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Shallow mixing and column performances of lime, fly ash and gypsum on the stabilization of swelling soils

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ABSTRACT

Swelling soils are problematic in terms of geotechnics, and they require mitigation actions in preliminary works. The most commonly used method to mitigate the damage caused by swelling soils is to stabilize the soil with chemical additives by using shallow mixing or column techniques. It is important to determine the most suitable additive material and the most appropriate technique when stabilizing swelling soils. The aim of this study is to investigate shallow mixing and column performances of various additives on the stabilization of swelling soils. Lime, fly ash and gypsum were chosen as the additives for this purpose. The study was conducted in the laboratory by creating the model of the land at the laboratory scale. Two different small scale models were designed for each additive, one for investigating their shallow mixing performances, and the other one for their column performances. A curing time of 4 months was considered for all of the models. At the end of the curing time, in order to determine the changes on the swelling behaviour of the soil, free swelling test was carried out on the specimens taken from the small scale model boxes. The results showed that the best improvement was achieved with lime for both techniques with reductions of 99.8% and 51.9% in the swelling percent of the soil when using the shallow mixing and column techniques, respectively. Gypsum, on the other hand, exhibited the lowest performance for both techniques by reducing the swelling percent of the soil by 65.42% with the shallow mixing technique and 25.3% with the column technique. Lastly, the shallow mixing technique showed 47.9%, 64.41% and 40.12% higher performances than the column technique for lime, fly ash and gypsum, respectively.

1. Introduction

Swelling soils are the soils that swell when they get wet and shrink when they get dry. These soils cause serious damages especially to the light structures such as roads, airports, garden walls, infrastructures and single-storey buildings. A significant part of the damages caused by swelling soils can be avoided by detecting these soils in preliminary studies and taking appropriate cautions. Among the precautions to be taken, the most preferred method is to stabilize soil with on-site operations. Soil stabilization can be defined as changing undesired properties of soils by physical or chemical processes to meet the engineering purpose. Although there are different soil stabilization methods, the most commonly used one for swelling soils is the chemical stabilization with additives. In the literature, the most commonly used additives to stabilize swelling soils are lime, fly ash, cement and bituminous materials (Van Impe, 1989).

There are two common methods used in order to stabilize swelling soils with additives. These are the shallow mixing and column techniques. In the shallow mixing technique, the soil is scarified to the specified depth and width and then it is mixed with a certain amount of additives in the appropriate water content, and compacted by suitable techniques (Negi et al., 2013). In the column technique, however, the additive is filled into the vertical deep holes created in the ground, without mixing it with the natural soil. The dimensions of the columns are generally about 0.5 m in diameter and 10 m or greater in depth (Abiodun and Nalbantoglu, 2015). The stabilization mechanism of the column technique is based on physicochemical reactions between clay and additive in consequence of ion migration from the column to the surrounding soil (Rogers and Glendining, 1994). Therefore, this technique is mostly used for cohesive soils rather than cohesionless soils. Although the shallow mixing technique can be applied in the areas with large width, the depth of its applicability is small. In the column technique, on the other hand, the areas with smaller width but greater depths can be improved. Additionally, while the improvement distance in the column technique depends significantly on the ion migration from the column, in the shallow mixing technique ion migration is not crucial.

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The aim of this study is to investigate and compare shallow mixing and column performances of different additives during the stabilization of swelling soils. Lime, fly ash and gypsum were chosen as the additive materials. Among these materials, lime is the most commonly used additive for stabilization of swelling soils in the international literature, and the researchers have been reached an agreement about its performance. There are many studies on both shallow mixing and column performances of lime in the literature (Bell, 1996; Basma and Al-Sharif, 1994; Rogers and Glendining, 1994; Tonoz et al., 2003; Cabalar et al., 2014; Abiodun and Nalbantoglu, 2015). When lime is added to a clay soil, firstly, cation exchange reactions occur between calcium (Ca^{2+}) ions of lime and metallic ions on the surfaces of clay particles. These reactions give rises to reduction in the swell potential of the soil. Besides Ca^{2+} ion, hydroxyl (OH^{-}) ion affects the soil behaviour, as well. OH^{-} ions increase the alkalinity of the soil and highly alkaline conditions cause puzzolonic reactions that increase the strength of the soil over a long period. (Bell and Coulthard, 1990). Fly ash is the second common additive used after lime for stabilization of swelling soils. However, it has been mostly used in the shallow mixing applications rather than the column applications (Sivapullaiah et al., 1995; Çokça, 2001; Phanikumar and Sharma, 2004; Ghosh and Subbarao, 2006; Phanikumar, 2009; Bose, 2012; Darikandeh and Viswanadham, 2016). Fly ash is a waste material produced in coal-fired electricity generation. The primary benefits of using fly ash for stabilization of soils are enviromental inducements, cost savings and its availability (Zumrawi and Mohammed, 2016). The stabilization effects of fly ash on clayey soils stem from its puzzolonic nature and its lime content. Gypsum, on the other hand, has been rarely used as an additive material for stabilization of swelling soils. The number of the studies that have investigated gypsum's performance on the soil stabilization is quite limited (Bell and Maud, 1994; Ameta et al., 2007; Yılmaz and Civelekoğlu, 2009; Kılıç et al., 2016; Yılmaz, 2019). Gypsum is a hydrous calcium sulfate and its chemical composition is expressed by the formula $CaSO_42H_2O$. It has been used for stabilization of swelling soils owing to Ca^{2+} ions in its structure. When gypsum is added to a clayey soil, Ca^{2+} ions of gypsum are replaced with Na^{+} ions on the surfaces of the clay particles. The use of gypsum as an additive can be attractive because of its relatively cheaper cost and its availability. The reason of choosing lime and fly ash as additive materials in this study is their common usage in the stabilization of swelling soils. The reason of choosing gypsum, however, is to contribute to the literature through revealing its performance as an additive material. Consequently, there have been studies in the literature investigating the performance of one or two of these additives on the soil stabilization in terms of a single method. However, a study in which these additives were evaluated together and compared in terms of different techniques nearly does not exist. It is important to evaluate different additives and different techniques together in order to determine the most suitable additive material and the most appropriate technique for the stabilization of swelling soils. Therefore, in this study, shallow mixing and column performances of lime, fly ash and gypsum on the stabilization of swelling soils were investigated and these performances were compared both in terms of technique and additive material. The heterogeneous and anisotropic structure of the soil in the land scale makes it impossible to compare different methods. Hence, the study was conducted in the laboratory by building the model of the land at the laboratory scale.

2. Material and methods

In the scope of the study, an artificial soil sample was prepared by mixing a natural soil and a bentonite. The reason for adding the bentonite to the natural soil is to obtain an expansive soil for applying the stabilization techniques. The natural soil was extracted from the campus of Sivas Cumhuriyet University, Turkey. The bentonite which contains Na-montmorillonite clay mineral and has a very high swell potential was acquired from a clay pit in Resadiye, Tokat, Turkey. In the study conducted by Toksoz and Yılmaz (2019), the highest ion migration distance for the column technique was observed in the soil with a content of 20% bentonite. Therefore, in this study, the bentonite content of the prepared soil sample was decided to be 20% by weight. The analyses applied on the soil sample involved X-ray diffraction, grain size distribution, standard Proctor compaction, Atterberg's limits, specific gravity and free swelling tests. The complete program for experimental work is presented in Table 1.

In order to evaluate shallow mixing and column performances of the additives, two small scale models were built for each additive, which means a total of six models. After a curing time of 4 months, free swelling test was carried out on the specimens taken from the small scale model boxes for the purpose of determining the changes on the soil sample's swelling behaviour. The test results obtained were evaluated and compared both in terms of technique and additive material.

2.1. Properties of the soil sample

The soil sample used in the study is a mix of a natural soil and a commercial bentonite. To prepare the soil sample, the natural soil was first air dried for 24 h, and then it was pulverized by using a porcelain hummer. The soil and the bentonite were then placed in an oven for 105 °C for 24 h to ensure complete dryness. Afterwards, 20% bentonite by weight is added to the natural soil and they were mixed until an apparently homogenous state was achieved. At this stage, the prepared soil sample was ready for being analysed. The properties of the prepared soil sample is shown in Table 2.

Skempton (1953) divided the clays into 3 classes according to activity coefficient; i) inactive, if A (activity) is less than 0.75, ii) normal, if A is between 0.75 and 1.25, iii) active, if A is greater than 1.25. Since the soil sample used in this study has an activity of 0.93 (Table 2), it is a normal clay according to this assessment. In addition, in order to evaluate the swell potential of the soil indirectly, the swell potential charts of Seed et al. (1962) and Van Der Merwe (1964) were taken into account. According to these charts, the soil used in this study is a soil with high swell potential.

XRD analyses were performed on the soil sample, since the mineralogical compound of clayey soils is crucial for stabilization with chemical additives. The XRD diffractograms were acquired using a Rigaku model diffractometer at Cumhuriyet University Mineralogy-Petrography- Geochemistry Research Laboratory. On an X-Ray diffractogram, the X-axis stands for the scanning angle (2θ°) and the wavelength of the X-ray radiation (CuKα), and the Y axis represents the intensity. Intensity is defined as peak height intensity and usually recorded as counts per second (cps). XRD diffractograms of the soil sample used in this study are presented in Fig. 1.

Clay, quartz, calcite, feldspar and dolomite are the existing minerals in the soil sample. The average semiquantitative clay mineral content of the soil is found to be 45% and its average semiquantitative Na-smectite and Ca-smectite contents are 15.59% and 42.39%, respectively (Fig. 1).

Table 1
Testing program followed in the study.

	Tests	According to
1	X-ray diffraction (XRD) for untreated soil and the additives	Rigaku Operating Procedure
2	Grain size distribution (Sieve Analysis and Hydrometer) for untreated soil	ASTM D 422, 2007 and ASTM D 7928, 2016
3	Standard Proctor compaction test for untreated soil and soil-additive mixtures	ASTM D 698, 2007
4	Atterberg's limits for untreated soil	ASTM D 4318, 2000
5	Specific gravity for untreated soil	ASTM D 854, 2006
6	Free swelling test for untreated soil and treated soil with additives by both techniques	ASTM D 4546 (1986)

Table 2
The properties of the soil.

Property	Value
Liquid limit, LL (%)	64
Plastic limit, PL (%)	17.4
Plasticity index, Ip (%)	46.6
Shrinkage limit, SL (%)	9.93
Soil class (USCS)	CH
Clayey fraction, CF (%)	49.6
Specific gravity, GS	2.70
Activity, A	0.93
Maximum dry unit weight, γ_{dmax} (gr/cm^3)	1,52
Optimum water content, w_{opt} (%)	20.5
Free swelling percent (%)	90.1

2.2. *Properties of the additives*

The lime used in this study is a hydrated lime which contains 90% calcium and is produced in a pit located in Niksar, Tokat, Turkey. The fly ash is a class C fly ash and it was obtained from Kangal Thermal Plant located in Kangal, Sivas, Turkey. Lastly, the gypsum was acquired from a gypsum pit in Adana, Turkey. XRD analyses were performed on the additives in order to identify their mineralogical composition. XRD diffractograms of the additives are shown in Fig. 2-4.

3. Building small scale models

Two separate small scale models were designed for each additive in the laboratory, one is for investigating the performance of shallow mixing technique, and the other one is for the evaluating the performance of column technique. Since the migration of ions is not crucial in the shallow mixing technique, the dimensions of the model boxes were decided based on the previous laboratory investigations on the column technique reported by Katti and Gupta (1970), Tonoz et al. (2003), Pei et al. (2015) and Yılmaz (2019). The ion migration distances obtained in these investigations change between 0.76 and 2 times of the column diameters. In this respect, in the present study, a dimension of $20 \times 20 \times 45$ cm was considered to be enough to investigate both shallow mixing and column performances of the additives.

There can be many factors causing differences between improvement performances obtained in laboratory and field scale models. Some of these factors are curing condition, boundary condition, mixing and mixing equipment or workmanship (Makusa, 2013). It is obvious that field scale models can predict the performances of the additives more accurately. However, the heterogeneous and anisotropic structure of the soil in the land scale makes it impossible to compare different methods. Since the present study is a comparative study, scaling and boundary effects of the small scale models were neglected. Additionally, due to the fact that ion migration distances obtained in the previous works on the column technique are limited to only two times of column diameter, the boundary effects of the models built for the investigation of column performances of the additives can be negligible.

Another factor that has an important role on the performances of the additives is curing time. To decide the curing time, the previous works on both shallow and column techniques were taken into consideration. In general, the more curing time, the better improvement due to the puzzolanic reactions (Kezd, 1979). Nelson and Miller (1992) suggested that the curing time should extent to at least 28 days in order to supply appropriate conditions for puzzolanic reactions. The previous studies on the shallow mixing technique have shown that curing time changes between 7 and 120 days (Nalbantoglu and Gucbilmez, 2002; Kumar et al., 2014; Bagheri et al., 2014; Wang et al., 2019) In the studies on the column technique, however, curing time varies between 28 days and 2 years (Rogers and Glendining, 1997; Tonoz et al., 2003; Chong and Kassim, 2014; Singh and Sangita, 2016; Ashok and Reddy, 2016). Therefore, in this study, a curing time of 4 months was considered to be suitable for all small scale models.

3.1. *The small scale models for the shallow mixing performances of the additives*

Before building the small scale models, firstly, the amount of the additives needed had been decided by considering the previous studies on the topic. Ingles and Metcalf (1972) suggested using 3–8% of lime to improve high plasticity clays. According to Ingles (1987), the basic rule to consider when determining the mixing ratios is to use 1% of lime for every 10% of clay content in the soil. Jha and Sivapullaiah (2019) used 6% of lime in their study. Wang et al. (2019) obtained the best performance with 4–6% of lime. In the studies on fly ash, Alkaya (2002) concluded that the optimum fly ash amount should be between 15 and 25%. Bhuvaneshwari et al. (2005) identified the optimum fly ash content as 25%. Sharma et al. (2012) concluded that 20% is the optimum percentage of fly ash. Vukićević et al. (2013) found out that the best performance is provided with 15% fly ash content. Lastly, in the studies on gypsum, Yılmaz and Civelekoğlu (2009) stated that the influence of gypsum content over 5% on the improvement will be low. Kılıç et al. (2016) concluded that 3% gypsum content is the optimum ratio for the swelling percent. Kolay and Pui (2010) found out that the improvement decreases after 6% gypsum content. Karthick et al. (2019) identified optimum gypsum content as 4% in their study. As a result, in the present study, it was decided to use 5% lime, 20% fly ash, 5% gypsum for building the small scale models that are for investigating the shallow mixing performances of the additives.

In order ro prepare additive and soil mixtures, the additives were separately mixed with the soil in these percentages by weight. Afterwards, standard Proctor compaction test (Method A) was applied on the mixtures according to ASTM D 698 standard procedure by using a mold that is 101.6 mm in diameter and 116.4 mm in height, and a 2.5 kg rammer. The test results are presented in Table 3.

To prepare the small scale models, the soil sample was separately mixed with the additives in the determined rates and at the optimum water content. The soil-additive mixtures were then compacted into the rigid metal boxes (20x20x45 cm) in a height of 13 cm with a constant standard compaction energy. To avoid the possible interactions between the mixtures and the metal boxes, the inside of the boxes were covered with membranes before the mixtures were compacted into the boxes. The compaction of the mixtures was performed in three layers using a standard rammer weighing 2.5 kg according to ASTM D 698 standard procedure. To protect the water content of the mixtures, each model box was covered with a membrane. A curing time of 4 months was taken into consideration for each model. A typical section of the small scale model boxes and the top view of a typical model are shown in Fig. 5 and Fig. 6, respectively.

3.2. *The small scale models for the column performances of the additives*

While preparing the small scale models for evaluating the column performances of the additives, the model preparation process applied by Toksoz and Yılmaz (2019) in their study was taken into consideration. For this aim, firstly, the inside of the rigid metal boxes ($20 \times 20 \times 45$ cm) were covered with membranes to avoid the possible interactions between the soil and the boxes. The soil sample was then compacted into three separate boxes in a height of 13 cm, at the optimum water content and with a constant standard compaction energy. To install the columns, a hole was created in the corner of each small scale model box using a sampler tube that is 50 mm in external diameter. Afterwards, the additives were filled into the holes in three layers by lightly compacting each layer. A hollow polyvinyl chloride (PVC) pipe was located on the upper part of the columns and PVC pipes were then filled with distilled water. In order to promote ion migration from the columns, the water supply was kept during the curing time. A curing time of 4 months was taken into consideration for each model. The upper part of the model boxes

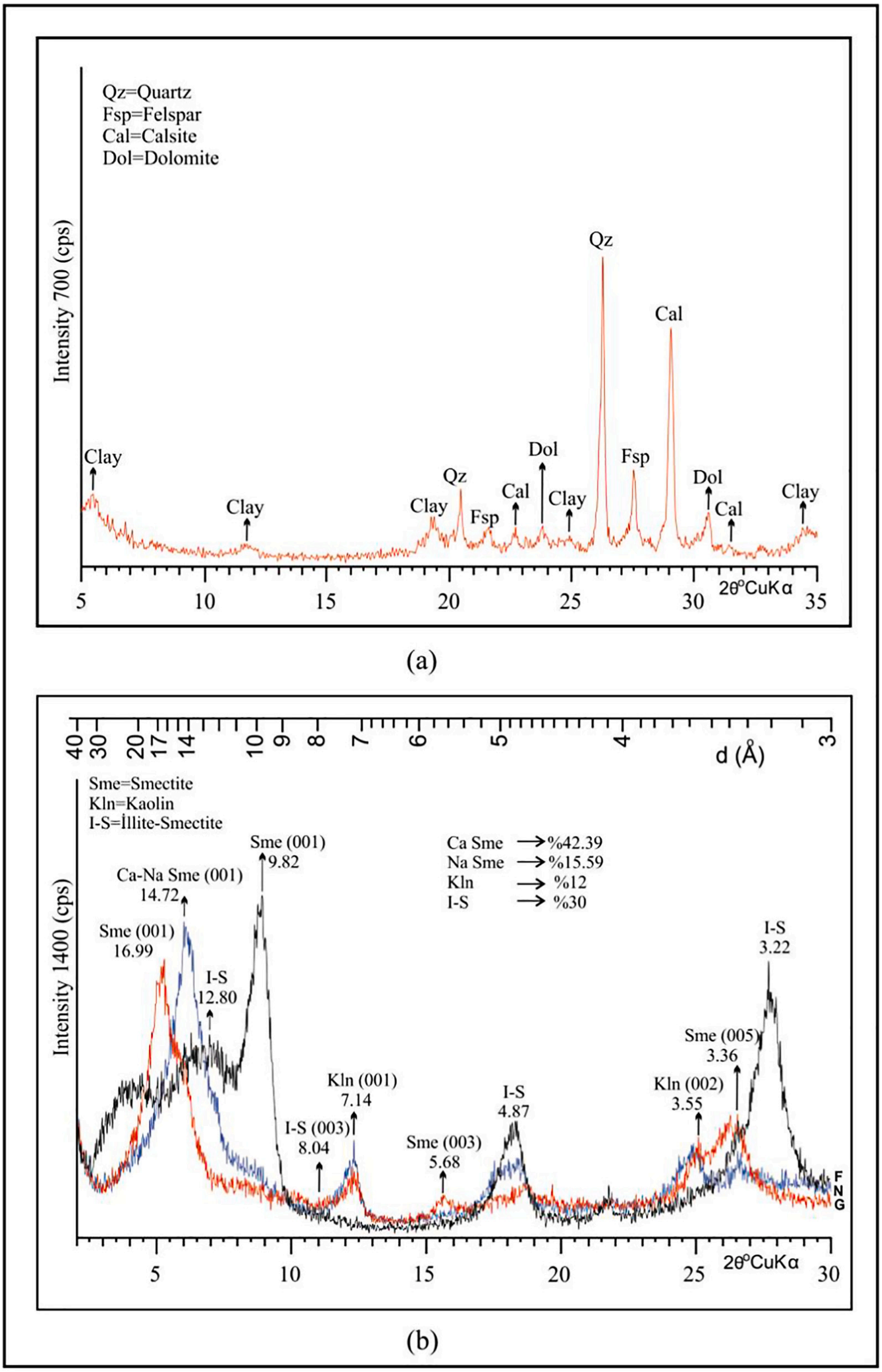

Fig. 1. Characteristic XRD graphs of the soil: (a) bulk (whole) sample (b) clay fraction.

was shielded by membranes for the purpose of protecting the homogeneity of water content of the soil. A typical section of the small scale models and the top view of a typical model are shown in Figs. 7 and 8, respectively.

4. Results and discussion

At the end of the curing time, the changes on the swelling behaviour of the soil were identified by carrying out free swelling test on the specimens taken from the small scale model boxes according to ASTM D 4546 (1986). The specimens were extracted by using the sampler tubes

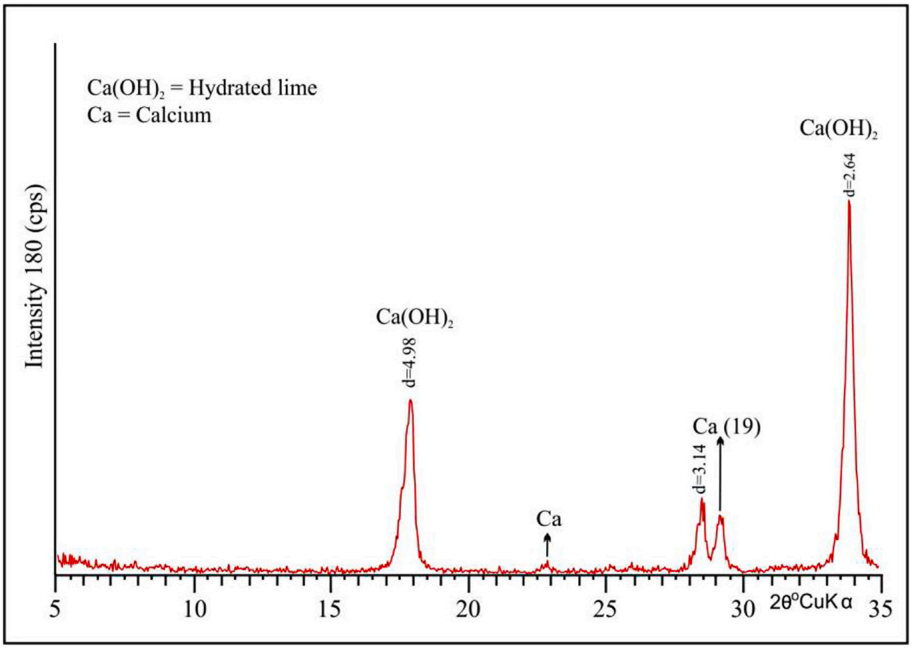

Fig. 2. Characteristic XRD graph of lime used.

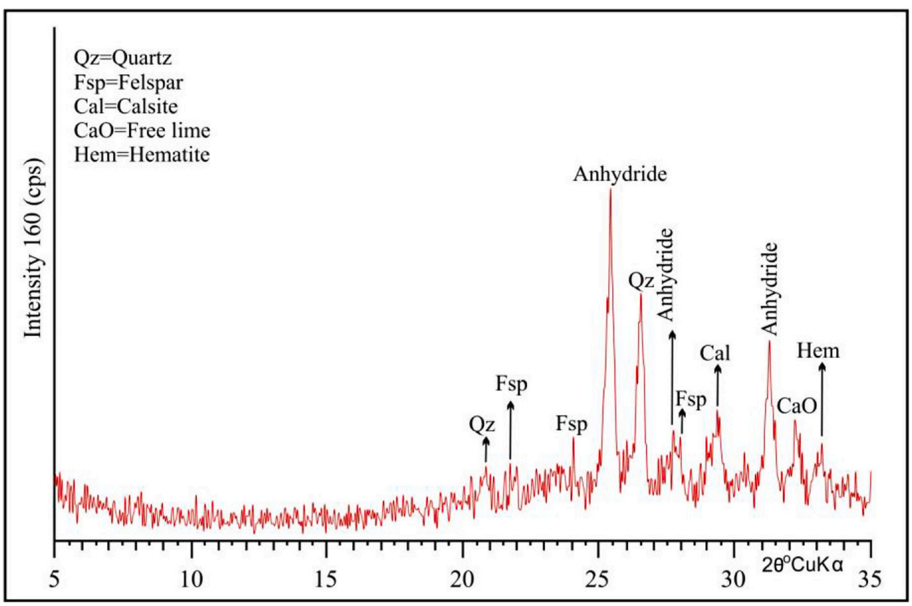

Fig. 3. Characteristic XRD graph of fly ash used.

that are in diameter of 50 mm. The specimens then were extruded from the samplers and their heights were adjusted to 20 mm by cutting them carefully. Afterwards, they were placed into consolidation rings that are 20 mm in height and 50 mm in diameter. Filter papers and porous stones were placed on the top and bottom surfaces of the specimens. The specimens were then placed into consolidometer cell, soaked with water and allowed to swell under 1 kPa load. The swell measurements were recorded until the heights of the specimens didn't change any longer. The free swelling percent is expressed as follow:

$$FS = (\Delta H/H_0)*100$$

where ΔH is the difference between the final height and the first height of the specimen and H_0 is the first height of the specimen.

4.1. The shallow mixing performances of the additives

In order to evaluate the shallow mixing performances of the additives, free swelling test was carried out on the specimens taken from the related model boxes. The test results are presented in Table 4.

The swelling percent of the soil stabilized with lime decreased from 90.1% to 0.2%. In other words, the decrement rate in the swelling percent of the soil mixed with 5% lime is 99.8%. Similarly, the decrement rates in the swelling percent of the soil mixed with 20% fly ash and 5% gypsum are found to be 98.11% and 65.42%, respectively. Therefore, it can be concluded that, the best improvement performance was obtained with lime and then with fly ash. Gypsum, on the other hand, exhibited the lowest improvement performance. The decrement rates in the swelling percent of the soil stabilized with the additives are shown in

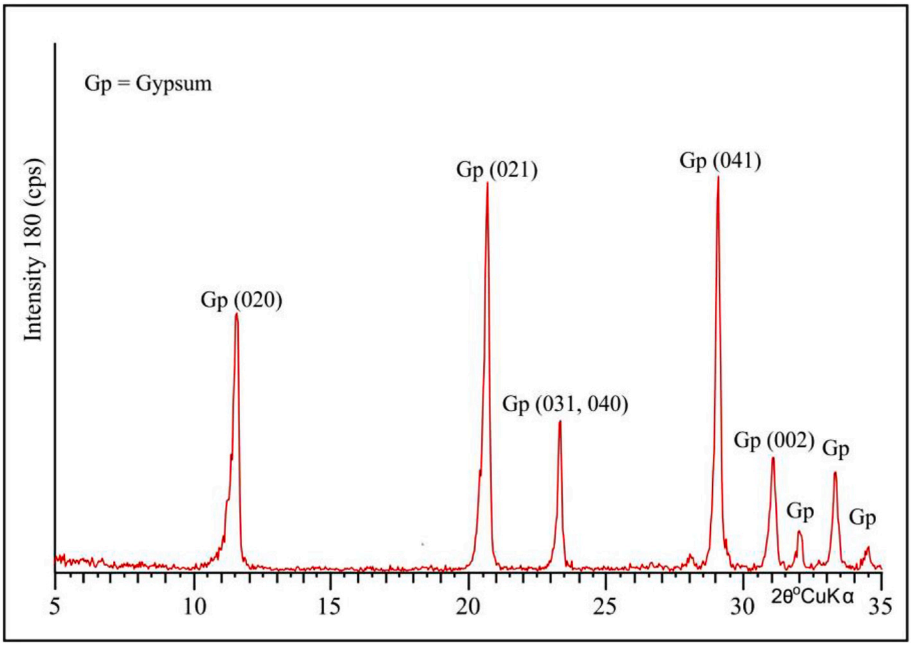

Fig. 4. Characteristic XRD graph of gypsum used.

Table 3
The results of standard Proctor compaction test for the mixtures.

Mixture	γ_{dmax} (g/cm^3)	w_{opt} (%)
5% lime + soil	1.48	23
20% fly ash + soil	1.42	25.5
5% gypsum + soil	1.52	24.3

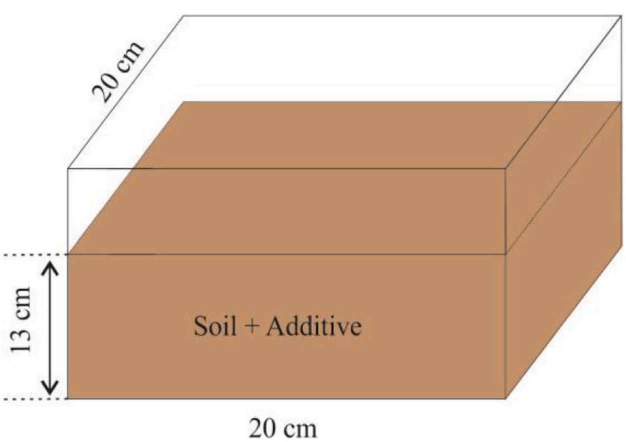

Fig. 5. A typical section of the models designed for the shallow mixing performances of the additives.

Fig. 6. The top view of a typical model designed for the shallow mixing performances of the additives.

Fig. 9.

The results are in accordance with the results of other studies (Al-Rawas et al., 2005; Phanikumar, 2009; Yılmaz and Civelekoğlu, 2009; Kılıç et al., 2016). Al-Rawas et al. (2005) investigated the effects of lime, cement and an artificial pozzolan on the swell potential of an expansive soil and they found out that with the addition 6% lime, the swelling percent of the soil reduced to zero. The researchers concluded that lime exhibited the best results when compared to the other stabilizers. Phanikumar (2009) conducted a study on the effects of lime and fly ash on swell, consolidation and shear strength characteristics of expansive clays and found out that the reduction in the swelling percent was significant at a lime content of 4%. Yılmaz and Civelekoğlu (2009) used 5% gypsum in order to stabilize an expansive soil and they obtained a decrement of 69.03% in the swell potential of the soil. Kılıç et al. (2016), investigated the effects of lime and gypsum on the stabilization of high plasticity clays and they obtained the best performance with lime with a decrement of 95.55% in the swelling percent of the soil. The authors stated that gypsum reduces the swelling percent, however, the reduction ratio is lower than that of lime.

4.2. *The column performances of the additives*

In order to evaluate the column performances of the additives, firstly,

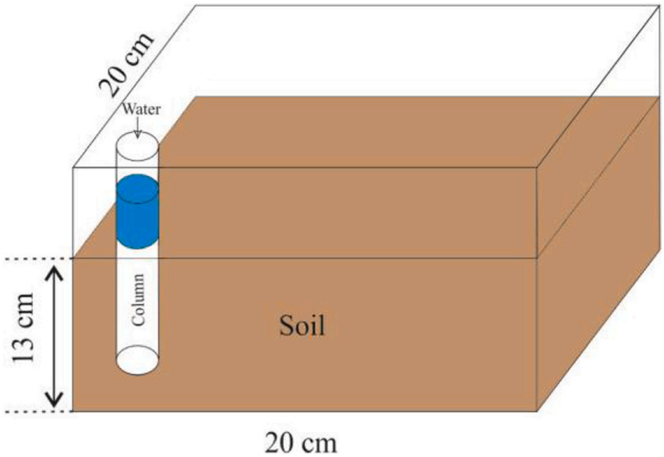

Fig. 7. A typical section of the models designed for the column performances of the additives.

Fig. 8. The top view of a typical model designed for the column performances of the additives.

Table 4
The free swelling percent of the soil-additive mixtures.

The additive type	Free swelling percent (%)
The soil without any additive	90.1
5% lime+ soil	0.2
20% fly ash + soil	1.7
5% gypsum + soil	31.15

the specimens were extracted from the model boxes according to the sampling method illustrated in Fig. 10. When determining the sampling positions, it was aimed to make it convenient to take the specimens using a special sampler tube and to get as many specimens as possible from the limited model box. Free swelling test was performed on the specimens in accordance with ASTM D 4546 (1986).

4.2.1. Lime column performance

The results of free swelling tests applied on the specimens taken from the small scale model boxes built for the determination of lime column performance are presented in Table 5. The changes in the swelling percent of the soil with distance to lime column are shown in Fig. 11.

It can be seen that the most efficient improvement has been obtained within a distance of 50 mm from lime column. The swelling percent of the soil decreased from 90.01% to 43.3% within this distance, which means a decrement of 51.9%. After this distance, the swelling percent of the soil continued decreasing at lower rates. However, after a certain distance (50–100 mm), the swelling percent values were nearly the same with untreated soil's swelling percent. This distance could be taken as the improvement distance achieved with lime column. Due to the partial overlap of the sampling distances, when calculating the improvement distances, the center points of the sampling distances were taken into consideration. In this case, it can be concluded that an improvement distance of 75 mm was obtained with lime column. In another saying, the improvement was achieved at a distance of 1.5 times the column diameter.

The results are similar to the results of previous investigations on lime column. In a study carried out by Katti and Gupta (1970) on lime migration, a migration distance of 75 mm was obtained in 120 days. Tonoz et al. (2003) obtained the maximum decrease in the swelling pressure at a distance equal to the column diameter. Their study also indicated that an effective treatment may be achieved at a distance of approximately twice the column diameter. Lastly, in the study of Toksoz and Yılmaz (2019), the most effective improvement was achieved at a distance equal to the column diameter.

4.2.2. Fly ash column performance

In order to determine the performance of fly ash column, free swelling test was applied on the specimens taken from the related model. The test results and the changes in the swelling percent of the soil with distance to fly ash column are presented in Table 6 and Fig. 12, respectively.

It can be seen that the most efficient improvement was obtained in a distance of 50 mm from the column. The swelling percent of the soil decreased from 90.01% to 59.75% within this distance, which means a decrement of 33.7%. After the sampling distance of 50–100 mm, the swelling percent values obtained were very close to the swelling percent of untreated soil. This means that the improvement distance achieved with fly ash column is 75 mm which equals to 1.5 times the column diameter.

The reduction rate in the swelling percent obtained with fly ash column is approximately in accordance with the average value of the reduction rates reported in the previous studies. In a study conducted by Phanikumar et al. (2009) on fly ash column, heave of an untreated expansive clay bed reduced from 36.6 mm to 28 mm, which means a reduction of 23.3% in heave. In another study carried out by Ramu (2009), the reduction in swelling percent of the soil was found to be 44.5%. Lastly, Pei et al. (2015) conducted a study on loess stabilization with lime and fly ash columns and found out that the most effective improvement for both columns was achieved at a distance of 50 mm from the columns. The researchers also stated that the performance of lime column was greater than that of fly ash column.

4.2.3. Gypsum column performance

The results of free swelling tests applied on the specimens taken from the related model box are presented in Table 7. The changes in the swelling percent of the soil with distance to gypsum column are shown in Fig. 13.

It can be seen from Table 7 that the most effective improvement was obtained in a distance of 50 mm from the column. The soil's swelling percent decreased from 90.01% to 67.3% within this distance, which means a decrement of 25.3%. After this distance, the swelling percent of the soil continued decreasing at lower rates. However, after the sampling distance of 50–100 mm, the swelling percent values were very close to the swelling percent of untreated soil. This means that an improvement distance of 75 mm was achieved with gypsum column,

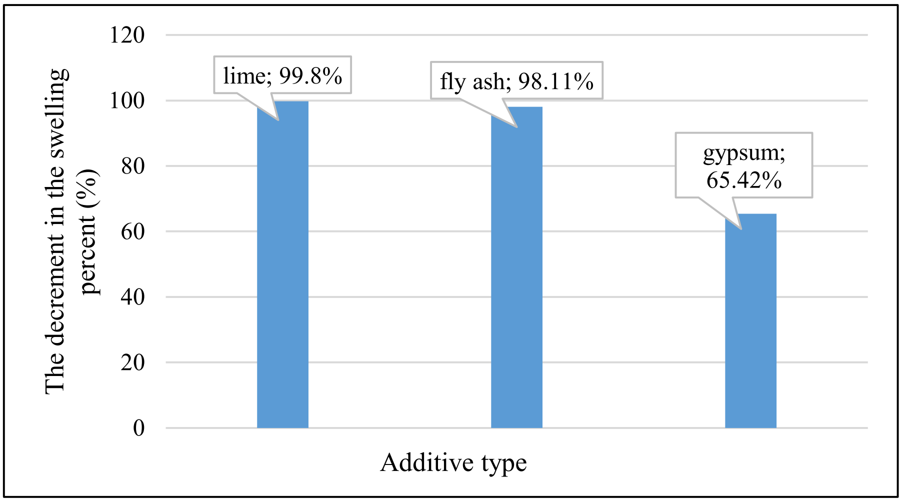

Fig. 9. The decrement rates in the swelling percent of the soil stabilized with different additives.

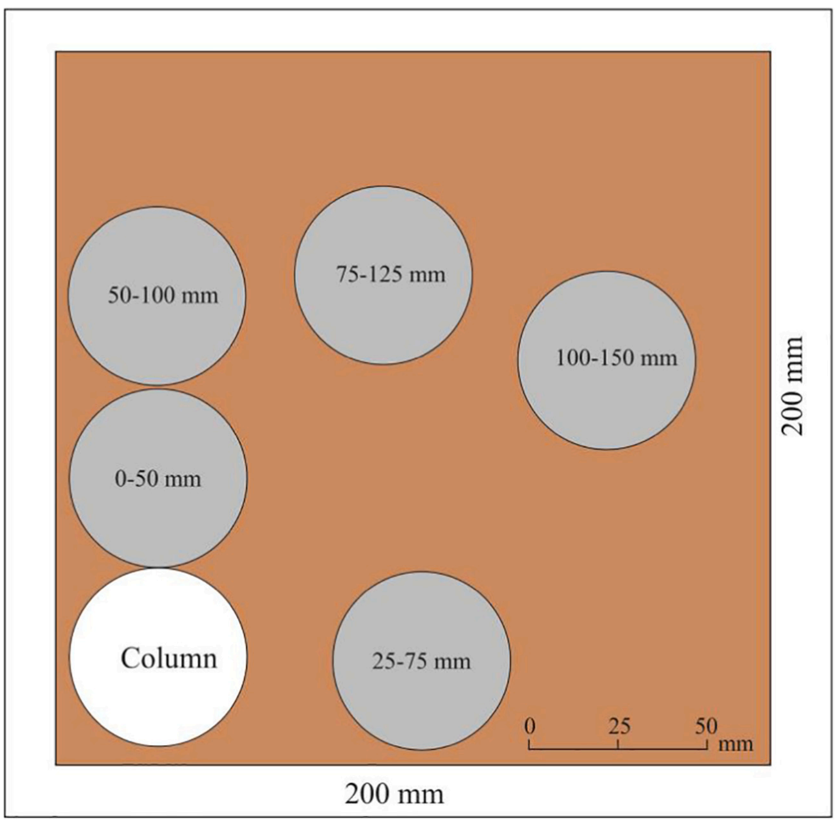

Fig. 10. The sampling method for the small scale models built for the investigation of column performances.

Table 5
The free swelling percent of the specimens taken at different distances from lime column.

Column type	Free swelling percent (%)					
	Untreated soil	Distance to lime column (mm)				
		0–50	25–75	50–100	75–125	100–150
Lime	90.01	43.3	63.85	82.5	88.85	90.95

which equals to the improvement distances obtained with lime and fly ash columns.

The reduction ratio in the swelling percent obtained with gypsum column is in accordance with the reduction ratio obtained in the study carried out by Yılmaz (2019). The author investigated gypsum column performance on the stabilization of a Na-bentonite clay and obtained a decrement of 27.69% in the swelling percent. However, the improvement distance achieved in the study of Yılmaz (2019) is equal to 0.76 times of the column diameter, which is smaller than the improvement distance obtained in this study. This might derive from the low permeability of the bentonite clay. The low permeability retards the migration of ions from the columns and thus causes short improvement distances.

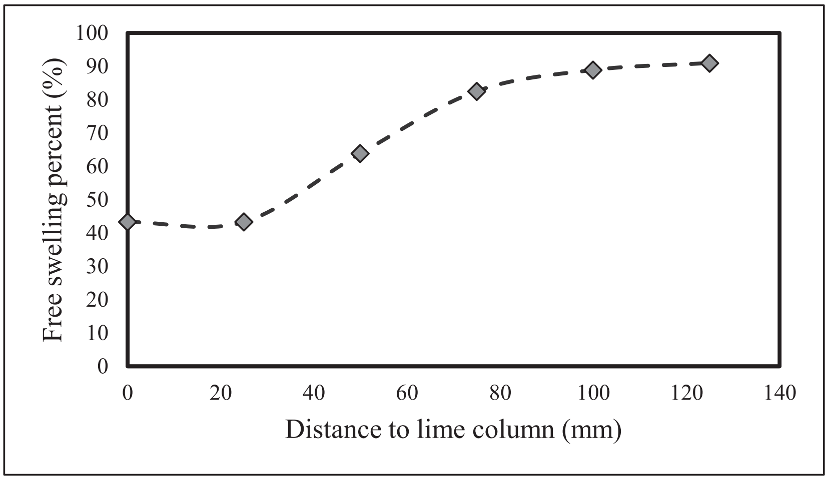

Fig. 11. The changes in the swelling percent of the soil with distance to lime column.

Table 6
The free swelling percent of the specimens taken at different distances from fly ash column.

Column type	Free swelling percent (%)					
	Untreated soil	Distance to fly ash column (mm)				
		0–50	25–75	50–100	75–125	100–150
Fly ash	90.01	59.75	64.8	70.5	84.9	98.65

In the present study, the improvement rates obtained by the shallow mixing and column techniques for each additive are shown in Fig. 14. It can be understood from the figure that, the best improvement was achieved with lime and the lowest improvement was obtained with gypsum for both techniques. The performance of fly ash is lower than the performance of lime and greater than the performance of gypsum. If a comparison is made in terms of technique used, it can be seen from the figure that the best improvement for all additives was achieved by the shallow mixing technique. Considering that the improvement distance obtained with the column technique is only 1.5 times the column diameter, it can be concluded that the performance of the shallow mixing technique is better than that of the column technique.

5. Conclusions

In this study, shallow mixing and column performances of various additives during the stabilization of swelling soils were investigated. The results obtained were compared both in terms of technique and additive material. The conclusions obtained in this study are as follow:

1. At the end of a curing time of 4 months, the best improvement was achieved with lime for both techniques with reductions of 99.8% and 51.9% in the swelling percent of the soil when using the shallow mixing and column techniques, respectively. Gypsum, on the other hand, exhibited the lowest performance for both techniques by reducing the swelling percent of the soil by 65.42% with the shallow mixing technique and 25.3% with the column technique. Fly ash reduced the swelling percent of the soil by 98.1% and 33.7% with the shallow mixing and column techniques, respectively.
2. The reason why lime performed the best improvement might be because it contains both Ca^{2+} and OH^{-} ions. For a high stabilization, both of the ions are necessary. Ca^{2+} ion content of fly ash used in this

Table 7
The free swelling percent of the specimens taken at different distances from gypsum column.

Column type	Free swelling percent (%)					
	Untreated soil	Distance to gypsum column (mm)				
		0–50	25–75	50–100	75–125	100–150
Gypsum	90.01	67.3	73.65	73.6	84.65	89.05

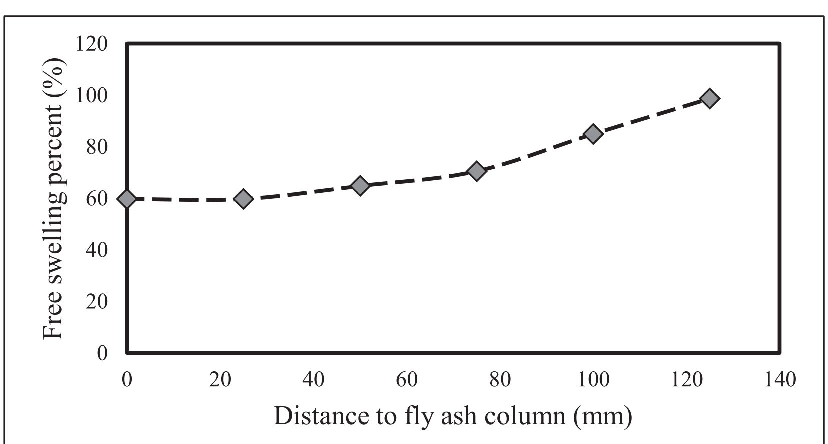

Fig. 12. The changes in the swelling percent of the soil with distance to fly ash column.

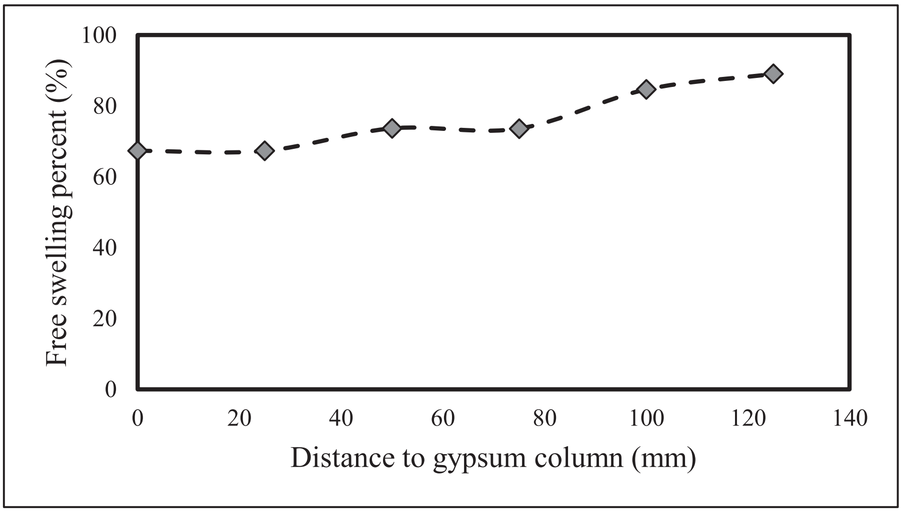

Fig. 13. The changes in the swelling percent of the soil with distance to gypsum column.

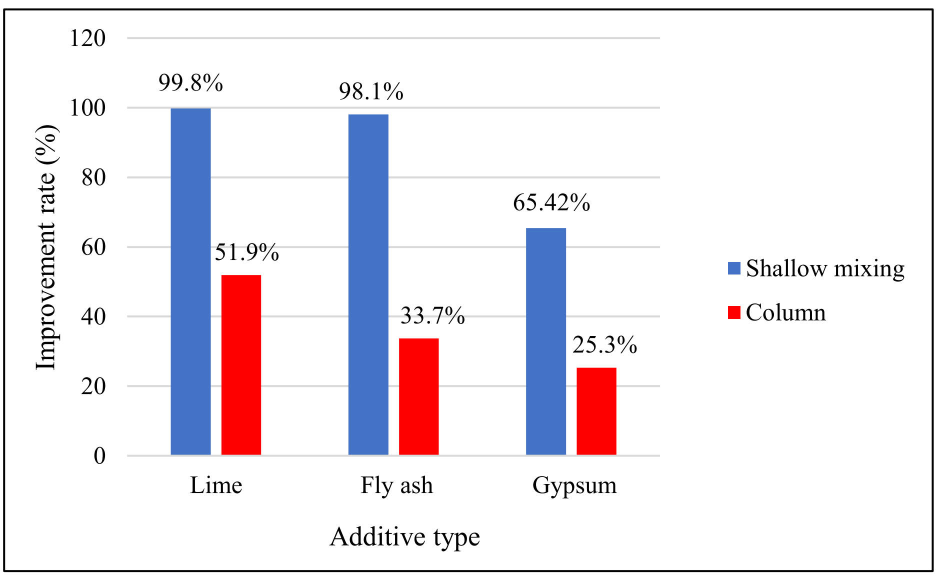

Fig. 14. The improvement rates on the swelling behaviour of the soil in terms of technique and additive material.

study is lower than that of lime. Additionally, gypsum contains only Ca^{2+} ion from these two ions.

3. In the column technique, the most effective improvement distance was 50 mm from the column for all additives. Additionally, the total improvement distance for all additives was found to be 75 mm from the column. This means that the ion migration distances for all additives are nearly the same. This situation might be result from using the same soil for all additives. Most of the factors affecting the ion migration in a clayey soil, such as water content, permeability, porosity and clay mineralogy, generally stem from the soil properties. The effect of the additive on ion migration is mostly result from the ions it contains. Lime, fly ash and gypsum have Ca^{2+} ion in common in their structures. This exchangeable cation migrates from the column to the surrounding soil and replaced with metallic ions on the surfaces of clay particles. The improvement mechanism of column technique is based on this reaction which is known as cation exchange reaction.
4. If a comparison is made in terms of the technique, for all of the additives used, the shallow mixing technique exhibited higher performance when compared to the column technique. The shallow mixing technique showed 47.9%, 64.41% and 40.12% higher performances than the column technique for lime, fly ash and gypsum, respectively. In the column technique, ion migration from the column has a crucial importance. In the shallow mixing technique, however, the improvement reactions can take place without the need for ions to migrate over great distances. Therefore, the stabilization with the shallow mixing technique can be easier and in higher rates when compared to the column technique.
5. If a comparison is made in terms of the size of the stabilized area, in the shallow mixing technique, the greater areas can be stabilized when compared to the column technique. In the column technique, the size of the stabilized area is controlled by the factors affecting ion migration. In the soil used in this study, an improvement distance of 1,5 times the column diameter was achieved, which is not desirable in geotechnical applications. Such an improvement distance would cause the columns to be installed in close distances and thus high costs. On the other hand, in the shallow mixing technique, despite the improvement in large areas, the depth that can be improved is quite small when compared to the column technique. In an area

where deep improvement is required, the column technique may be preferred rather than the shallow mixing technique.

6. As a result, when a swelling soil is planned to be stabilized, all factors should be taken into account. Some of these factors are the price, availability and improvement performance of the additive material, the applicability of the technique for the soil and its economic aspect. These factors should be evaluated together in order to choose the most appropriate technique and the most suitable additive material when stabilizing swelling soils.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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References

Abiodun, A.A., Nalbantoglu, Z., 2015. Lime pile techniques for the improvement of clay soils. Can. Geotech. J. 52 (6), 760–768.
Alkaya, D., 2002. The Effect of Fly Ash Addition on the Stability of Filled Soils. Doctoral Thesis. Pamukkale University, Institute of Science and Technology, Denizli, Turkey.
Al-Rawas, A.A., Hago, A.W., Al-Sarmi, H., 2005. Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman. Build. Environ. 40 (5), 681–687.
Ameta, N.K., Prohit, D.G.M., Wayal, A.S., Sandeep, D., 2007. Economics of stabilizing bentonite soil with lime–gypsum. Electron. J. Geotech. Eng. 12 (Bundle E).
Ashok, P., Reddy, G.S., 2016. Lime pile technique for the improvement of properties of clay soil. Intern. J. Sci. Res. 5 (11), 1204–1210.
ASTM D 422, 2007. Standard test method for particle-size analysis of soil. Annual Book of ASTM Standards, pp. 2–7.
ASTM D 4318, 2000. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. American Society for Testing and Materials, West Conshohocken, Pa.
ASTM D 4546, 1986. Standard Test Methods for one Dimensional Swell or Settlement Potential of Cohesive Soils, 4(8). Annual Book of ASTM Standards, pp. 992–1100.
ASTM D 698, 2007. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. American Society for Testing and Materials, West Conshohocken, Pa.
ASTM D 7928, 2016. Standard Test Methods for Particle Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. West Conshohocken, PA.
ASTM D 854, 2006. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. American Society for Testing and Materials, West Conshohocken, Pa.
Bagheri, Y., Ahmad, F., Ismail, M.A.M., 2014. Strength and mechanical behavior of soil–cement–lime–rice husk ash (soil–CLR) mixture. Mater. Struct. 47, 55–66.
Basma, A.A., Al-Sharif, M.A., 1994. Treatment of expansive soils to control swelling. Geotech. Eng. J. 25 (2), 3–19.
Bell, F.G., 1996. Lime stabilization of clay minerals and soils. Eng. Geol. 42 (4), 223–237.
Bell, F.G., Coulthard, J.M., 1990. Stabilization of clay soils with lime. Munic. Eng. 7 (3), 125–140.
Bell, F.G., Maud, R.R., 1994. Dispersive soils and earth dams with some experiences from South Africa. Bull. Assoc. Eng. Geol. 31 (4), 433–446.
Bhuvaneshwari, S., Robinson, R.G., Gandhi, S.R., 2005. Stabilization of Expansive Soils Using Flyash. Fly Ash Utilization Programme (FAUP), TIFAC, DST, New Delhi.
Bose, B., 2012. Geo engineering properties of expansive soil stabilized with fly ash. Electron. J. Geotech. Eng. 17, 1339–1353.
Cabalar, A.F., Karabash, Z., Mustafa, W.S., 2014. Stabilising a clay using Tyre buffings and lime. Road Mater. Pavement Design 15 (4), 872–891.
Chong, S.Y., Kassim, K.A., 2014. Consolidation characteristics of lime column and geotextile encapsulated lime column (gelc) stabilized pontian marine clay. Electron. J. Geotech. Eng. 19 (Bund. A.).
Çokça, E., 2001. Use of class C fly ashes for the stabilization of an expansive soil. ASCE J. Geotech. Geoenviron. Eng. 127 (7), 568–573.
Darikandeh, F., Viswanadham, B.V.S., 2016. Swell Behavior of Expansive Soils with Stabilized Fly Ash Columns. Indian Geotechnical Conference, Chennai, India.
Ghosh, A., Subbarao, C., 2006. Tensile strength bearing ratio and slake durability of class F fly ash stabilized with lime and gypsum. J. Mater. Civ. Eng. 18 (1), 18–27.
Ingles, O.G., Metcalf, J.B., 1972. Soil Stabilization. Butterworth pty, Ltd., Australia.
Ingles, O.H., 1987. Soil stabilization. Chapter 38. In: Bell, F.G. (Ed.), Ground Engineer's Reference Book. Butterworths, London, pp. 38/1–38/26.
Jha, A.K., Sivapullaiah, P.V., 2019. Lime stabilization of soil: a physico-chemical and micro-mechanistic perspective. Indian Geotech. J. 50 (3), 339–347.
Karthick, S.Y.S., Vasanthanarayanan, R., Ayswarya, S., Meenakshi, C., 2019. Soil stabilization using plastics and gypsum. Intern. J. Res. Eng. Sci. Manage. 2 (1), 351–360.
Katti, R.K., Gupta, A.K., 1970. Studies on the diffusion of lime in expansive soil. In: Proceedings of the 2nd South East Asian Conference on Soil Mechanics and Foundation Engineering, Singapore, pp. 611–619.
Kezd, A., 1979. Stabilized Earth Roads. Development in Geotechnical Engineering. Elseiver Scientific, New York.
Kılıç, R., Küçükali, Ö., Ulamış, K., 2016. Stabilization of high plasticity clay with lime and gypsum. Bull. Eng. Geol. Environ. 75, 735–744.
Kolay, P.K., Pui, M.P., 2010. Peat stabilization using gypsum and fly ash. UNIMAS E-J. Civil Eng. 1 (2), 1–5.
Kumar, S., Dutta, R.K., Mohanty, B., 2014. Engineering properties of bentonite stabilized with lime and phosphogypsum. Slovak J. Civil Eng. 22 (4), 35–44.
Makusa, G.P., 2013. A Review of Geotechnical Behavior of Stabilized Soils: Design and Analysis Considerations. Lulea University of Technology, Sweden, p. 62.
Nalbantoglu, Z., Gucbilmez, E., 2002. Utilization of an industrial waste in calcareous expansive clay stabilization. Geotech. Test. J. 25 (1), 78–84.
Negi, A.S., Faizan, M., Siddharth, D.P., Singh, R., 2013. Soil stabilization using lime. Intern. J. Innov. Res. Sci. Eng. Technol. 2 (2), 448–453.
Nelson, J.D., Miller, D.J., 1992. Expansive Soils, Problems and Practise in Foundation and Pavement Engineering. Wiley, New York.
Pei, X., Zhang, F., Wu, W., Liang, S., 2015. Physicochemical and index properties of loess stabilized with lime and fly ash piles. Appl. Clay Sci. 114, 77–84. https://doi.org/10.1016/j. clay.2015.05.007.
Phanikumar, B.R., 2009. Effect of lime and fly ash on swell, consolidation and shear strength characteristics of expansive clays: a comparative study. J. Geomech. Geoeng. 4 (2), 175–181.
Phanikumar, B.R., Sharma, R.S., 2004. Effect of flyash on Engg properties of expansive soil. J. Geotech. Geoenviron. 130 (7), 764–767.
Phanikumar, B.R., Mani, A.J., Sathiyasheelan, S., Reddy, P.R., 2009. Fly ash columns (FAC) as an innovative foundation technique for expansive clay beds. Geomech. Geoeng. 4 (3), 183–188. https://doi.org/10.1080/17486020902857007.
Ramu, K., 2009. An Experimental Study of Fly Ash Columned Bed in Expansive Soil. Geotechnics in Infrastructures Development, Guntur, India, pp. 77–79.
Rogers, C.D.F., Glendining, S., 1994. Deep Slope Stabilisation using Lime. Transportation Research Record 1440. Transportation Research Board, National Research Council, Washington D.C., USA, pp. 63–70.
Rogers, C.D.F., Glendining, S., 1997. Improvement of clay soils in situ using lime piles in the UK. Eng. Geol. 47, 243–257.
Seed, H.B., Woodward, R.J., Lundgren, R., 1962. Prediction of swelling potential of compacted clays. J. Soil Mech. Found. Division, Am. Soc. Civil Eng 88, 53–87 no. SM3.
Sharma, N.K., Swain, S.K., Sahoo, U.C., 2012. Stabilization of a clayey soil with fly ash and lime: a micro level investigation. Geotech. Geol. Eng. 30, 1197–1205.
Singh, S.P., Sangita, S., 2016. Mitigation of leaching of major and trace elements from pond ash deposits by lime column treatment. Geotech. Geol. Eng. 34, 2019–2031.
Sivapullaiah, P., Prashanth, J., Sridharan, A., 1995. Optimization of lime content for fly ash. J. Test. Eval. 23 (3), 222–227.
Skempton, A.W., 1953. The colloidal activity of clays. In: Proc. 3rd Intl. Conf. Soil Mech. Found. Eng., 1, pp. 57–61.
Toksoz, D., Yılmaz, I., 2019. Influence of swelling clay content on ion migration and column performance in lime column treated soils. Geotech. Geol. Eng. 38 (1), 813–832.
Tonoz, M.C., Gökçeoğlu, C., Ulusay, R., 2003. A laboratory – scale experimental investigation on the performance of lime columns in expensive Ankara (Turkey) Clay. Bull. Eng. Geol. Environ. 62, 91–106.
Van Der Merwe, D.H., 1964. The prediction of heave from the plasticity index and percentage clay fraction of soils. Civil Eng. S. Afr. 6 (6), 103–106.
Van Impe, W.F., 1989. Soil Improvement Techniques and their Evolution (A.A. Balkema Rotterdam Brookfield).
Vukićević, M., Maraš-Dragojević, S., Jocković, S., Marjanović, M., Pujević, M., 2013. Research results of fine-grained soil stabilization using fly ash from serbian electric power plants. In: Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.
Wang, Y., Guo, P., Li, X., Lin, H., Liu, Y., Yuan, H., 2019. Behavior of fiber-reinforced and lime-stabilized clayey soil in triaxial tests. Appl. Sci. 9 (5), 900.
Yılmaz, I., 2019. A laboratory model study related with the determination of gypsum column performance in treatment of expansive soils. J. Geol. Eng. 43 (1), 23–38.
Yılmaz, I., Civelekoğlu, B., 2009. Gypsum: an additive for stabilization for swelling clay soils. Appl. Clay Sci. 44, 166–172.
Zumrawi, M.M.E., Mohammed, M.H., 2016. Effect of fly ash on the characteristics of expansive soils in Sudan. In: 7th Annual Conference for Postgraduate Studies and Scientific Research Basic Sciences and Engineering Studies, Sudan.