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IMPROVEMENT OF HIGH PLASTICITY CLAY BY USING FILTER SLUDGE

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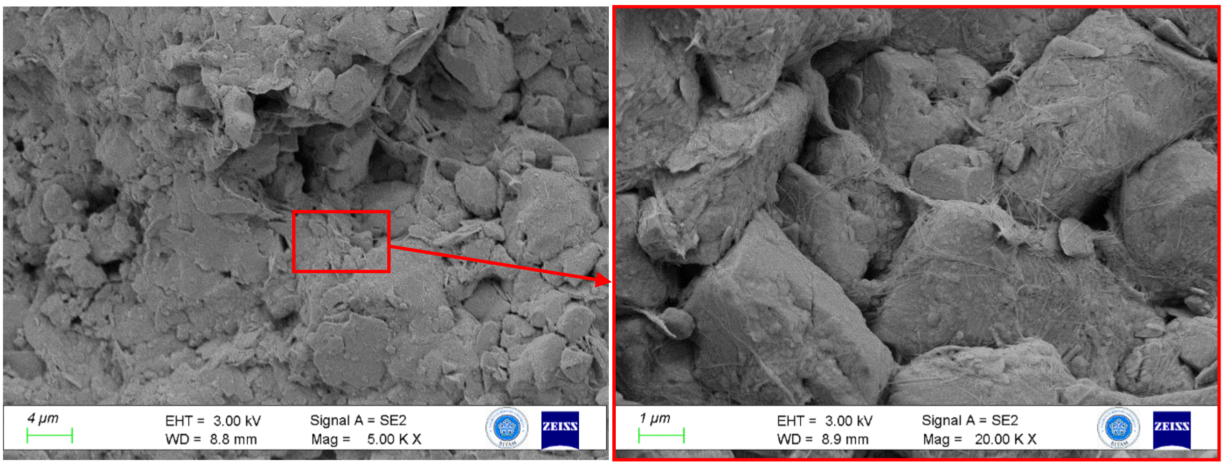
Highlights

- Feasible usage of the filter sludge, a waste material of the sugar industry, is investigated to stabilize high plasticity clay.
- The plastic limit and optimum water content increase as the FS content increases; liquid limit, plasticity index, and maximum dry density decrease.
- Improved soil strength increases as the curing time and FS amount increase, and the highest strength was obtained with 15% of FS.
- At the optimum additive ratio, the unconfined compressive strength increases by 33% and the swelling percentage decreases by 53%.
- With the use of filter sludge in soil improvement applications, the storage cost of the waste material and its harm to the environment will be reduced.

Graphical Abstract



Microstructural change of the clay stabilized with filter sludge

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ABSTRACT: Filter sludge (FS) is a waste material that occurs during sugar production in the sugar industry, and since it is not used anywhere, it creates a problem due to storage costs and environmental damage. In the present study, high plasticity clay was stabilized with a filter sludge which has never been used for soil stabilization in field cases. The changes in the geotechnical properties of a high plasticity clay (CH) with the additive of filter sludge (FS) were investigated. The amount of FS mixed into CH soil is 3-6-9-12-15% by dry weight of the soil. Changes in geotechnical properties such as consistency limits, compaction parameters, strength, swelling potential, CBR value of improved soils were determined. The plastic limit and optimum water content increase as the FS content added to the soil increases; liquid limit, plasticity index, and maximum dry density decrease. Improved soil strength increases as the curing time and FS amount increase, and the highest strength was obtained with 15% of FS. At the optimum additive ratio, the unconfined compressive strength increases by 33%. The swelling percentage of CH clay decreases from 42.5% to 20%. According to the wet CBR test results, the bearing capacity of the improved soil increased from %1.1 to %4.4. As a result of this study, it was seen that the FS waste material improved the geotechnical properties of the soil.

Keywords: *Clay, Filter Sludge, Soil Stabilization, Strength, Swelling Potential*

1. INTRODUCTION

In geotechnical engineering, soft clayey or silty soils and loose sandy or gravelly soils pose significant challenges. Engineering structures built on such these soils may encounter problems with bearing capacity, settlement, liquefaction, stability, and stiffness under static and dynamic loads. Before proceeding to the design and construction of engineering structures on problematic soils, these soils need improvement with surface or deep soil improvement methods depending on the superstructure and soil properties.

High plasticity clayey soils can lead to various issues such as bearing capacity, settlement, swelling, and shrinkage depending on the void ratio, water content, and consistency properties. Semi-saturated high-plasticity clays have a variety of volume changes according to their initial water content, which results in swelling or shrinking due to an increase or decrease in water content, respectively. Swelling soils can cause substantial damage to lightweight structures, roads, highways, airport runways, and pipelines. Lightweight structures built on swelling soils require special precautions during the construction process, as they are prone to damage but not life-threatening. As a result, swelling soils are a worldwide problem that poses several challenges for civil engineers [1].

The regions most affected by swelling soils are found in semi-arid climatic regions, encompassing six continents and forty countries [2]. In Turkey, swelling soils are prevalent in Central Anatolia and a part of Western Anatolia, Southeastern Anatolia, and Eastern Anatolia [3].

According to the Highways Technical Specification [4], high-plasticity clays with a plasticity index greater than 10%, must be stabilized with lime. High plasticity clays with a liquid limit value greater than 90% and a plasticity index greater than 65% cannot be used as filling material. Therefore, swelling soils need to be improved before using as construction materials [5].

Various methods are employed for the stabilization of high plasticity clays with high swelling potential and low bearing capacity. These methods include replacing soil, pre-wetting, chemical

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stabilization, geotextile usage, preloading, thermal methods, and compaction in the field [6], [7]. Chemical stabilization is commonly preferred in the improvement process of high-plasticity clays.

The materials used in the chemical stabilization method are cement [6]–[8], lime [9]–[11], fly ash [12]–[14], marble dust [15]–[17], silica fume [18]–[20], and blast furnace slag [21]–[23]. When clayey soils are stabilized with these additives, liquid limit, plasticity index, and optimum water content decrease, and plastic limit, maximum dry density, and strength increase.

Sugar production stages in the sugar industry are listed as follows: 1) washing, slicing, and boiling the sugar beet; 2) separating the raw sherbet from the beet pulp; 3) precipitating non-sugar substances by mixing raw sherbet with lime milk; 4) precipitation of raw sherbet by carbonation. In the final stage, muddy sherbet comes out with the precipitation of the raw sherbet, which is compressed in the press filters, and the sugar and sludge are separated from each other. The resulting sludge is "filter sludge". The filtered sludge released during sugar production is stored around the factory or in waste storage centers. As a result, the storage costs of waste increase and environmental problems occur. Filter sludge was used to increase soil fertility [24], to produce biodiesel [25], and to use in animal breeding [26]. Studies on the use of filter sludge are very limited.

In this study, the potential use of filter sludge in the stabilization of high-plasticity clays was investigated to reduce the storage cost of the waste material and mitigate its environmental impact. The study aimed to determine the consistency limits, compaction behavior, strength, and swelling properties of the improved soil by incorporating filter sludge in different proportions into the high plasticity clayey soil.

2. MATERIAL AND METHODS

2.1. Materials

The soil used in the study was obtained from the plain of Konya. Before conducting the experiments, the soil was sieved using a No. 40 sieve to obtain a homogenous specimen. According to the Unified Soil Classification System (USCS) [29], the soil is classified as high plasticity clay (CH), as shown in Table 1.

Table 1. The geotechnical properties of soil

Properties	Value
Plastic limit (%)	24
Liquid limit (%)	99
Plasticity index (%)	75
Maximum dry density (g/cm^3)	1.570
Optimum water content (%)	23.15

Filter sludge (FS) is a waste material that obtained from Konya Şeker Factory. The initial water content of FS was 30%. Filter sludge is not an effective material for soil stabilization due to its organic content. The presence of organic matter in waste materials added to soils can lead to decay over time, resulting in mold growth. Consequently, the strength of stabilized soils decreases over time. To address this issue, it is essential to purify the filter sludge from these organic materials before using it in soil stabilization. Before purification, FS was dried in the oven at 60°C for 24 hours to avoid mass loss since organic matter may burn at higher temperatures. After that, FS was sieved through No. 40 sieve before usage. In the purification stage, the filter sludge was incinerated at 440°C following the ASTM D2974 [27] standard. The amount of organic matter was determined as ~10. Figure 1 illustrates the natural and burned filter sludge used in this study.

Furthermore, the chemical composition of both CH (high plasticity clay) and FS materials was determined through X-ray Fluorescence (XRF) analysis, and the results are presented in Table 2.

Figure 1. Natural (left side) and burned (right side) filter sludge

Table 2. Chemical composition of materials

Material	Al_2O_3	SiO_2	Fe_2O_3	CaO	MgO	K_2O	TiO_2	ZrO_2	SO_3
CH	10.9	36.7	4.82	19.9	1.73	2.58	0.64	0.34	0.05
FS (natural)	0.45	1.51	0.23	49.6	1.84	0.13	0.05	0.33	0.71
FS (burned)	0.66	2.10	0.39	51.4	1.75	0.19	0.09	0.35	0.72

2.2. Testing procedures

Some laboratory test and analyzes were performed to investigate the stabilization of high plasticity clay with filter sludge. At the scope of this study, experimental program consists of three parts that are index properties, engineering properties, and mineralogical properties, respectively.

2.2.1 Index properties

The influence of the filter sludge on the index properties of CH specimen was investigated by evaluating various parameters, including Atterberg limits, maximum dry densities, optimum water contents, and swelling potentials of the stabilized soil specimens.

While determining the geotechnical properties of the FS stabilized CH soil samples, the materials were mixed with a spatula in dry condition and then sieved twice through the No.40 sieve to increase the homogeneity of the mixture. The dry weight percentages of stabilized soil specimens with filter sludge are presented in Table 3. The maximum amount of FS is limited to 15% because lime stabilization usually includes between 7-9% lime [28]. Since 51.4% CaO is present in FS waste, ettringite formation may occur if more than 15% FS is added, which causes swelling in the improved soil structure. Moreover, since FS waste is burned at 440 °C, the amount of FS is limited to 15% in order not to increase energy consumption.

Table 3. The dry weight percentages of stabilized soil specimens with filter sludge

Stabilized Specimens	CH	Filter sludge
%3 FS	97	3
%6 FS	94	6
%9 FS	91	9
%12 FS	88	12
%15 FS	85	15

Atterberg limits (liquid limit, plastic limit, and plasticity index) are key parameters for high plasticity clay. It is important to note that the Atterberg limits may change due to the chemical interactions between filter sludge (FS), high plasticity clay (CH), and water when these materials are mixed. The consistency properties of stabilized soils were specified with respect to ASTM D4318 [29].

In the shallow stabilization process, the soil and additive (filter sludge) were compacted together to enhance the durability and strength of the stabilized soil. The outputs of standard proctor test that maximum dry density and optimum water content are essential parameters for stabilization process. The standard proctor test was performed according to ASTM D 698 [30].

2.2.2 Engineering properties

A parameter called as swelling potential should be determined before the design of the lightweight structures such as one-story buildings, pavements, etc. Since most of the damage that occurs on these structures results from the volume change of high plasticity clay soils. Swelling potentials of both CH and stabilized soils were found after free swell tests were performed with respect to ASTM D4546 [31].

The strength of soil depends on many factors such as field condition, ground water table, soil type, air content, and more. For this reason, some strength parameters of soils such as angle of internal friction, cohesion, value of CBR, and unconfined compressive strength have been developed for last decades. Two laboratory tests were done to determine the strength parameters of both CH and stabilized soils in this study are given below;

1. High plasticity clay is known for its cohesive nature, and as such, unconfined compression tests were conducted in this study to assess the unconfined compressive strength, which is a more suitable strength parameter for cohesive soils. The testing procedure followed in this part was ASTM D 2166 [33].
2. The usage of filter sludge in the subgrade of either pavement or highway was thought due to the storage problem of waste material. California Bearing Ratio (CBR) test generally performed for quality control of subgrade of some structures such as pavement and highway. ASTM D1883 [32] was pursued. CBR test can be done at two different types that are dry and wet. Wet CBR test was done on stabilized soil specimen since it was more suitable for cohesive soils.

The samples used in the UCS, standard proctor, CBR and swelling tests were obtained by compressing in suitable molds according to the optimum water content and maximum dry density of each mixture. The diameters of UCS, standard proctor, CBR and swelling test specimens are 50, 105.6, 152, and 50 mm, and their lengths are 100, 115.5, 127, and 20 mm. The stabilized soil specimens were subjected to curing for 7 days, 28 days, and 56 days to observe the effect of curing duration on the engineering properties of the stabilized high plasticity clay. This investigation aimed to understand how the inclusion of filter sludge influenced the strength and other engineering properties of the stabilized soil over time. Figure 2 shows the laboratory tests on stabilized specimens.

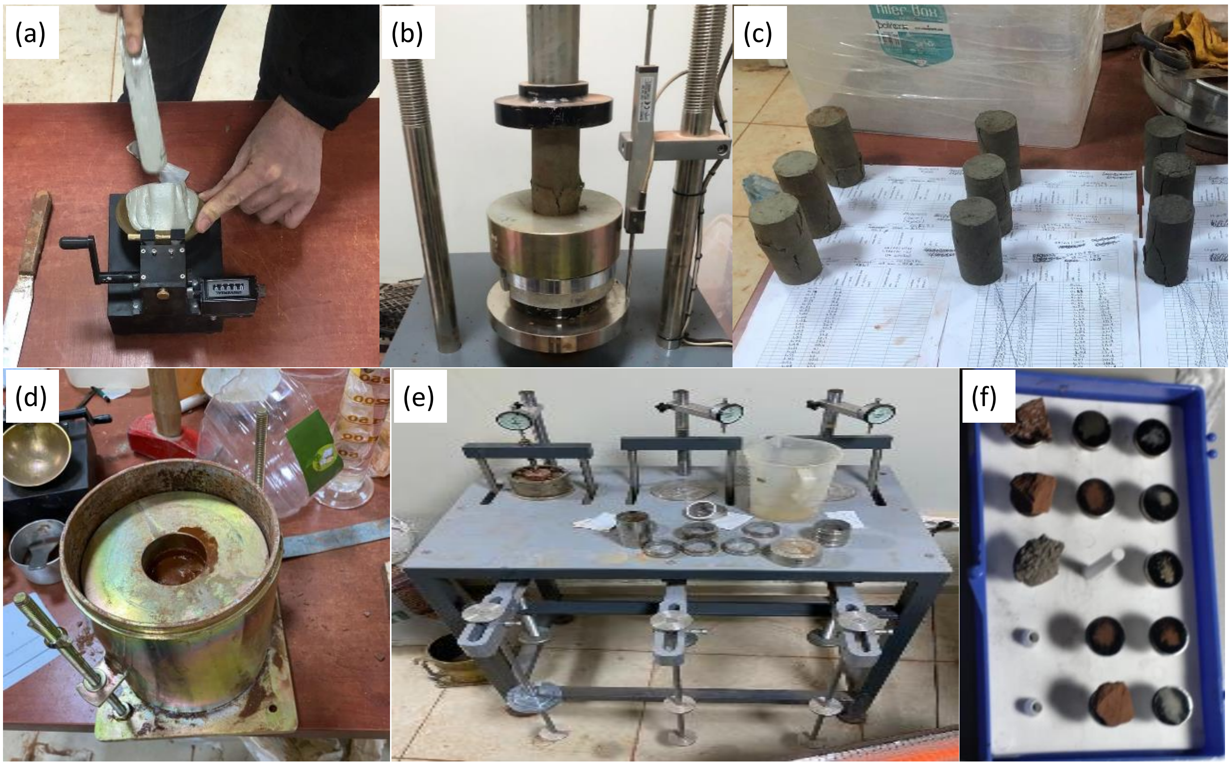


Figure 2. Laboratory tests on stabilized specimens: a) liquid limit test, b) UCS test, c) shear surface of stabilized specimens after UCS tests, d) CBR test specimen, e) swelling test, and f) SEM testing

2.2.3 Microstructural properties

The alteration of CH, FS and stabilized soil microstructure was observed by Scanning Electron Microscope (SEM) analyses. SEM images were taken by using a ZEISS EVO LS10 field emission machine at NEÜ BİTAM Laboratory. Firstly, samples used in the analysis were dried at 105°C to obtain dry specimen. Since water vapor into the specimen may damage the scanning electron microscope. CH and FS materials were pulverized before SEM imaging. For the SEM analysis of the stabilized soil samples, SEM images were taken from 1x1x1 cm cubic pieces extracted from the shear surfaces of unconfined compression (UCS) test samples. Then, these specimens were coated with gold and palladium for SEM Analysis.

SEM images were taken at different magnification factors to observe the change of microstructural characteristic for selected specimens.

3. RESULTS AND DISCUSSION

The parameters of stabilized soils were divided into two groups that are index properties and engineering properties. First group that is called as index properties that consist of Atterberg limits, maximum dry density and optimum water content. Then, engineering properties include the swelling potentials and strength parameters of stabilized soils.

3.1. Index Properties

Index properties play a crucial role in understanding the fundamental characteristics of both soils and the stabilization process in this study. Thus, the change of some parameters of stabilized soil specimens prepared in this study were determined. These specimen parameters determined in this study are plastic limit (PL), liquid limit (LL), maximum dry density (MDD), and optimum water content (OWC).

3.1.1 Atterberg limits of stabilized soil specimens

The values of plastic limit and liquid limit of stabilized specimens were measured and the plasticity index (PI) of them were calculated. Consistency limits of stabilized specimens are illustrated in Figure 3.

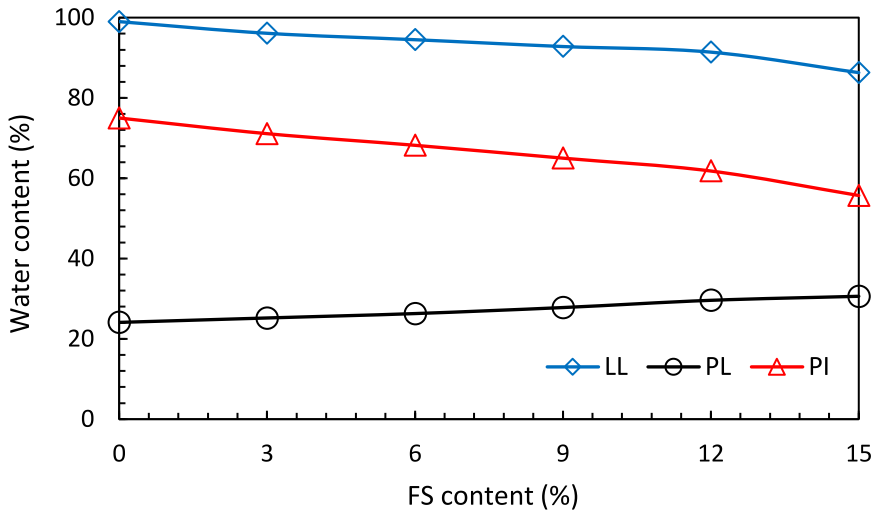


Figure 3. Plastic limit, liquid limit, and plasticity index of stabilized soil specimens

The addition of filter sludge (FS) to the high plasticity clay (CH) soil leads to a decrease in the liquid limits of the stabilized specimens. This is a notable observation because of the cation exchange mechanism, flocculation, and agglomeration that occur when the waste material is mixed with the CH specimens. Since Filter sludge, being a calcareous material with 51.4% CaO, plays a significant role in triggering both the flocculation and agglomeration processes. As a result of these processes, the workability of the soil specimens improves, and they reach a liquid-like consistency with less water. Consequently, the liquid limit of the stabilized soil specimens decreases as the ratio of filter sludge additive increases.

According to these results, the increase of the addition percentage of FS result in rise of the plastic limit of stabilized soil specimens. Since the water requirements of the stabilized soil specimens increase with the addition amount of FS into CH. The reason is that ss FS is a calcareous material, it has a higher water demand when mixed with the CH soil. Therefore, as the stabilized soil specimen reach a plastic consistency with more water, the plastic limit increases as the additive ratio increases.

The plasticity index is the difference between the liquid limit and the plastic limit and shows the plasticity of the soil. As the additive ratio increases, the plasticity properties of stabilized soil specimens decrease. This indicates that the relationship between the stabilized soil specimens and water weakens with the addition of FS.

The change in the plasticity index directly affects the engineering parameters of the stabilized soil specimens such as strength and swelling. The decrease in the plasticity index both generally causes an increase in strength parameters and result in the reduction of the swelling potential of clays. Therefore, the changes in the strength parameters of the stabilized soil specimens with FS were monitored by unconfined compressive strength and CBR tests. In addition to these experiments, free swelling test was performed to observe the changes in swelling potential.

3.1.2 Compaction characteristics of stabilized soil specimens

The alteration of both maximum dry density (MDD) and optimum water content (OWC) of stabilized soil specimens were observed by performing standard proctor test (Figure 4).

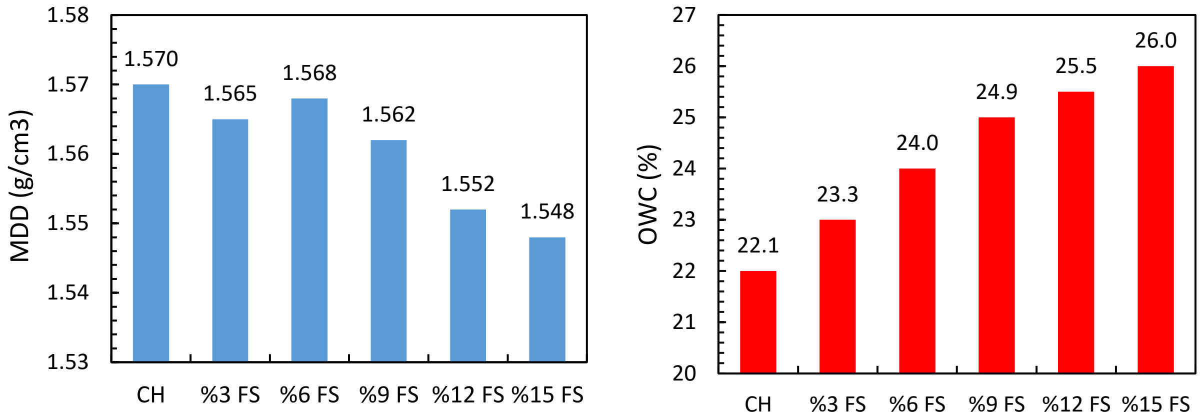


Figure 4. The values of a) MDD and b) OWC of stabilized soil specimens with FS

According to the results of standard proctor tests, the values of MDD of stabilized soil specimens decrease from 1.570 g/cm³ to 1.548 g/cm³ with the amount of FS increases. This is because the specific density of the FS material is lower than that of the CH specimen. As the amount of additive increases, the optimum water content values of the mixtures increase from 22.1% to 26%. The reason for this is that due to the small grain structure of FS, the water requirements of the stabilized soil specimens increase.

3.2. Engineering Properties

Engineering properties of stabilized soil specimens prepared in this study are divided into two subtitles that are swelling potential and strength parameters of stabilized soil specimens.

3.2.1 Swelling potentials of stabilized soil specimens

Swelling potentials of stabilized soil specimens were determined under 1 kPa surcharge pressure. The results obtained from these tests are given in Figure 5. As the addition ratio of FS increases, the swelling potential of stabilized soil specimens gradually decrease. Additionally, the curing time also influences the swelling potentials, as they decrease with an increase in curing duration.

The lowest swelling potential (%20) was obtained by specimen with %15 FS waited in 56 days curing. It was determined that the swelling potential of this specimen was reduced by more than % 50.

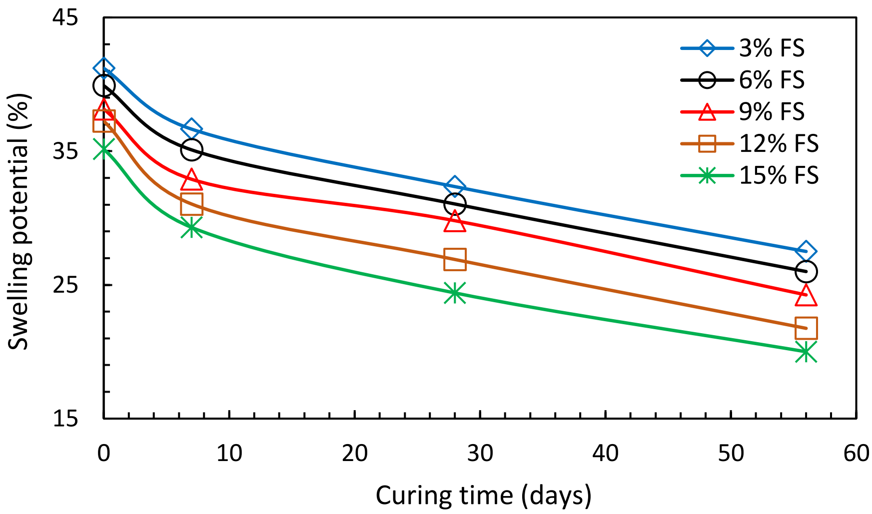


Figure 5. Swelling potentials of stabilized soil specimens with FS

3.2.2 Strength parameters of stabilized soil specimens

Firstly, the unconfined compressive strength tests were done to determine the alteration of strength parameter of stabilized soil specimens. This test was chosen as a reference test for the California Bearing Ratio (CBR) test due to its quicker and simpler nature. The unconfined compressive strength test provides valuable insights into the strength behavior of the stabilized soil. The results of unconfined compression test are presented in Figure 6.

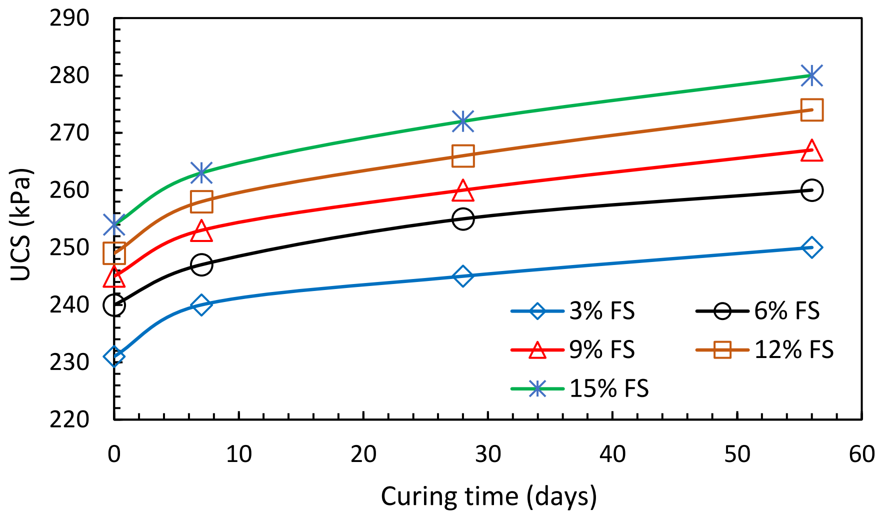


Figure 6. Unconfined compressive strengths of stabilized soil specimens with FS

The unconfined compressive strength (UCS) of CH was measured 210 kPa. This parameter of all stabilized soil specimens increased with both addition ratio of FS and curing period. For instance, this parameter of stabilized soil specimen included %15 FS was increased from 250 kPa to 280 kPa for 56 days curing period. This result can mean that there is an interaction between FC and CH. This condition will be investigated by SEM analysis.

According to both free swell tests and unconfined compression test, the best parameters of this study were obtained from stabilized soil specimen with %15 FS in 56 days curing period. For this reason, both CBR test and SEM analysis were only performed on this stabilized soil specimens.

High plasticity clay swells when it is submerged in water. Then, the strength of this soil decreases. For this reason, CH specimen was separately tested by following procedures of both dry and wet CBR tests to determine the difference of CBR values. The outputs obtained from these tests are given in Table 4.

Table 4. Dry and wet CBR tests results on CH

Test	CBR swell (%)	CBR (%)
Dry CBR	-	17.5
Wet CBR	%38.3	1.1

CH specimen swells when it is submerged in water. While the strength of CH specimen is sufficient at the dry condition, the strength of this specimen at wet condition is very poor and insufficient.

Graphs of both load-displacement and CBR swelling drawn at wet CBR tests conducted within the scope of the study are given in Figure 7.

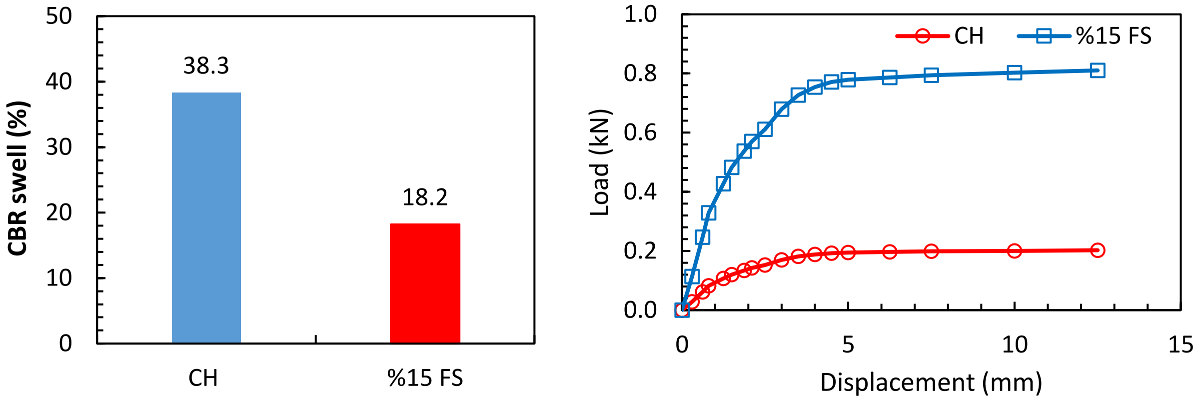


Figure 7. Wet CBR test results: a) swell ratio and b) load-displacement curves

As a result of the experiment, it was found that the CBR swelling value of the stabilized soil specimen with 15% filter sludge (FS) and 56 days of curing was 18.2%, while the CBR value was 4.375%. Comparatively, the CBR swelling value of the high plasticity clay (CH) specimen decreased by more than 50%, and the CBR value of CH increased by approximately four times after the addition of filter sludge.

The addition of filter sludge to CH specimen provided firstly the reduction of swelling potential and then the increase of the strength of this soil. This condition will be analyzed by SEM images.

3.3 Mineralogical properties of stabilized soil specimens

The microstructure of the CH clay was determined by SEM images of the unimproved soil. Kaolin type clay minerals are visible in the image magnified 10000 times (Figure 8a). The shapes of CH crystals are thin plate-like particles. When the image is approached 50000 times, the presence of montmorillonite type clay minerals has been detected in some regions (Figure 8b). The montmorillonite type clays in the soil impart high plasticity to the soil. The results obtained from the SEM images support the consistency limit results.

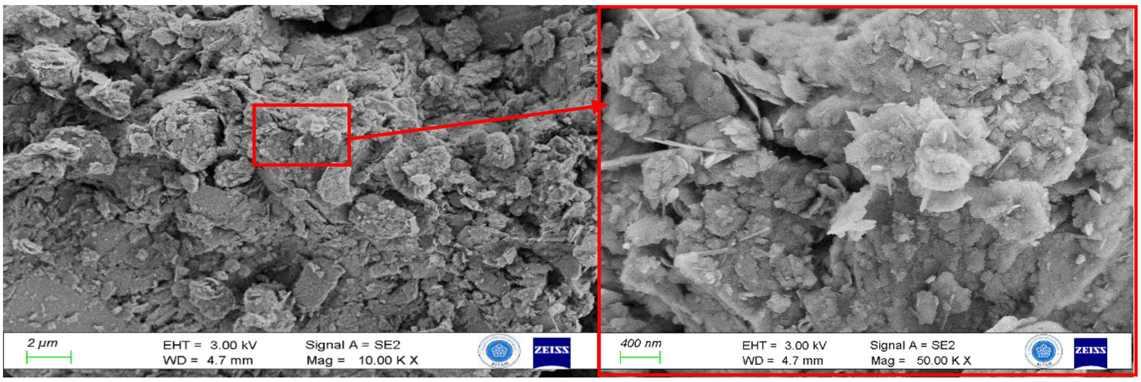
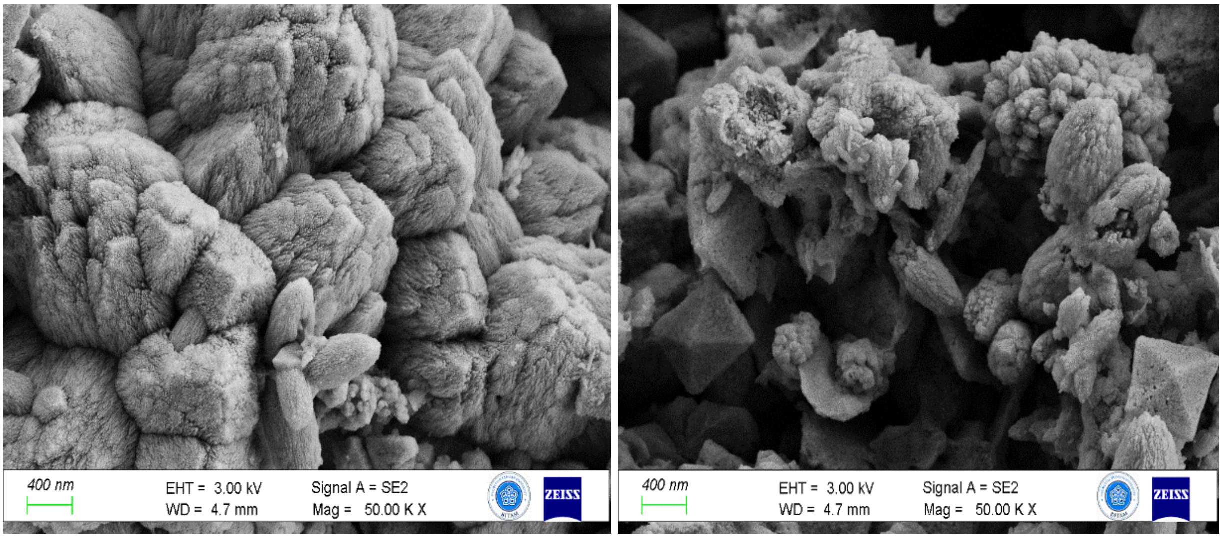


Figure 8. SEM image of CH: magnification factor is 10000 (left) and 50000 (right)

Figure 9 shows the SEM images of natural and burned filter sludge. Since the filter sludge contains organic matter, a fibrous and amorphous structure appears in the SEM image of natural filter sludge (Figure 9a). Figure 9b illustrates that the fibrous structure reduces by burning process of filter sludge. When organic materials are burned, it is seen that pyramidal structures appear in the FS microstructure, the amorphous structure changes somewhat and the spacing between minerals increases (shrinkage effect).



a) Natural FS b) Burned FS

Figure 9. SEM image of filter sludge (magnification factor=50000)

Amongst the stabilized soil samples, the mixture has the best performance (maximum strength, minimum swelling and plasticity properties) is the CH sample amended with 15% FS and cured 56 days. The SEM image of the stabilized specimen is given in Figure 10. Clay minerals appear to be covered with FS in 5000 times magnified SEM images (Figure 10a). However, in SEM images taken at 20000 times magnification, it was observed that there was interaction between the CH-FS particles, the grains were bonded to each other and the grain size increased, as a result, there was agglomeration, and there were filamentous structures on the newly formed large grains (Figure 10b).

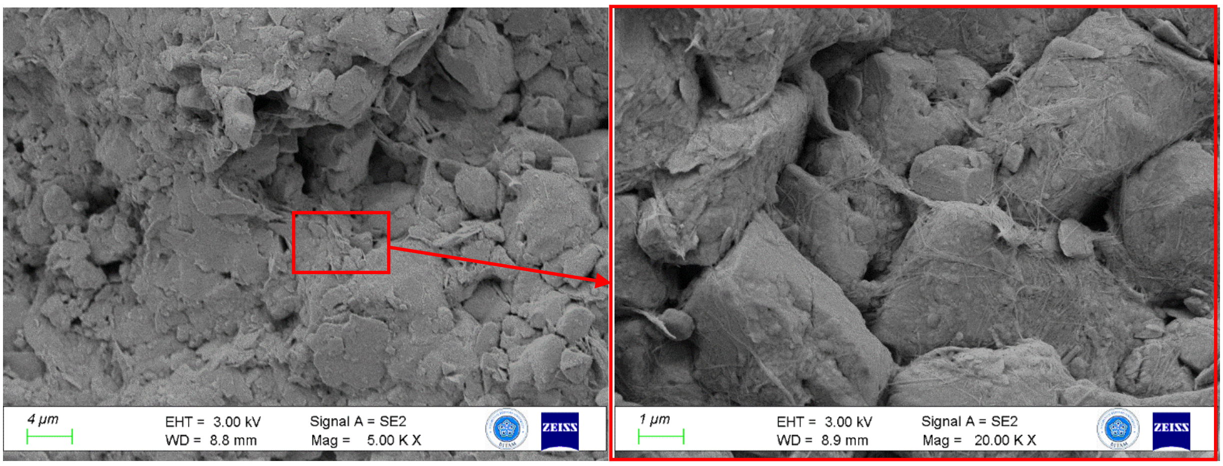


Figure 10. SEM image of the stabilized specimen with filter sludge for 56 days curing period

4. CONCLUSIONS

In the present study, high plasticity clay soil was stabilized by using filter sludge, a waste product of sugar industry. Meanwhile, geotechnical properties of stabilized soil were investigated. The findings and evaluations obtained within the scope of this study are summarized in below.

1. Since the filter sludge material contains organic matter, it is not suitable for use in soil improvement in natural form. Because organic materials rot in the soil over time, and the specimen becomes moldy. This situation reduces the strength parameters of the soil. Therefore, before using the filter sludge, the organic substances in it were removed by burning at 450°C.

2. With the addition of filter sludge to the high plasticity clay specimens, the plasticity properties of these soils decreased.
3. Addition of FS to the high plasticity clay specimens; while decreasing the maximum dry density, it increased the optimum water content.
4. The unconfined compressive strength of the specimens improved with both the addition of filter sludge and increased curing time (0-56 days).
5. As a result of wet CBR test, belonging to high plasticity clay specimens; while the CBR swelling value was high, the CBR value was very low. Wet CBR test was carried out on the specimens with 15% filter sludge. As a result of this experiment; while the CBR swelling value decreased by 52.5%, the CBR value increased approximately 4 times.
6. The swelling potential values obtained from the free swell test indicated that the filter sludge additive ratio and curing time positively affected the improvement of the stabilized soil.
7. According to the SEM analysis, filamentous binders between the thin plate particles of CH specimen formed with FS stabilization process of high plasticity clay.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author 1: Resources, Investigation, Experimentation, Writing – original draft **Author 2:** Resources, Investigation, Experimentation, Formal analysis, Validation, Methodology, Visualization, Writing – original draft

Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Data Avaibility

All data generated or analyzed during this study are included in this published article.

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