD was found to be a successful waste material in improving expansive soil by using 10% as the best addition percent, which usefully saves the environment.

KEYWORDS: Expansive soil, Stabilization, Steel factory dust, Swelling, Unconfined compressive strength.

INTRODUCTION

In construction processes, weak soils, such as expansive soils, may exist, which may cause problems for the construction process. The infrastructure foundations are important in safely transferring the existing loads from the superstructure to the underlying soil layer without influencing serviceability. However, the constructed foundations on weak soils may be facing excessive settlements because of the soil's lower bearing capacity, which can lead to reductions in durability, cause damages and deteriorate the performance level (Gowtham et al., 2018; Iravanian and Haider, 2020). Expansive soils are sensitive to moisture variations, which result in volume changes within seasonal changes. Soil volume changes can cause extreme deformation in a structure, which is destructive for the civil-engineering infrastructure. These soils are present in large amounts globally (Wang et al., 2019; Uge, 2017; Abdalqadir et al., 2020; Abdalqadir and Salih, 2020; Amena and Kabeta, 2022; Salih et al., 2022).

Expansive clayey soils are a type of soil that shows significant volume changes when absorbing water. In dry seasons, expansive soils can be easily identified in the field through the existing deep cracks with polygonal patterns. Therefore, swelling and shrinkage behaviors of expansive soils influence the structure stability, resulting in vulnerabilities for construction projects. It is prudent to stabilize expansive soils and improve their mechanical properties before any structure is erected on them (Abdalqadir et al., 2020; Abdalqadir and Salih, 2020; Hamza et al., 2022). Large quantities of minerals, such as montmorillonite and illite, are available in

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expansive soils, causing expansion and shrinking due to water absorption and discharge (Yadav and Tiwari, 2017). Hence, various projects, such as roads, rails, channel structures and foundations that are constructed on expansive soils, may be subject to contraction stress because of unexpected variations in soil volume, which might lead to cause fractures and significant loss (Ikeagwuani and Nwonu, 2019). Geotechnical engineers have been utilizing various techniques to decrease expansive-soil influences by practicing soil stabilization (Atahu et al., 2019; Abdalqadir et al., 2020; Abdalqadir and Salih, 2020; Garg et al., 2021; Hamza et al., 2022; Salih et al., 2022).

Soil stabilization is a critical process to amend the engineering characteristics of soils. It involves the utilization of various types of materials that will be helpful to increase the load-bearing capacity, decrease settlement and improve the soil's durability. Therefore, SFD, which is a byproduct of steelmaking factories, was chosen to be used for soil-stabilization purposes (Bijarniya et al., 2020; Abdalqadir and Salih, 2020; Salih & Abdalla, 2022). The process of stabilization has several objectives; namely, soil-strength amendment and soil-resistance increase for softening due to water penetration through bonding the soil particles together, providing waterproofing for the soil particles. The common waste products that can be considered as stabilizing agents are: lime, fly ash, rice-husk ash, blast-furnace slag, cement-kiln dust, … etc. The utilization of waste products for construction purposes has obtained notable attention due to their benefits for the economy and the environment. Therefore, the use of waste products is an essential task for civil engineers to protect the environment (Adeyanju and Okeke, 2019; Abdalqadir and Salih, 2020; Abdalqadir et al., 2020; Salih et al., 2022).

Several studies have tried to minimize the negative impact of expansive soil on construction projects. These studies have used additives, such as fly ash (Choudhary et al., 2014; Al-Malack et al., 2016), lime (Rouaiguia and Abd El Aal, 2020), hydrated lime (Abdalla and Salih, 2020), marble dust (Abdelkader et al., 2021; Amena and Kabeta, 2022), plastic strips (Peddaiah et al., 2018; Kabeta, 2022) bentonite mixed with sand (Fattah et al., 2021), geogrid reinforced columns (Al-Omari et al., 2016; Masood et al., 2021), ceramic waste (Al-Bared et al., 2018), granite waste (Zainuddin et al., 2019) and steel slag (Aldeeky and Al Hattamleh, 2017; Abdalqadir and Salih, 2020; Abdalqadir et al., 2020).

Steel dust is produced during steel manufacturing, like steel bars, sheets and plates. Steel dust can be a possible candidate for soil stabilization, as it contains iron fine particles, carbon and other trace elements. Steel dust has been successfully used for soil stabilization in several studies (Bijarniya et al., 2020). The utilization of steel dust reduces the need for disposal processes in landfills. Moreover, the utilization of steel dust can reduce greenhouse gas emissions and reduce the energy consumption associated with the production processes of traditional stabilizers (Bijarniya et al., 2020).

In the Sulaimani governorate, several steel factories produce large quantities of steel slag and this waste material causes damage to the environment. To eliminate this problem, steel slag can be used as an expansive-soil stabilizer (Abdalqadir et al., 2020; Salih et al., 2022). It was found that none of recent studies utilized SFD in soil-stabilization purposes. Therefore, it has been decided to discover SFD suitability for expansive-soil stabilization. This study aims to improve expansive soils through using SFD in various replacement percentages from the soil dry mass.

MATERIALS AND METHODS

The utilized materials for soil-SFD mixtures are explained in this section. Two raw materials were used; namely, SFD and expansive soil. According to the conducted work on expansive soils so far (Aldeeky and Al Hattamleh, 2017; Al-Bared et al., 2018; Adeyanju and Okeke, 2019; Zainuddin et al., 2019; Abdalqadir and Salih, 2020; Abdalqadir and Salih, 2020; Abdalqadir et al., 2020; Abdelkader et al., 2021; Salih et al., 2022), the decision was made to utilize SFD for expansive-soil stabilization.

Soil Sample

The used soil is categorized as high-plasticity clay (CH) soil based on Casagrande's plasticity chart. The sample was collected from 1.5 meters beneath the natural surface in the Bakrajo area, Sulaimani city, Iraq (35° 32' 47.9" N and 45° 21' 13.7" E). The sample has been protected in plastic bags, transported to a soil laboratory and then oven-dried. The oven-dried sample has been sieved through a no. 4 sieve and the passed part has been used for the geotechnical-testing program. The physical and geotechnical properties of the sample are presented in Table 1.

Steel Factory Dust (SFD)

SFD is a by-product of the steel-manufacturing process. SFD has been collected from the Suli-Steel factory in Sulaimani city, Iraq. SFD material is a black-coloured powder. The used SFD has been mixed as a replacement with the dry mass of the soil sample in various percentages of 0, 2, 4, 6, 8 and 10% that have been used to prepare the soil-SFD mixtures for the testing program. The chemical composition of the SFD is presented in Table 2.

Table 1. Physical and geotechnical characteristics of the used expansive soil

Physical and Geotechnical Properties		Unit	Value
Particle-size Distribution	Sand (0.075mm - 4.75mm)	%	16
	Silt (0.005mm - 0.075mm)	%	35
	Clay (< 0.005mm)	%	49
Atterberg Limits	Liquid Limit (LL)	%	52.9
	Plastic Limit (PL)	%	27.45
	Plasticity Index (PI)	%	25.45
Soil Symbols (According to USCS)		-	CH
Specific Gravity (Gs)		-	2.69
Compaction Characteristics	OMC	%	16.8
	MDD	gm/cm^3	1.76
Swelling Characteristics	Swelling Percent	%	8.16
	Swelling Pressure	kPa	166.8
Unconfined Compressive Strength (UCS)		kPa	475

Table 2. Chemical composition of SFD sample

Compound	Value (%)
SiO_2	17.42
CaO	19.41
SO_3	14.33
Al_2O_3	6.262
Fe_2O_3	4.228
K_2O	0.7902
MgO	0.738
Na_2O	0.425
P_2O_5	0.3029
Ti	0.2188
Chloride (Cl-)	0.01965
Others	35.855

Experimental Program

The study investigates the effects of SFD on the geotechnical properties of expansive soils. The experimental program is divided into three stages: material collection, laboratory testing and data analysis. To gather information about expansive soils and SFD, an extensive search in various databases has been carried out. Soil-SFD mixtures have been prepared and assessed based on the results of consistency, expansion and unconfined strength tests. To obtain SFD-soil homogeneous mixtures, the SFD was thoroughly mixed with the soil. The samples for Atterberg limits (ASTM D4318, 2000), the samples for unconfined compression tests (ASTM D2166, 2000) and the samples for expansion tests have been prepared and used for soil index properties' determination. Immediately, after preparing the mixtures, they were placed in airtight bags to prevent any changes in the moisture content. The samples were then stored in a controlled room for the samples to be matured. After 24 hours, the samples have been tested.

RESULTS AND DISCUSSION

Consistency Characteristics' Improvement

As can be noticed from the obtained results in Figure 1, 4%, 6% and 8% addition percentages have significantly improved the consistency parameters. After that, the increased percentage of SFD also worked positively to decrease LL, PL and PI. Overall, an increase in the SFD content has resulted in Atterberg limits' reduction, similar to the findings of Amu et al. (2011), Dash and Hussain (2012), Gharib et al. (2012), Mohammed and Elsharief (2015). The cation interchange occurrence as a consequence of several ions' exchange with the SFD particles may result in an instant variation in the soil workability, which may happen internally in the clay structure. Therefore, LL, PL and PI values decreased. The plasticity changes take place quickly, due to the instant influence of SFD reactions that start to affect, so that Atterberg limits continue to decrease. This plasticity reduction gives a less brittle texture for the soil-SFD mixtures, rendering the soil more suitable for construction projects.

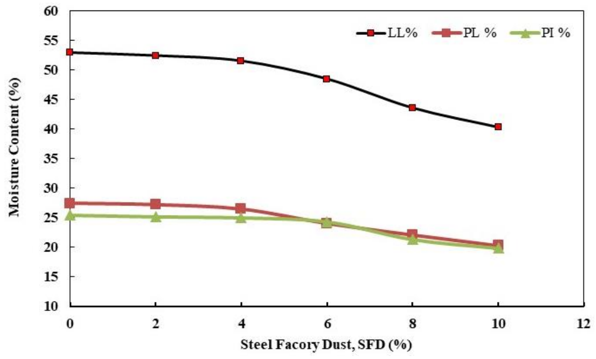

Figure (1): Effect of SFD on the soil's LL,PL and PI

Swelling Characteristics' Improvement

In Figures 2 and 3, SP and SPr results experience changes with the variation of SFD content. Both properties have dropped significantly. The reduction is 26.78% and 25.35% for SP and SPr, respectively. Swelling characteristics' improvement at the highest SFD dose can be ascribed to a reduction in the water absorption of the expansive soil, which caused the SP and SPr values to be decreased.

SP decreased due to 2% SFD, which may result from the reduction in the amount of soil that was replaced by SFD. It seems that within the increase in the SFD particles, the clay minerals have reduced, which resulted in lower capability to absorb water and then in lower SP values. SPr also showed similar behavior to SP; however, with a bit of difference within 2% SFD. As long as the SFD quantity increases, the SPr capability decreases to enlarge the soil volume.

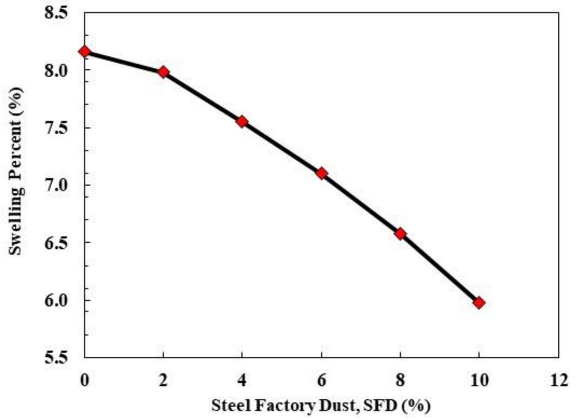

Figure (2): Effect of SFD on the soil's swelling percent

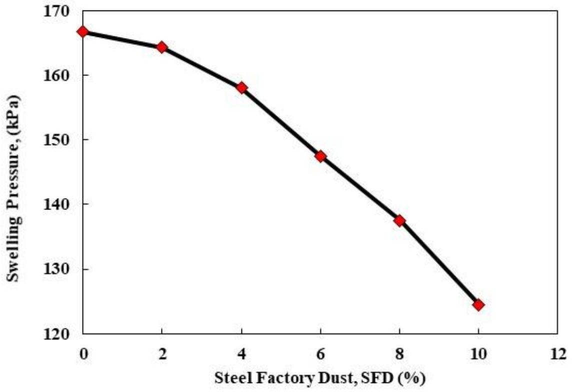

Figure (3): Effect of SFD on the soil's swelling pressure

Unconfined Compressive Strength Improvement

It was found that UCS (Figure 4) showed continuous improvement as the dosage on intact expansive soil increased up to 10%. This result was attributed to filling the pores inside the expansive soil with SFD, which makes the mixes denser and more compact. In addition, the chemical composition of the SFD (see Table 2), which has a good percentage of calcium oxide and silica, accelerates the SFD reactions and makes it stronger, which eventually improves the expansive soil's strength. Also, good dispersion of SFD inside soil-SFD mixtures positively affects the performance of soil-SFD mixtures, resulting in increasing the UCS.

The achieved strength increase due to the SFD content is notable. The addition of SFD (0 % to 10%) enhanced the UCS to be increased (from 475 kPa to 692 kPa). Higher strength was achieved as a comparison between 8% and 10% SFD, which is around a 13.26% increase. This shows that the SFD content does not only cause modification, but a significant role can also be achieved in accelerating the mixture of SFD and soil reactions (Figure 4). The results clearly show that SFD-treated expansive soil is very successful in gaining strength. Importantly, 10% SFD is essential to gain higher strength. In addition, the strength gain rate increased gradually due to the SFD-dose increase. Similarly, UCS modification for soils was obtained by Ola (1977) and Amadi and Okeiyi (2017) by lime.

The physico-chemical phenomenon of cation interchange that might happen between clay particles and SFD, in addition to the flocculation-agglomeration process, may be due to the shear-strength enhancement of the soil treated by SFD. Instant changes in the soil properties have been taking place quickly because of the explained actions. After that, the pozzolanic reactions among silica ions, aluminum oxide and calcium oxide will happen for clay minerals. Similarly, the outcomes achieved are similar to the results of other studies, like Alzubaidi and Lafta (2013), Zhao et al (2014) and Jha and Sivapullaiah (2015) for strength increase in the production process of cement products.

Proposed SFD Performance

The study has tried to determine the exact role of SFD in expansive-soil improvement. Considering Figures 1-3 and Figures 4-5, it can be observed that all the selected characteristics have been notably improved. The samples for testing were prepared by using the SFD and the natural characteristics of the expansive soil and then, laboratory testing was carried out to predict the role of SFD in stabilizing the expansive soil (Figures 4-5).

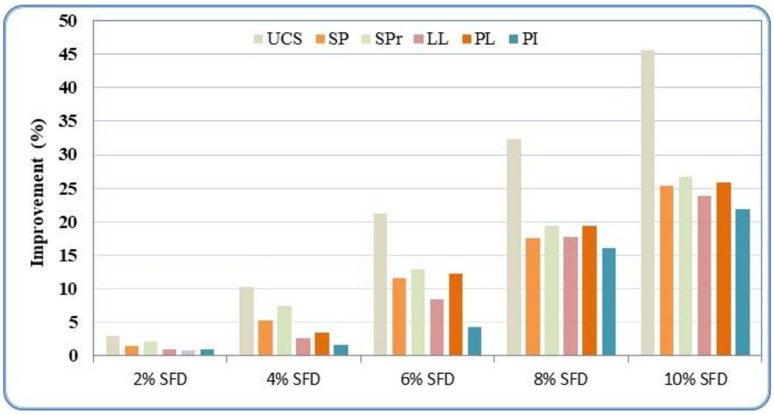

Figure (4): Effect of SFD on the soil's UCS, SP, SPr, LL, PL and PI

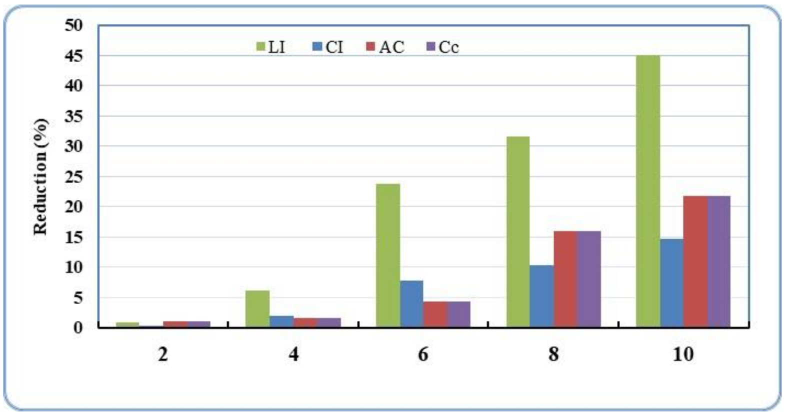

Figure (5): Effect of SFD on the soil's LI, CI, Ac and Cc

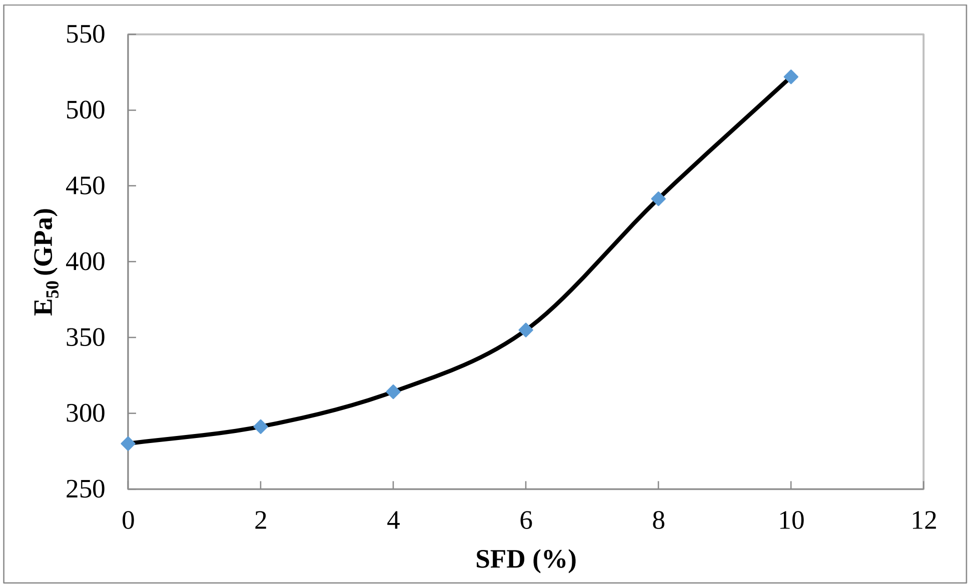

Figure (6): Effect of SFD on the soil's stiffness (Young's modulus)

Moreover, to prove the role of SFD in stabilizing expansive soil and amending the geotechnical parameters, E50 (Figure 6) and allowable bearing capacity (Figure 7) have been studied. For the lower percentages of SFD (2% and 4%), the sample response is lower than for the higher percentages of SFD (8% and 10%). This phenomenon may happen due to the strong role of expansive soil to resist the E50 to increase and then, the soil capability significantly decreased with high percentages of SFD. The SFD particles cannot absorb water due to the unavailability of clay minerals, which leads to minimizing the lubrication surfaces of the particles and enhancing the strength capability. As a result, the modulus of elasticity and bearing capacity continue to increase with the percentage of SFD increase.

The differences among the failure shapes illustrated in Figure 8 are notable. The natural soil is almost divided into two longitudinal parts by a continuous failure line, while the failure line for the treated sample by 8% SFD has reduced to about 60% of the sample height. The load application effects were deducted due to the use of SFD. Significantly, the failure line was either reduced in terms of length or location along the sample height. Moreover, the mid-distance of the soil-SFD mixtures was almost not affected by the applied load (Figure 8) and the top and bottom parts were nearly affected by the load applied from the testing procedure.

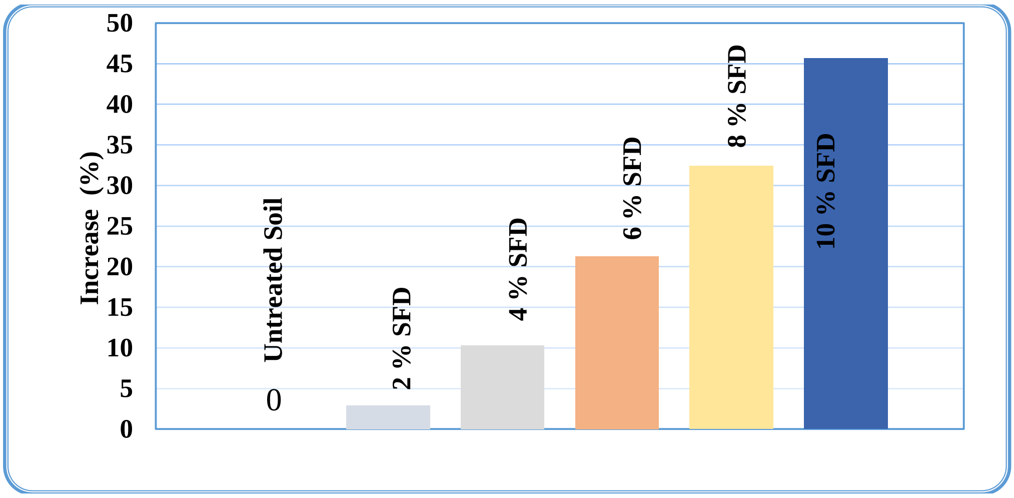

Figure (7): Effect of SFD on the soil's allowable bearing capacity

Based on the outcomes achieved of the tested soil-SFD samples (Figures 1-8), there is a direct interaction between the soil and SFD. Therefore, a laboratory stabilization technique can be employed to develop soil-SFD mixtures, which will result in a useful forecast of the SFD incorporated in different mix proportions with expansive soil.

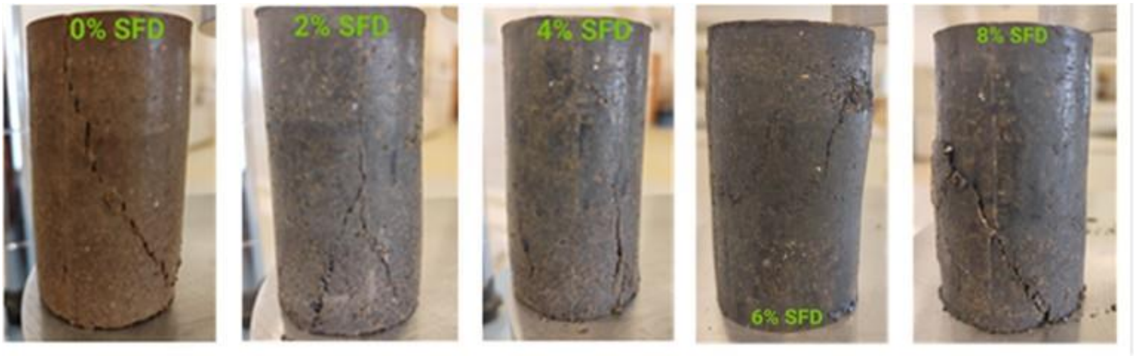

Figure (8): Unconfined-compression samples after failure

As shown in the results (Figures 1-7), 10% SFD could be used and revealed that SFD could be successfully used for expansive-soil stabilization. Generally, UCS is significantly affected by the utilization of SFD (Figure 6) compared to the other studied parameters. The increase in the UCS values may be because SFD is a steel factory waste, which is usually stronger than the soil particles. Therefore, SFD particles significantly increased the strength characteristics (UCS) compared to SDF effects on the other geotechnical characteristics, such as consistency and expansion parameters.

CONCLUSIONS

Based on the outcomes obtained from the extensive experimental tests, this study has drawn the following conclusions:

1) Utilization of SFD decreases the Atterberg limits. The positive effect of SFD on LL, PL and PI is observed at all utilized percentages, with the highest effect being caused by the highest dose of SFD (10%). SFD notably improves the consistency characteristics of expansive soil with improvements reaching 23.93%, 25.87% and 21.85% for LL, PL and PI, respectively.
2) SFD significantly increases the UCS, which gradually increases with the SFD percentage increase. SFD improves the UCS of expansive soil notably; the highest strength increase reached 45.68%.
3) SFD importantly resulted in an appreciable effect on decreasing the swelling characteristics; both SP and SPr gradually decreased with the SFD dose increase. SFD notably improves the SP and SPr, with improvements reaching 25.35% and 26.78%, respectively.
4) The addition of SFD notably causes increasing the stiffness (Young's modulus) of expansive soil. SFD improves the E_{50}, which increased from 280 GPa for an intact sample to 522 GPa for soil -10% SFD mixture.
5) The addition of SFD significantly increases the allowable bearing capacity of expansive soil. 10% of SFD improves the allowable bearing capacity by a 45.67% increase.
6) The addition of SFD is changing the mode and length of the failure line. In general, SFD decreases the failure influence and makes it smaller, which minimizes the deteriorated places along the soil body and structure.

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