

The effect of lime, gypsum and fly ash on the strength and plasticity of clayey soils

Kireç, jips ve uçucu külün killerin dayanımı ve plastisitesi üzerindeki etkisi

Derya Toksöz Hozatlıoğlu^{1*} 

¹Department of Geological Engineering, Faculty of Engineering, Sivas Cumhuriyet University, Sivas, Türkiye.
detoksoz@gmail.com

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Abstract

Some clayey soils tend to show weakness in strength and they necessitate additional improvements before design studies. For the purpose of achieving the desired strength, the soil can be stabilized chemically with some additives by using the shallow mixing technique. The aim of this paper is investigation and comparison of different additives' shallow mixing performances on improving the strength and plasticity of clayey soils. As additive materials lime, gypsum and fly ash were used. The study was performed in the laboratory by preparing cylindrical samples of the additive and soil mixtures. After a four month curing period, unconfined compression test and Atterberg limit tests were performed on the specimens extracted from the cylindrical samples. The results showed that the best performance was achieved with fly ash with an increase of 172.59% on the soil's unconfined compressive strength. Lime provided a medium degree of improvement in comparison with fly ash with an increase of 65.38% on the soil's strength. Gypsum, however, reduced the soil's strength by 4.33%. Lastly, all additive materials showed a decrement in the soil plasticity.

Keywords: Lime, fly ash, gypsum, unconfined compressive strength, plasticity.

Öz

Bazı killi zeminler dayanım açısından zayıflık gösterme eğilimindedir ve tasarım çalışmaları öncesinde ek iyileştirmeler gerektirir. İstenilen dayanıma ulaşmak için zemin yüzeysel karıştırma tekniği kullanılarak katkı maddeleri ile kimyasal olarak iyileştirilebilir. Bu çalışmanın amacı farklı katkı maddelerinin killi zeminlerin dayanımını ve plastisitesini iyileştirmedeki yüzeysel karıştırma performanslarının bulunması ve karşılaştırılmasıdır. Katkı maddesi olarak kireç, jips ve uçucu kül kullanılmıştır. Çalışma laboratuvarında katkı maddesi ve zemin karışımlarının silindirik örnekleri hazırlanarak gerçekleştirilmiştir. Dört aylık bir kür süresi sonunda silindirik örneklerden alınan zemin numuneleri üzerinde tek eksenli basınç dayanımı deneyi ve Atterberg limit testleri uygulanmıştır. Elde edilen sonuçlar incelendiğinde en iyi performansın %172.59 bir iyileştirmeyle uçucu kül ile sağlandığı görülmüştür. Kireç zeminin dayanımını %65.38 arttırarak orta derecede bir iyileştirme sağlamıştır. Diğer taraftan jips zeminin dayanımını %4.33 oranında azaltmıştır. Son olarak ise bütün katkı malzemeleri zemin plastisitesinde bir azalma sağlamıştır.

Anahtar kelimeler: Kireç, uçucu kül, jips, serbest basınç dayanımı, plastisite.

1 Introduction

Since the existence of humankind, people has been building the structures on the soils or use the soils in the building of several structures such as earthfill dam and road foundation. In order to build safe and economic constructions, it is crucial to examine the soil's geotechnical properties. Some soil conditions are problematic and they require additional improvements before design studies. Clayey soils, in particular, have a complex structure and are generally problematic for geotechnical engineers. This situation stems from their properties such as high plasticity, volume change, low permeability, and their mineralogy and chemistry [1]. In engineering applications, most of the problems encountered with soils derive from the strength problems of clayey soils. Particularly, the soils that consist of a large quantity of swelling clay minerals such as Na-montmorillonite may cause significant damages to structures. The most common and economical method used to avoid the problems sourced by such soils is to treat the soil chemically with some additive materials. The shallow mixing technique is the most commonly used method for stabilizing soils chemically. In this technique, the soil is scarified to a certain width and depth and partially pulverized. Then, at an appropriate water content, the additive material is mixed with the soil. After this process, the soil is compacted with suitable

techniques [2]. Stabilization mechanism of this method is based on the chemical reactions which occur between the soil and the additive. These reactions give rise to an important improvement in the strength characteristic of the soil. The most widely used additives in the literature are fly ash, lime, cement and bituminous materials [3]. When choosing the additive material to be used, things to be taken into consideration are its availability, economic aspect, environmental effects, accessibility and stabilization performance [4].

The purpose of the present investigation is to examine and compare the shallow mixing performances of lime, gypsum and fly ash on improving the strength and plasticity of clayey soils. An investigation into these additives' column and shallow mixing performances on the treatment of swelling soils was conducted by Toksoz Hozatlioglu and Yilmaz [5]. However, the researchers discussed the performances only in terms of decrement in swelling amount of the soil. They didn't take the improvement in the soil's strength characteristic into consideration. This research is a follow up study of Toksoz Hozatlioglu and Yilmaz's study and its aim is to examine the shallow mixing performances of lime, gypsum and fly ash in terms of the improvement in the soil strength and soil plasticity [5]. In this paper, column performances of the additives were not investigated. Because Toksoz Hozatlioglu and Yilmaz noted

*Corresponding author/Yazışılan Yazar

in their study that the shallow mixing technique's performance is higher than that of column technique for all of the additives used [5]. Therefore in the present study only the shallow mixing technique was taken into consideration.

Among the additives used, lime is the most widely used one in the literature. A great number of studies have searched for the influence of lime on several engineering properties of soils by using shallow mixing technique [6]-[10]. When lime is put in clayey soils, four different mechanisms are formed. These are cation exchange reactions, flocculation, carbonation and puzzolonic reactions. The first two reactions occur within a short time. Puzzolonic reactions, on the other hand, occur slowly over a long amount of time. In this process, cement products are formed and the strength of the soil increases [11]. Similarly, fly ash has been widely chosen for stabilization of soils and has attracted attention of researchers because of its lime content and puzzolonic action [12]-[15]. Gypsum, on the other hand, was considered as an additive material in only a few studies [16]-[19]. Gypsum is composed of hydrated calcium sulfate. It is a soft white mineral. Its availability and relatively cheaper cost make it attractive as an additive material for researchers. In the present study, these additives' shallow mixing performances on improving the strength and plasticity of clayey soils were investigated and the results were compared with regard to additive type.

2 Materials and method

The soil used in the present investigation is the same with that used in Toksoz Hozatlıoğlu and Yılmaz's study [5]. It is an artificial soil which is a mixture of bentonite and a natural soil. The aim of using an artificial soil is to make the natural soil problematic in terms of the strength. The bentonite was acquired from a clay kiln situated in Tokat, Türkiye and the natural soil was taken from an excavation site located in Sivas Cumhuriyet University's campus, Türkiye. The bentonite used is composed of a large amount of Na-montmorillonite which causes the soil to have a high swell potential and accordingly a low strength. The artificial soil sample's bentonite content was chosen to be 20% considering the study conducted by Toksoz and Yılmaz [20]. In this study which is about the effect of swelling clay content on migration of ions, the authors found that the biggest ion migration distance was achieved with 20% bentonite content, except that of 0% bentonite content. Therefore, the soil sample prepared for the present investigation is comprised of 20% bentonite and 80% natural soil by weight. After preparing the soil sample, the cylindrical samples of the additive and soil mixtures were created in the laboratory for each additive (lime, gypsum and fly ash) to investigate their shallow mixing performances. After a certain curing time, for the purpose of examining the additives' performances, unconfined compression test and Atterberg limit tests were performed on the specimens extracted from the cylindrical samples. The results obtained were evaluated and compared at the end of the study.

2.1 Characteristics of the soil sample

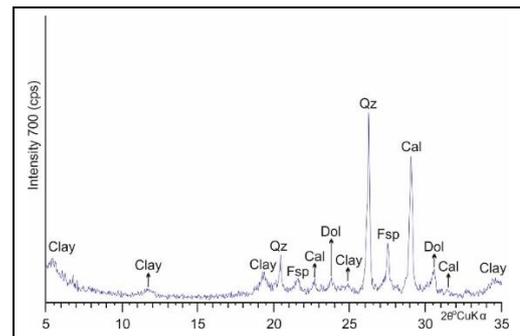
Since the soil and the additives used for the present investigation are the same as that used in Toksoz Hozatlıoğlu and Yılmaz's study, the soil sample's properties and the additives were taken from their study [5] (Table 1).

Liquid limit, plastic limit and plasticity index of the soil sample are detected to be 64%, 17.4% and 46.6%, respectively, in accordance with ASTM D 4318 standard process [21].

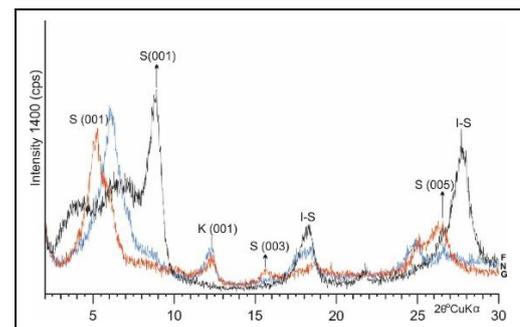
Table 1. The soil properties [5].

Characteristic	Value
Liquid limit, (%)	64
Plastic limit, (%)	17.4
Plasticity index, (%)	46.6
USCS-Soil class	CH
Clayey fraction, (%)	49.6
Specific gravity	2.70
Maximum dry unit weight (gr/cm ³)	1.55
Optimum water content (%)	20.5
Unconfined compressive strength (kg/cm ²)	2.08

In compliance with USCS (Unified Soil Classification System), the class of the soil sample is CH (high plasticity clay). Its clay fraction is found to be 49.6% by performing the hydrometer analysis in accordance with ASTM D 7928 standard procedure [22]. By considering ASTM D 854 standard procedure, its specific gravity is calculated as 2.70 [23]. Lastly, its maximum dry unit weight and optimum water content are 1.55 gr/cm³ and 20.5%, respectively, in accordance with ASTM D 698 standard test procedure [24]. Additionally, the soil sample's XRD diffractograms are given in Figure 1. The existing minerals in the soil sample are clay, calcite, quartz, feldspar and dolomite. The content of its average semiquantitative clay mineral is calculated as 45%.



(a)



(b)

Figure 1. The soil sample's XRD patterns. (a): Whole sample. (b): Clay fraction (Qz: Quartz, Dol: Dolomite, Cal: Calcite, Fsp: Felspar, S: Smectite, K: Kaolin, I-S: Illite-Smectite) [5].

2.2 Characteristics of the additive materials

The lime is a hydrated lime and it consists of 90% Ca (calcium). It was obtained from a lime kiln situated in Tokat, Türkiye. The fly ash was produced in a thermal plant situated in Sivas, Türkiye and it is a class C fly ash. Lastly, gypsum was obtained from a gypsum pit situated in Adana, Türkiye. The additives' XRD diagrams are presented in Figure 2.

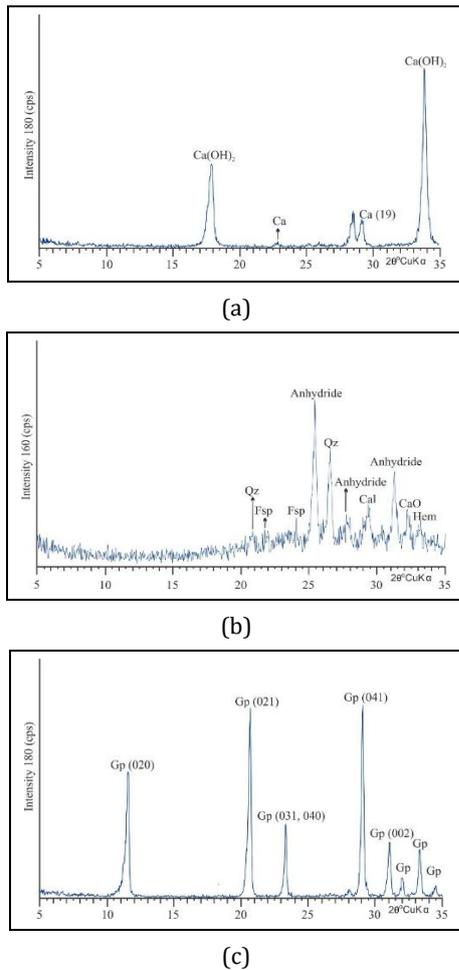


Figure 2. XRD diagrams of the additives. (a): Lime. (b) fly ash (c) gypsum ($\text{Ca}(\text{OH})_2$: Hydrated lime, Ca: Calcium, Qz: Quartz, Cal: Calsite, Fsp: Felspar, Hem: Hematite, Cao: Free lime, Gp: Gypsum) [5].

3 Creating cylindrical samples of the additive and soil mixtures

Before creating the cylindrical samples, firstly, the mixtures of soil and additive were prepared. The lime, gypsum and fly ash percentages in the mixtures were chosen by considering the previous studies. Bell reported that, for maximum stabilization of the soil, the optimum lime content should be between 1% and 3% by weight [25]. Basma and Tuncer suggested that the lime content need is between 2% and 8% in soil stabilization [26]. Also, in the studies on gypsum, Kolay and Pui reported that the soil's unconfined compressive strength increases with the gypsum inclusion, but after adding more than 6% of gypsum, the UCS is decreased [27]. Yilmaz and Civelekoglu found that 5% gypsum content provided the maximum increase on the unconfined compressive strength [28]. Lastly, Bose found that the content of optimum fly ash is 20% for increasing the soils' shear strength [29]. Similarly, Sharma et al. stated that the fly ash content needed for increasing the soil's unconfined strength is 20% [30]. Consequently, 5% lime, 5% gypsum and 20% fly ash were used for soil additive mixtures in the present study. The mixtures of soil and additive were produced by separately adding the additives into the soil in these percentages by weight.

For the purpose of creating the cylindrical samples, the soil and additive mixtures were compacted in proctor molds, which are 115 mm in height and 152 mm in diameter, at their optimum water content. The mixtures' optimum water content are presented in Table 2.

Table 2. Optimum water contents of the mixtures [5].

The soil and additive mixtures	w_{opt} (%)
5% lime + soil	23
5% gypsum + soil	24.3
20% fly ash + soil	25.5

Also, the compaction curves showing maximum dry density ($\gamma_{k\text{max}}$) and optimum moisture content (w_{opt}) values of the soil and the soil-additive mixtures are given in Figure 3. The mixtures were compacted in three layers with a modified rammer.

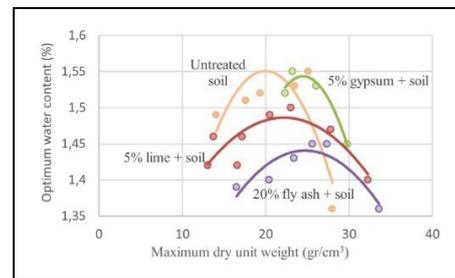


Figure 3. Compaction curves of the soil and the soil-additive mixtures.

After preparing the cylindrical samples of the additive and soil mixtures, they were left in cure. Curing time has an important role on the performances of additives. To decide the curing time, the previous studies conducted on this topic were taken into consideration. Basically, the more curing time, the better improvement due to the pozzolanic reactions. The previous studies indicate that curing period varies between 7 and 120 days in stabilization of soils using the shallow mixing technique [31]-[33]. Toksoz Hozatlioglu and Yilmaz considered a curing period of 4 months in their study [5]. To be able to compare the results obtained in two studies, the same curing time was chosen in the present study. The cylindrical samples of the additive and soil mixtures were cured at ambient temperature (about 25 °C) for 4 months. To prevent the moisture loss during curing, the upper parts of the cylindrical samples were surrounded with a membrane. A typical profile of the cylindrical samples of the additive and soil mixtures is presented in Figure 4.

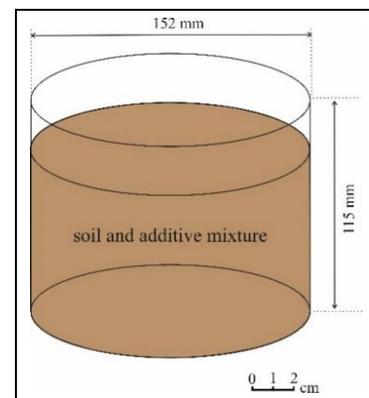


Figure 4. A typical profile of the cylindrical samples of the additive and soil mixtures.

4 Results and discussion

After a 4 month curing time, for the purpose of examining the shallow mixing performances of the additives, unconfined compression tests and Atterberg limit tests were applied on the soil specimens extracted from the cylindrical samples in accordance with ASTM-D 2166 and ASTM D 4318 standard procedures, respectively. In Table 3, the results obtained are given. A few soil specimens on which unconfined compression tests were performed are given in Figure 5. Additionally, the stress-strain curves acquired for the mixtures are shown in Figure 6.

Table 3. Unconfined compressive strength and Atterberg limit values of the soil stabilized with various additives.

Mixture	UCS (kg/cm ²)	LL	PL	PI
Untreated soil	2.08	64	17.4	46.6
5% lime + soil	3.44	55.8	21.57	34.23
5% gypsum + soil	1.99	58	16.66	41.34
20% fly ash + soil	5.67	60.5	27.25	33.25



Figure 5. The failure pattern of a few soil specimens as a result of the unconfined compression test.

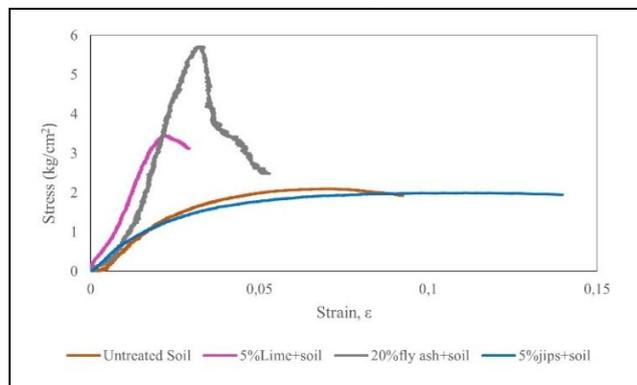


Figure 6. Stress-strain curves for the soil stabilized with various additives.

5% lime addition increased the soil's unconfined compressive strength from 2.08 kg/cm² to 3.44 kg/cm², which means an increase of 65.38% on the soil strength. Also, the increase on the unconfined compressive strength of the soil stabilized with 20% fly ash is found to be 172.59%. Nevertheless, the unconfined compressive strength of the soil stabilized with 5% gypsum decreased by 4.33%. Consequently, in terms of the improvement on the soil strength, the highest performance was acquired with fly ash. Lime provided a medium degree of improvement. Gypsum, on the other hand, reduced the strength of the soil. The changes on the unconfined compressive strength of the soil stabilized with different additives are given in Figure 7.

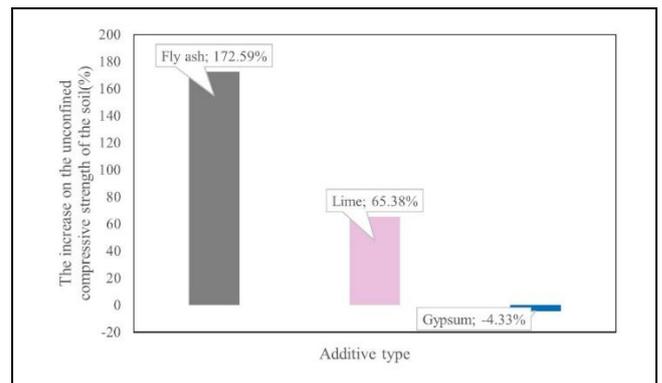


Figure 7. The increase on the unconfined compressive strength of the soil stabilized with different additives.

If a comparison is made between two studies, in Toksoz Hozatlioglu and Yilmaz's study, the best stabilization was obtained with lime and then fly ash with a performance of 99.8% and 98.1%, respectively [5]. Gypsum, however, exhibited the lowest performance with a reduction 65.42% in the soil's swelling percent. In the present investigation, on the other hand, the highest performance was acquired with fly ash. Lime provided a medium degree of improvement compared to fly ash. Gypsum, however, didn't show any improvement, conversely it decreased the soil's unconfined compressive strength by 4.33%. Therefore, it can be said that, in terms of the decrement in the soil's swelling percent, the best performance was provided with lime, whereas in terms of the improvement in the soil strength, the best performance was obtained with fly ash. The reason why lime showed the highest performance on stabilization of swelling behaviour might be because of its high calcium (Ca²⁺) ion content. This exchangeable cation replaces with Na⁺ ions in the soil structure and gives rise to reduction in the soil's swell potential. The fly ash used in the study contains lower Ca²⁺ ion content than that of lime. On the other hand, with regards to the improvement in the soil strength, fly ash showed the best performance. This can be explained by its puzzolonic nature. Puzzolonic reactions cause increment on the soil strength over a period of time. Lastly, while gypsum provided an improvement in the soil's swelling behaviour, it didn't improve the strength of the soil. Gypsum consists of hydrated calcium sulfate and (CaSO₄. 2(H₂O)) is its chemical formula. The reason why gypsum decreased the soil's swelling percent might be because of its Ca²⁺ ion content. However for puzzolonic reactions to happen, the presence of hydroxyl (OH⁻) ions are necessary, too. OH⁻ ions lead to increment on the soil alkalinity. High alkaline conditions induce puzzolonic reactions which improve the soil strength in the long term [35]. Gypsum doesn't have OH⁻ ion in its structure, therefore it didn't improve the soil's unconfined compressive strength. Conversely, it decreased the soil strength by 4.33%. However, this amount of decrement can be negligible. In the previous works related to gypsum performance as an additive material, there are different findings. While some researchers found that gypsum increases the strength of soils [30], [36]-[38], other researchers found that it has minor impact on the strength of soils or it decreases the strength [39],[40]. This may be explained by curing time effect on the strength while stabilizing soil with gypsum. Gypsum has sulphate ion (SO₄²⁻) in its structure, as well and it may have negative effect on the soil strength in the long run. In the long periods, sulfate crystals may lead to the increase of soil porosity and roughness, which leads to decrement on compressive strength. In the studies which suggests that

gypsum increases the strength of soils, the maximum curing time is 28 days. In the present study however the curing time is 4 months which might be too long for improving the strength of the soil with gypsum.

In the present investigation, the effectiveness of lime, gypsum and fly ash on Atterberg limits of the soil was investigated, as well. Atterberg limits are significant for the characterization of soil in a wide category [41]. Even though there are many studies on the influences of lime and fly ash on Atterberg limits of clayey soils [42]-[44],[25],[27],[28],[45],[46], the effect of gypsum has been investigated only in a few studies [16]-[19].

In general, lime addition leads to increment on the plastic limit of a soil with a corresponding reduction in the plasticity. The Ca^{2+} ions from lime cause a decrease in plasticity and the soil becomes more easily worked and more friable [25]. Also some researchers found that fly ash addition decreases the liquid limit due to the reduction in the diffused double layer thickness [47]-[49]. Finally, Yilmaz and Civelekoglu pointed out that gypsum addition decreases liquid limit and plasticity due to the replacement of Na^{+} ions by Ca^{2+} ions which causes a decrease in diffuse double layer thickness [28]. The results acquired in the present investigation are align with the previous studies. After 4 months of curing time, the liquid limit (LL), plastic limit (PL) and plasticity index (PI) of the soil and additive mixtures were detected and the results are presented in Table 3.

All additive materials showed a decrease in liquid limit value. While lime caused a decrease of 15.45% in the soil's liquid limit, gypsum and fly ash provided a decrement of 12.12% and 8.33%, respectively (Figure 8).

Plastic limit of the soil stabilized with fly ash increased by 66.35%. Lime showed an increase of 31.68% whereas gypsum provided an increase of just 1.72% on the soil's plastic limit (Figure 9).

Lastly, the influences of lime and fly ash on the soil's plasticity index are almost same, which are 31.01% and 32.99% decrement, respectively. Gypsum, however, showed the lowest performance and decreased the soil's plasticity index by 16.69% (Figure 10).

5 Conclusions

In this study, the influences of lime, gypsum and fly ash on improving the strength and plasticity of soils were investigated. As stabilization technique, the shallow mixing technique which is the most common used one was chosen. The curing time in the study was selected as 4 months.

The highest performance was acquired with fly ash. Lime provided a medium degree of improvement. Gypsum, however, reduced the soil strength. The reason why fly ash showed the best performance on the improvement of the soil strength might be due to its puzzolonic nature. Puzzolonic reactions lead to increase the soil strength in the long term.

Gypsum provided an increase on the swelling behaviour of the soil, whereas it didn't increase the soil strength. The reason why gypsum decreased the soil's swelling percent might be because of its Ca^{+2} ion content. However, for puzzolonic reactions to happen, the presence of hydroxyl (OH^{-}) ions are necessary, as well. Gypsum doesn't have OH^{-} ion in its structure, therefore it didn't increase the soil's unconfined compressive strength. Conversely, it decreased soil strength by 4.33%. However, this amount of decrement can be negligible.

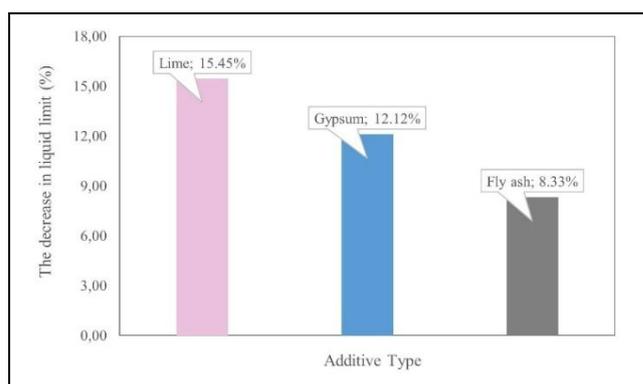


Figure 8. The decrease in the liquid limit of the soil stabilized with various additives.

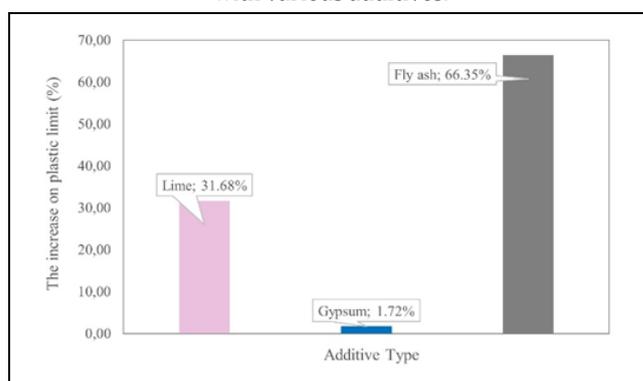


Figure 9. The increase on the plastic limit of the soil stabilized with various additives.

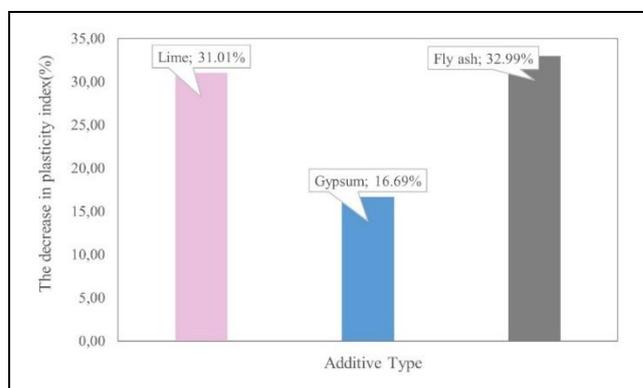


Figure 10. The decrement in the plasticity index of the soil stabilized with various additives.

If a comparison is made between the performances of the additives in terms of the improvement in the strength and in the swelling behaviour, lime exhibited the best performance on the soil's swelling behaviour according to the study of Toksöz Hozatlıoğlu and Yilmaz [5]. This might be because of high Ca^{2+} ion content of lime. However, in the present study it was found that fly ash's performance is much more than that of lime in terms of the improvement in the soil strength. This is because fly ash has puzzolonic nature which means it reacts and hardens in the water presence. The puzzolonic reactions occur in a long period of time and lead to a slower strength gain but result in a more durable soil in the long term.

All additive materials showed a decrement on liquid limit and an increment on plastic limit value. The influences of lime and fly ash on the soil's plasticity index are almost same. Gypsum,

nevertheless, showed the lowest performance on decreasing the soil's plasticity index. The reason why all additives showed a decrease on liquid limit and plasticity is due to their Ca^{2+} ion content. Ca^{2+} ions replace with Na^+ ions in the soil structure and this reaction causes a decrease in diffuse double layer thickness.

As a result, when stabilizing problematic soils with additive materials, their performances both on the soil strength and on the soil's swelling behaviour must be investigated. Also, when planning to stabilize a problematic soil, all factors such as the availability, price and improvement performance of the additive material should be evaluated together and the most appropriate additive material should be selected.

6 Author contribution statement

In the study conducted, Derya Toksöz Hozatlıoğlu contributed to producing the idea, literature review, provision of the materials used, the laboratory studies, evaluating of the results and writing the article.

7 Ethics committee approval and conflict of interest statement

"There is no need for ethics committee approval for the prepared article". "There is no conflict of interest with any person/institution in the prepared article".

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