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ORIGINAL PAPER

Stabilization of swelling soil by lime, fly ash, and calcium carbide residue

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Abstract
This study aimed to compare the swelling and strength parameters of weak and swellable soils with calcium carbide residue remaining from acetylene industrial production with lime and fly ash. For this purpose, bentonite and river sand were mixed as a 75–25% bentonite–sand mixture to obtain the pure test sample. Five percent, 10%, and 15% by weight of calcium carbide residue, lime, and fly ash were added to pure sample. All test samples were prepared at the optimum water content of each mixture. The prepared samples were left to cure for 1, 7, 14, 21, and 28 days and then undergo liquid limit, plastic limit, compaction test, unconfined compression test, direct shear box test, and swelling pressure tests which were performed on the samples at the mixing ratios determined for all additives on each curing day. The soil improvement performances of these additives were evaluated considering the curing times. Results revealed that the calcium carbide residue significantly improved the unconfined compressive strength, cohesion, internal friction angle, and swelling pressure value of the pure sample. When evaluated together with other additives used in the study, it was observed that calcium carbide residue was within acceptable limits. In addition, the samples were exposed to XRD test for each mixing ratio on the 7th and 30th days. The mineralogical structures of the samples were examined, and the effect of the additives on the mineralogical structure of the mixture was discussed.

Keywords Calcium carbide residue · Soil improvement · Lime · Fly ash · Swelling

Introduction

Expansive soils spread over a wide area in the world is an important problem of most countries (Ramos et al. 2015; Ito and Wagai 2017; Daraei et al. 2018; Behnood 2018) Enhancing the problems caused by weak or swelling soils is a quite old endeavour. Rome's famous Appian Way was built in 600 BC with lime-cured floors (Nicholson 2015). When the water content increases, expansive soil is prone to form expansion causing stresses and deformations, and when the water content decreases, shrinkage stresses and cracks often occur (Al-Taie et al. 2016; Abhishek and Bhardwaj 2018; Khadka et al. 2020). Expansive soils cause various problems for civil engineering projects such as channel walls, dams, highways, railways, and embankments due to their cyclic swell-shrink behaviour and low strength (Yang and Zheng 2006; Zheng et al. 2009; Chittoori et al. 2018; Daraei et al. 2019a; Ikeagwuani and Nwonu 2019; Darvishi et al. 2020; Blayi et al. 2020) Therefore, the improvement of such a type of soil is crucial. There are many stabilization measures proposed for expansive soil, generally involving soil replacement, humidity controlling, chemical modification, and special foundation systems to reduce the adverse effect caused by expansive soil. Due to its effectiveness and adaptability, the chemical modification method is favoured by engineers. Traditional chemical binders in soil stabilization are regarded as lime, cement, fly ash, and clinker. However, the common binders are under discussion not only for their negative environmental effects but also for their costs (Liu et al. 2019).

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One of the techniques used for improving the geotechnical properties of expansive soil is using various by-product industrial waste materials (Horpibulsuk et al. 2013; Dang et al. 2016; Liu et al. 2019; Blayi et al. 2020; Yılmaz and Sadoğlu 2022). Therefore, during the last decades, different researchers tried to use these waste materials for soil stabilization, and some of them have been proposed to be utilized as construction materials (Baruah et al. 2020). The widespread use of this non-recyclable material in the construction industry will be a great economic gain. In some applications for soil improvement, cement, resin, lime, organic, or inorganic waste materials are frequently used singly or mixed with each other to reduce stabilization costs. In recent years, researchers have tended to use various types of wastes as stabilizing for swelling soil and poor soil (Mosa et al. 2017; Liu et al. 2019; Daraei et al. 2019b; Adeyanju et al. 2020), such as fly ash (Kolay and Ramesh 2016; Al-Malack et al. 2016; Siddiqua and Barreto 2018; Khadka et al. 2020), blast furnace slag (Thomas and Tripathi 2018; Salimi et al. 2018; Li et al. 2019; Abdila et al. 2022; Mahmudi and Eskisar 2022), cement kiln dust (Ismail and Belal 2016; Al-Homidy et al. 2017; Rimal et al. 2019; Ismeik et al. 2021), alkali residue (Yang et al. 2018; Abdila et al. 2022), quicklime (calcium oxide–CaO), hydrated lime (calcium hydroxide–$Ca[OH]_2$), and hydrated lime slurry (Bell 1996; Babu and Poulose 2008; Azam et al. 2020; Parthiban et al. 2020), and so on. Many factors such as water content, additive content, curing condition, displacement rate, and compression energy were also discussed in these studies (Tatsuoka 1983; Yin and La 1998; Consoli et al. 2000; Kasama et al. 2000; Mıura et al. 2001; Horpibulsuk et al. 2004; Taher et al. 2011). Numerous studies show that silicate and aluminate gel formation is the main reason for the improved strength parameters of stabilized soil in soils stabilized with lime, pozzolan-lime, and pozzolan-cement (Granizo et al. 2002; Escalante-García et al. 2003; Moayedi et al. 2013; Li et al. 2019, 2020; Fares et al. 2019; Tokgöz Hozatlıoğlu and Yılmaz 2022). For this purpose, natural or chemical pozzolans are used. When soil improvement studies are evaluated in general, there are many studies in the literature on the use of lime ($Ca(OH)_2$-rich material) and fly ash, even though they suggest different implications. However, the study on calcium carbide residue is quite limited.

Calcium carbide residue (CCR) is a by-product of acetylene (C_2H_2) production process through the hydrolysis of calcium carbide (CaC_2). Sixty-four g of calcium carbide generates 26 g of acetylene gas (C_2H_2) and 74 g of CCR in the form of $Ca(OH)_2$ (Horpibulsuk et al. 2013). Due to the increase in acetylene production, carbide waste is increasing day by day, and its disposal causes waste management difficulties. CCR is generally recognized as industrial waste. For this reason, improper disposal and accumulation in unregulated storage areas will cause pollution of nearby ecosystems (Krammart and Tangtermsirikul 2004; Ben Haha et al. 2011; Li et al. 2021). For this reason, it will be very important to generate new methods contributing the disposal endeavours. When CCR is mixed with materials such as fly ash and bottom ash, it is likely to be an alternative material to cement (Horpibulsuk et al. 2014). It is a suitable alternative binder for stabilizing soft subgrades of CCR (Jiang et al. 2015; Du et al. 2016; Li et al. 2021). Furthermore, CCR has been applied successfully in subgrade engineering. Therefore, it is thought that the utilization of these wastes will be a valuable gain in terms of both the environment and engineering. Therefore, recycling waste materials and using them as stabilized materials are both sustainable and economical. The geotechnical literature is constantly evolving for this purpose. The paper aims to stabilize expansive soil by utilizing CCR provided from acetylene companies as waste material and compare the results with fly ash and lime, which are frequently used in the literature. Liquid limit and plastic limit test, swelling pressure test, unconfined pressure test, and shear box tests were carried out on the samples prepared with these additives at various curing times, and the effect of the additives on liquid limit and plastic limit, strength, and swelling pressure of the soil was observed. In addition, improvement effect on soil of fly ash (FA) — calcium carbide residue (CCR) — lime (LS) additives considering their curing times applying the x-ray diffraction (XRD) method was evaluated mineralogically, and the results were discussed.

Materials and methods

Materials

Expansive soil (bentonite–sand mixture)

A mixture of bentonite and sand was used in the study to observe the effect of additives alone by ensuring that the soil properties in each sample are the same. For this purpose, all experiments were carried out on samples prepared with soil at a ratio of 75–25% bentonite–sand mixture. River sand used in this study for mixed soil was provided from a local company which is typically used as a construction material. The sand was sieved through sieve No. 4 (4.75 mm), and the grain size distribution curve of the sand is presented in Fig. 1. In addition, natural bentonite whose chemical and physical properties are given in Table 1 was used as the swelling soil in the mixture. The bentonite consisted of 75% montmorillonite with other components such as silica and feldspar. Bentonite, a type of clay, is soft, decomposable in water, and has an oily feeling when touched by hand. Bentonite has a very high water absorption capability and swelling potential due to its very small crystal structure and

Fig. 1 Gradation curve of sand

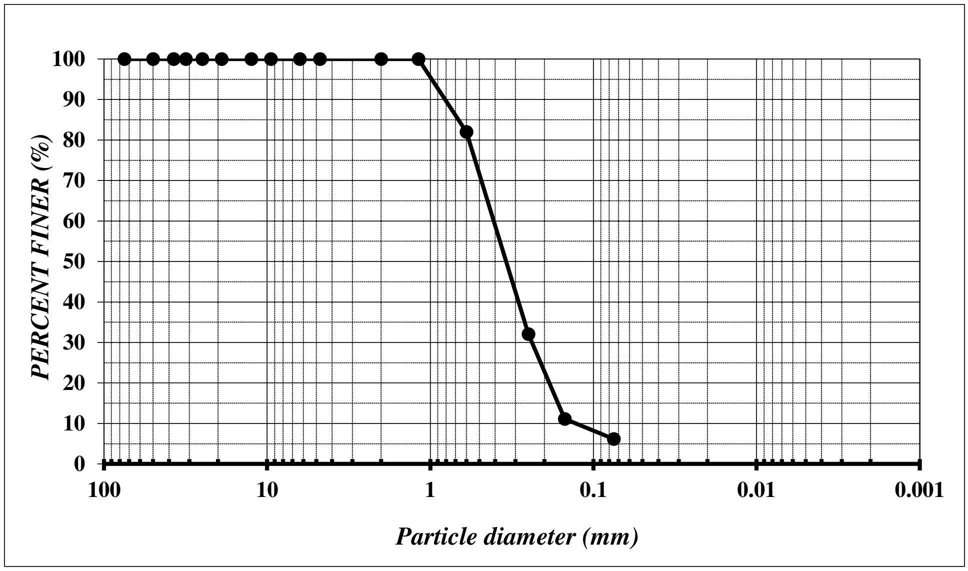


Table 1 The fundamental properties of bentonite

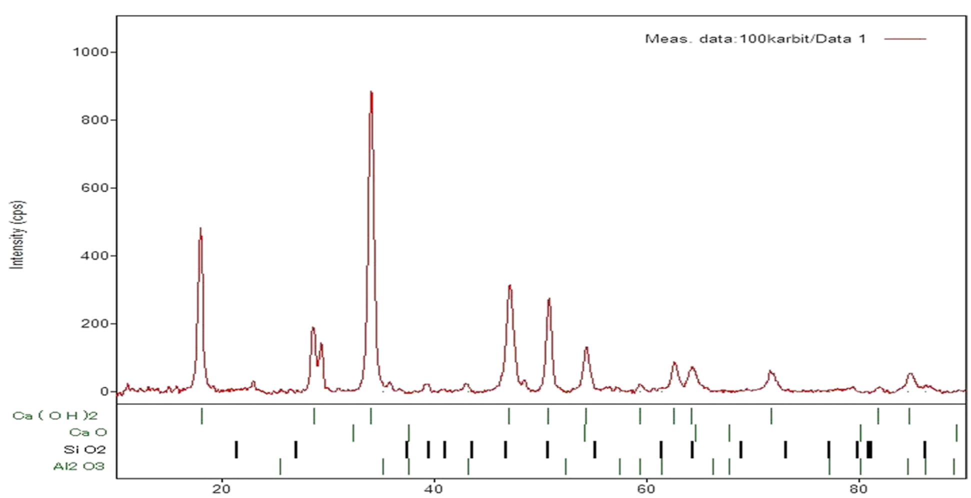
Definition	Bentonite
> 75 µm	2.5% (by weight)
E (methylene blue concentration (0.01 N))	310 ml
Montmorillonite content	75%
SiO_2	61.28%
Al_2O_3	17.79%
Fe_2O_3	3.01%
CaO	4.54%
MgO	2.10%
K_2O	1.24%
Na_2O	2.70%
Liquid limit	300%
Plastic limit	47%

large contact surface. Sodium bentonite has a higher swelling percentage compared to other bentonites. For this reason, mostly sodium bentonite was used to be able to observe the effect on swelling more clearly. In order to interpret the mineralogical composition before and after the stabilization process, XRD analysis were performed on the pure bentonite/sand mixture, and the analysis results are presented in Fig. 2. The liquid limit value was obtained as 210%, and the plastic limit value was obtained as 31% following (ASTM 2000) standard.

Calcium carbide residue

Calcium carbide residue is mainly a by-product of the acetylene production process containing calcium hydroxide, Ca

Fig. 2 XRD diffraction trace of %75 to %25 bentonite–sand mixture



$(OH)_2$. Calcium carbide reacts with water to form acetylene and calcium hydroxide (calcium carbide residue). Industrial quality calcium carbide contains approximately 80% CaC_2, 15% CaO, and 5% other foreign chemicals in the raw material. The calcium carbide residue being liquid at high temperature is then subjected to a cooling and solidification process. In the experiments, calcium carbide which is a waste material from the acetylene industry was used, and its chemical properties are as in Table 2.

Fly ash

In the experiments, F type fly ash provided from Türkiye Zonguldak Çates Electricity Generation Company was used, and its chemical properties are as in Table 2.

Lime

Lime provided from Türkiye Bartın Kimtaş company was used in the experiments, and its chemical properties are as in Table 2.

Experiment methods

Bentonite–sand mixture was prepared by passing through a 40-number sieve and dried in an oven. Optimum water content and Atterberg limit values of 75–25% bentonite/sand sample were determined. By adding 5%, 10%, and 15% calcium carbide residue, lime, and fly ash to this mixture, optimum water content, liquid limit, and plastic limit values of each mixture were obtained. Each mixture was prepared at optimum water content and exposed to cure on during 1, 7, 14, 21, and 28 days. The unconfined compressive strength (UCS) test, swelling pressure test, and shear box test were carried out on the mixtures at the determined curing times in accordance with the ASTM standards (ASTM D 1988, 2000, 2011, 2016). All samples were performed at the maximum dry density and optimum water content according to the values that is obtained from standard compaction test. Experiments were carried out on samples that were compressed and saturated at optimum water content. The specimens were cut with a velocity value of 0.24 mm/min until a displacement of 12 mm (20% deformation) was occurred. During the cutting process, horizontal deformations, vertical deformations, and cutting forces were followed, and readings were taken from the force ring corresponding to the horizontal deformation at regular intervals. Since the cohesion values of bentonites and bentonites with additives were high in the shear box cell, they held themselves together with the loading. In this context, the cohesion, internal friction angle, and swelling pressure values of the soils were measured. In addition, samples from 7- to 30-day curing periods were subjected to the XRD test. The flow chart at the beginning and at the end of the study is given in Fig. 3.

Table 2 Chemical properties of additives material used in the study

Chemical content	*Fly ash (%)*	*Calcium carbide (%)*	*Lime (%)*
SiO_2	55.9	6.49	1.05
Al_2O_3	26.42	2.55	
Fe_2O_3	6.705	3.25	–
CaO	1.544	70.78	-
MgO	2.299	0.69	2.50
SO_3	0.012	0.66	1.05
Na_2O	1.153	-	-
K_2O	4.237	7.93	-
Cl	0.10	-	-
$SiO_2+Al_2O_3+Fe_2O_3$	Min 70	-	-
$Ca(OH)_2$	-	-	85
$R_2O_3(Fe2O_3+Al_2O_3)$	-	-	0.45

Results and discussion

In this section, the effect of the additives used in the experimental study on the geotechnical properties of soils is evaluated. It is very important that the experiments are carried out with the same water content and compression. For this reason, the optimum water content and maximum dry unit weight of all mixtures, especially the pure samples, were determined, and the samples were prepared for all mixtures considering these parameters. In this context, the compaction tests of the bentonite/sand mixture to be used in the experiments were carried out, and the dry unit weight of the 75–25% bentonite–sand mixture

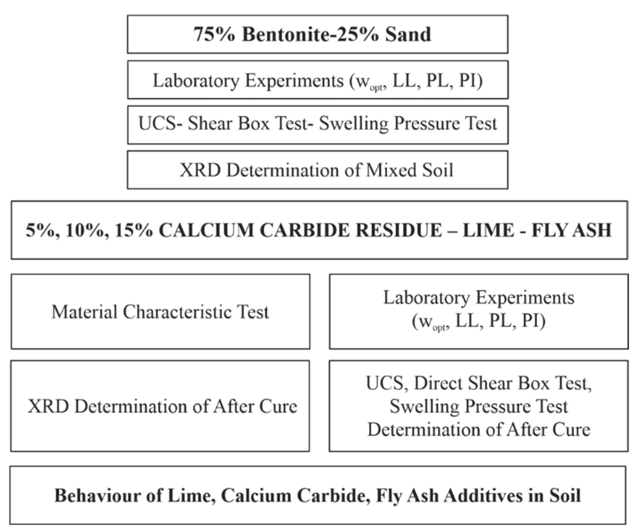


Fig. 3 Flowchart of the study

was obtained to be 13.2 kN/m^3, and the optimum water content was 32%. In addition, the changes in the compaction parameters of each additive added to the pure mixture sample were determined, and samples were prepared with the various proportion additives. Accordingly, with the increase in the ratio of calcium carbide residue, lime, and fly ash in the mixture, the optimum water content increases, and the dry unit weight decrease (Fig. 4).

The results indicate that there is a decrease in the plasticity index with the increase in the amount of additives (Table 3). The results for the CCR is consistent with the traditional additives (lime and fly ash), and plasticity index decreases with the increase in the calcium carbide residue rate. With the decrease in the plasticity index, the sensitivity of the mixture to the water will decrease, and the swelling potential will increase.

The highest unconfined compressive strength of each mixture during the curing period is given in Fig. 5a. The maximum increase in unconfined compressive strength was achieved with lime additives. A significant increase in the strength of calcium carbide residue was observed, and after evaluating Fig. 5a, the curing time beyond 7 days will not have a considerable effect on unconfined compressive strength. The maximum increase in strength was achieved with 10% lime additive, while fly ash provided a lesser increase in strength compared to other additives. The most increase in the unconfined compressive strength was achieved in lime, CCR, and fly ash, respectively. The curing time beyond 7 days lost the influence on the strength for all types of additives. The cohesion values of the mixtures are given in Fig. 5b. It can be said that calcium carbide residue and lime additives have a positive effect on cohesion. It is concluded that the effect of fly ash additive is relatively less than other additives. The internal friction angle values of the mixtures are given in Fig. 5c. All additives increased the internal friction angle. In addition, the calcium carbide residue additive is as effective as the lime additive.

Table 3 Consistency index values of the mixtures

	W_L (%)	W_P (%)	PI (%)
Bentonite	300	47	253
75% bentonite, 25% sand	210	31	179
5% CCR	225	63	162
10% CCR	175	73	102
15% CCR	160	92	68
5% LS	220	60	140
10% LS	160	45	115
15% LS	170	46	124
5% FA	220	60	160
10% FA	195	66	129
15% FA	160	45	115

A fixed volume experiment set with automatic recording and 4-channel data acquisition feature (ASTM D 1988) was employed to determine the effect of each additive along with the curing on the swelling pressure (Fig. 6). Samples prepared at optimum water content were used in the experiments. The swelling pressure of each mixture was evaluated graphically (Fig. 7). The results indicate that the swelling pressure of clayey soils decreases with the increase of the lime and calcium carbide residue ratio. On the contrary, fly ash did not have a positive effect on the swelling pressure of clayey soils. Therefore, in order to initiate the reaction, lime or cement must be added to the medium. It should also be noted that the pozzolanic effect in fly ash will vary depending on the composition and fineness of the ash (Goñi et al. 2003; Tangpagasit et al. 2005).

Based on 28 days of curing, the effect on soil improvement for all additives at all ratios is expressed comparatively according to the pure sample with a relative coefficient (Table 4). It is seen that the additives increase the strength to a noteworthy level. It can be said that the contribution of calcium carbide residue to the unconfined

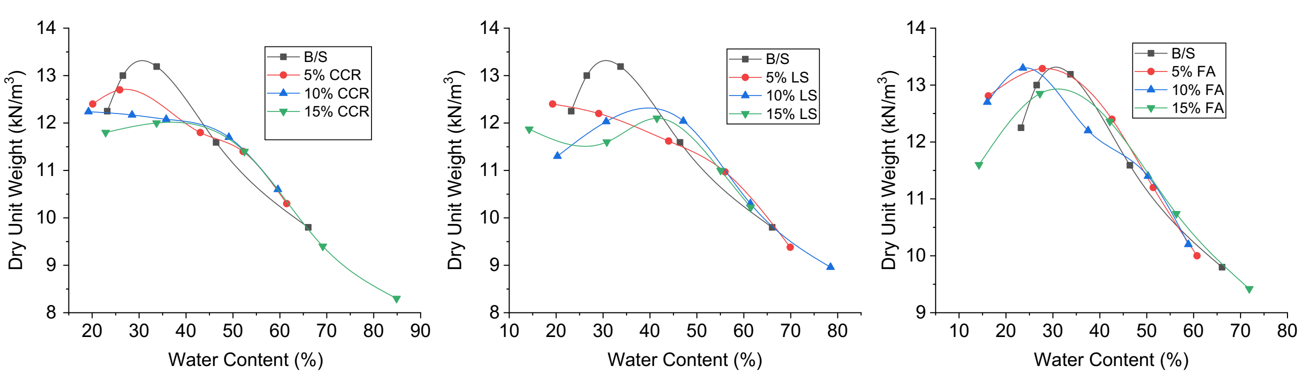


Fig. 4 Optimum water content values and dry unit volume weight of mixtures

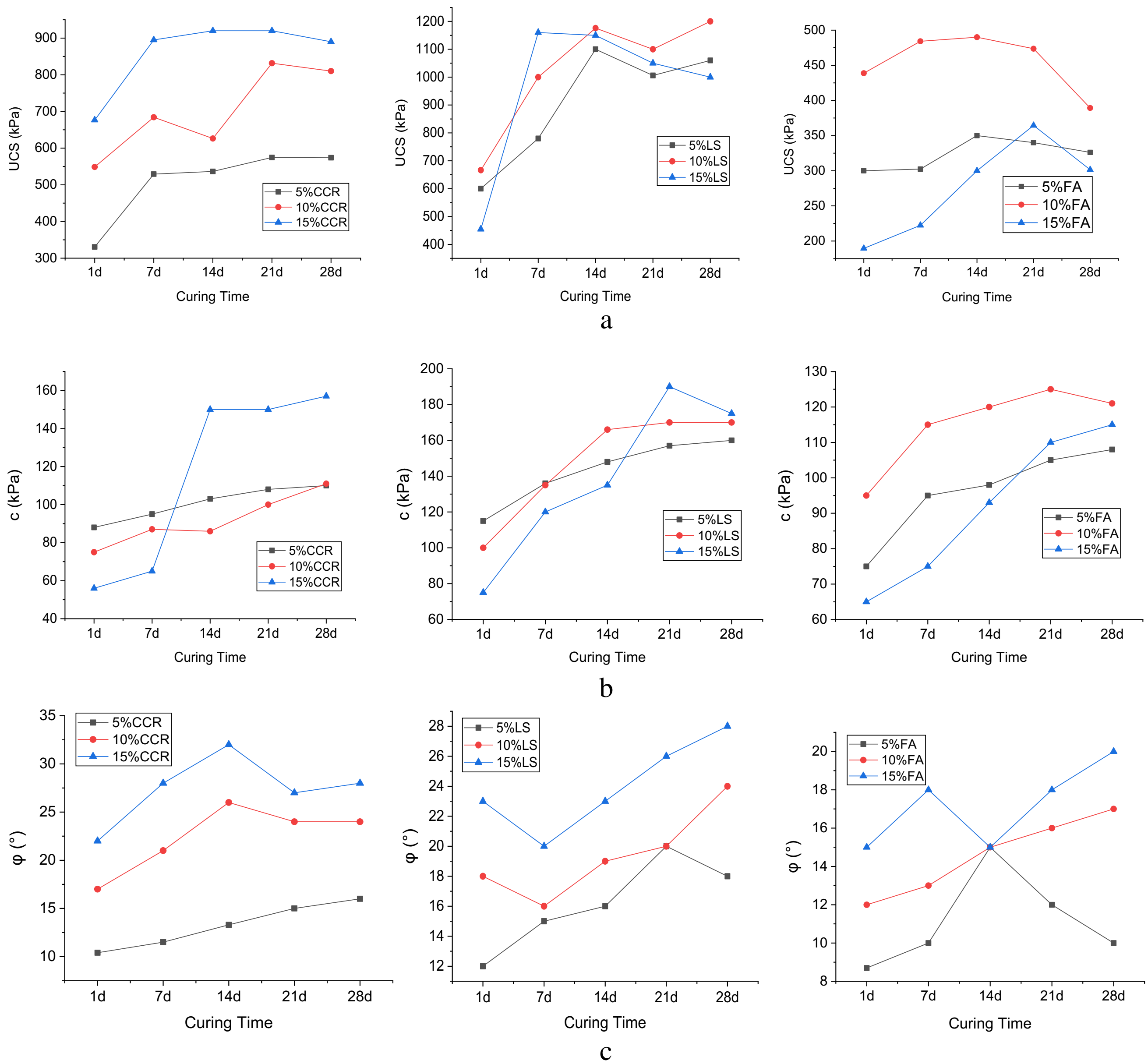


Fig. 5 **a** UCS of expansive soil stabilized. **b** Cohesion of expansive soil stabilized. **c** Internal friction angle of expansive soil stabilized

compressive strength is remarkable. As seen in Table 4, based on 28 days of curing, maximum cohesion was obtained at the rate of 15% for both calcium carbide residue and lime additives and 10% for fly ash additive. It can be said that calcium carbide residue and lime increase the internal friction angle of the pure sample approximately 5 times with 15% additive and 3 times with 15% fly ash additive. Fifteen percent calcium carbide residue increased the swelling pressure of the pure sample approximately 10 times. Ten percent lime additive improved the swelling pressure of the soils at the highest level among all additives. It was observed that fly ash had an adverse effect on swelling pressure.

The samples for each additive were exposed to X-ray diffraction (XRD) test for each mixing ratio on the 7th and 30th days, and their mineralogical structures were investigated (Fig. 8). It was observed that calcium silica hydrate (CSH), calcium aluminate (CAH), and calcium hydra (CH) gels were formed as a result of hydration in soil mixtures with calcium carbide residue, lime, and fly ash depending on the increased curing time and the additive ratio. From the XRD results, it was seen that the Ca^{+2} ions in the additives were replaced by the monovalent Na^{+} ions present in the clay. In addition to Ca^{+2} ions, hydroxyl (OH^{-}) ions migrated into the soil, and hydroxyl ions increased the alkalinity of the soil. High alkaline conditions caused silica and alumina

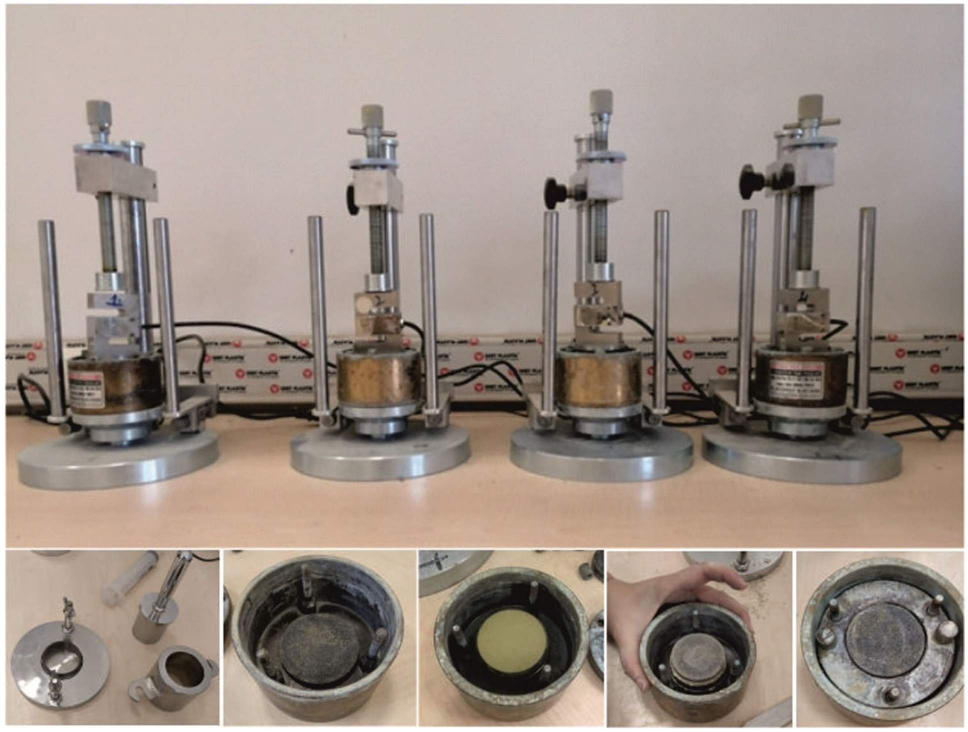


Fig. 6 Swelling pressure test set

components to decompose from clay minerals, and these decomposed components reacted with Ca^{+2} ions from the additives to form pozzolanic components such as calcium silica hydrate (CSH), calcium alumina hydrate (CAH), and calcium hydra (CH) that cement the soil. With these pozzolanic reactions, the strength of the soil was increased during the curing period. These data have indicated that additive materials, as an alkali activator, could accelerate the hydration and produce hydration products similar to those of cement, such as CSH, CAH, or CH which can increase the soil strength and resistance to swelling.

Conclusion

The usability of calcium carbide residue in soil improvement was investigated and compared to traditional additives, fly ash, and lime. Calcium carbide residue, lime, and fly ash were added to the bentonite–sand mixture sample at different ratios. Various experiments were carried out considering curing periods, and the results were evaluated.

As the mixing ratio increased, the optimum water content increased, and the maximum dry unit weight decreased. Fifteen percent calcium carbide residue and fly ash and 10% lime reduced liquid limit by 24% at the maximum level. The plastic limit value of the bentonite/sand mixture was increased three times for 15% calcium carbide residue however less considerable for traditional additives (lime and fly ash). In addition, as the additive ratio increases, the plasticity index generally increases.

The unconfined compression strength increases with the increase in the additive ratio. It was observed that 15% calcium carbide residue additive increased the unconfined compressive strength of the pure sample by 3.63 times. The curing time has no influence on the strength. The highest increase among all additives, in the strength of the pure sample, was obtained for 10% lime additive at 7-day curing period. For fly ash, the optimum improvement effect was obtained with 10% additive ratio at 7-day curing period and did not cause a remarkable change beyond this period. In this context, calcium carbide residue can be regarded as an effective waste material to enhance the soil compression strength.

As the ratio of calcium carbide residue, lime, and fly ash additives increased, the cohesion value decreased, while the cohesion value increased with curing. The cohesion reached the peak value for 10% fly ash additive and 15% calcium carbide residue and lime additive after 14th day based on 28-day curing time.

The internal friction angle reached the maximum value at 15% additive ratio for calcium carbide residue, lime, and fly ash. In parallel with the increase in the curing time, the internal friction angle increased for all types of additives. It has been evaluated that the increase in the internal friction angle with the increase in the amount of additives is due to the binder effect, which increases the strength of the sample through cementation and reduces

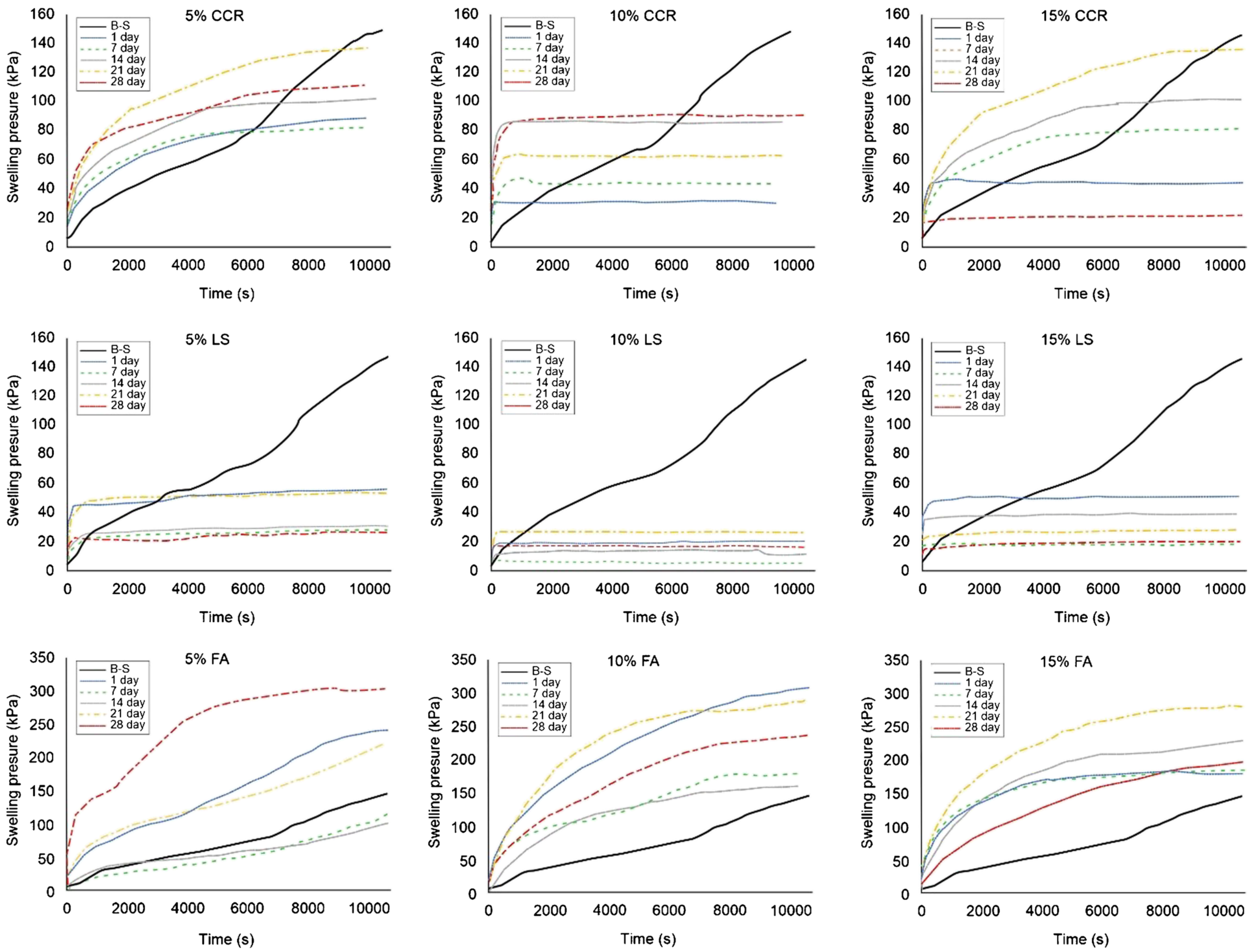
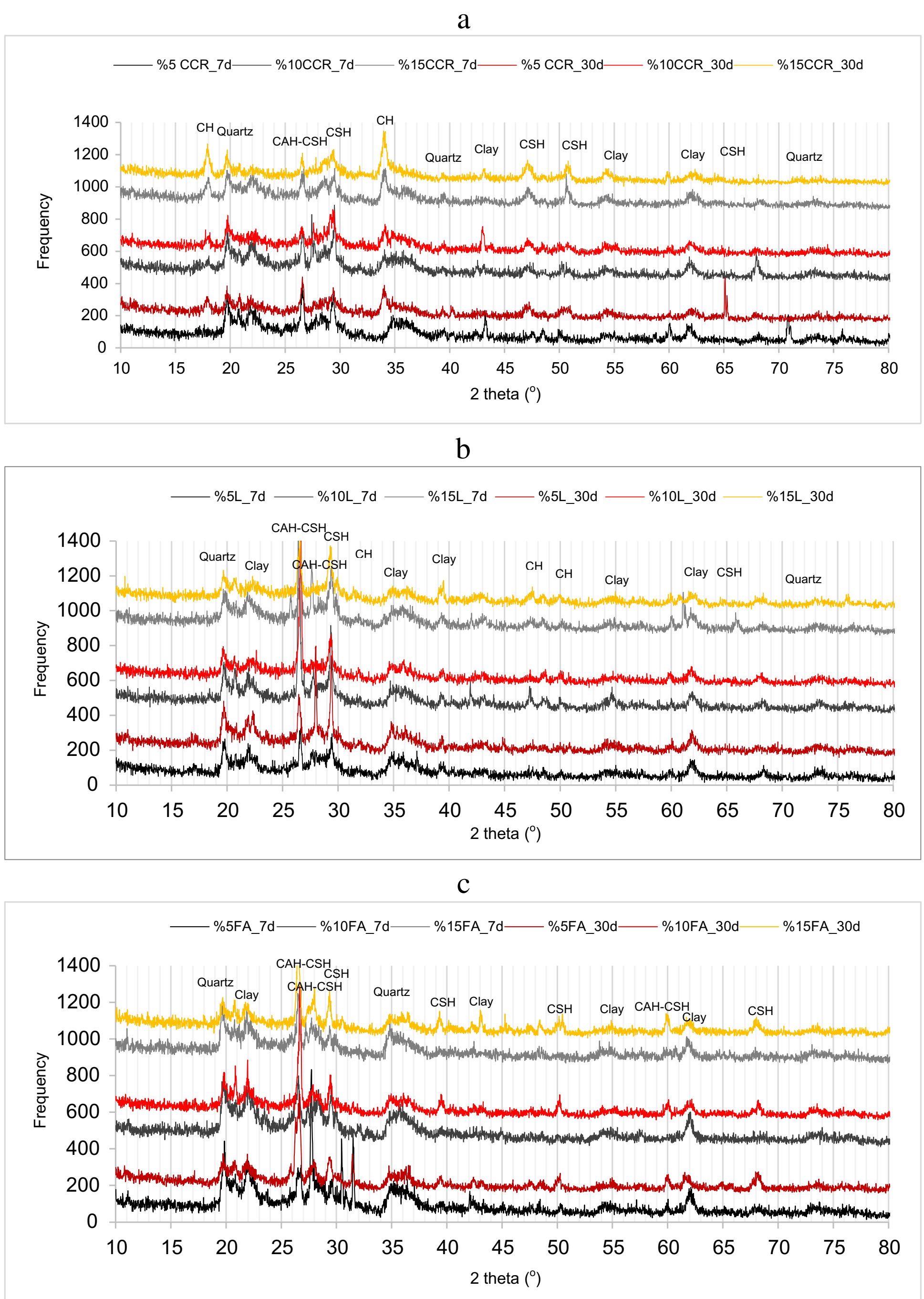


Fig. 7 Swelling pressure values

Table 4 Improvement factor of all additives

Mixing ratios	Swelling pressure		Cohesion		Unconfined compressive strength		Internal friction angle	
	Value (kPa)	Relative enhance coefficient	Value (kPa)	Relative enhance coefficient	Value (kPa)	Relative enhance coefficient	Value (°)	Relative enhance coefficient
Bentonite–sand mixture	186.36	-	80	-	253.36	-	6.1	-
5% CCR	81.57	2.3	110	1.38	574.58	2.27	16	2.62
10% CCR	31.30	5.94	111	1.38	831.56	3.28	26	4.26
15% CCR	21.35	8.71	157	1.96	920.35	3.63	32	5.24
5% LS	27.95	6.65	135	1.68	1102.56	4.35	20	3.28
10% LS	10.98	16.97	170	2.12	1200.90	4.74	24	3.93
15% LS	18.43	10.11	190	2.38	1163.21	4.59	28	4.59
5% FA	302.5	−1.62	108	1.35	352.45	1.39	13	2.13
10% FA	160.40	1.16	125	1.56	489.91	1.93	17	2.78
15% FA	310.93	−1.67	115	1.43	364.47	1.44	20	3.28

Fig. 8 **a** CCR XRD. **b** Lime XRD. **c** Fly ash XRD



the sensitivity of the shear strength to the limiting pressure. For all types of additives, the shear strength parameters of the pure sample improved positively.

Calcium carbide residue and lime additives reduced the swelling pressure of the pure sample at all ratios and reduced it at the highest level for 15% additive ratio. The swell pressure of pure sample decreased 8 times for 15% calcium carbide residue additive ratio. For the lime additive, a maximum improvement in swelling pressure was observed at the rate of 10% additive. However, fly ash did not cause any positive improvement in the swelling pressure of the sample when all ratios and curing time were taken into account. For this reason, it is recommended to use fly ash together with other calcium-based additives such as lime and/or cement to improve such high plasticity swelling clays and meet the design criteria due to swelling.

XRD analysis was carried out for the pure sample and for all additive mixed soils on 30-day curing time. The samples were evaluated and examined mineralogically;

as a result each additive material formed calcium silica hydrate (CSH), calcium aluminate (CAH), and calcium hydra (CH) gels on the soil. Following these results, it was evaluated that additives are a significant factor that improves soils.

Results so far have been very encouraging to employ calcium carbide residue in soil improvement and are expected to contribute to the diversification of utilization areas of various waste materials. Thus, the use of calcium carbide residue will be important both in terms of its contribution to the economy, waste storage management, and environmental pollution.

Author contribution All experiments, analysis, and evaluations in the manuscript were made with the equal participation of the co-authors.

Data availability Although all data are transparently presented in the article, raw data can be given if requested.

Code availability There is no code in the article.

Declarations

Ethics approval Ethical approval is not required.

Consent for publication If the article is accepted and published, the publication permission will be transferred to the "Arabian Journal of Geosciences".

Conflict of interest The authors declare no competing interests.

References

Abdila SR, Abdullah MMAB, Ahmad R et al (2022) Potential of soil stabilization using ground granulated blast furnace slag (GGBFS) and fly ash via geopolymerization method: a review. Mater 15:375. https://doi.org/10.3390/MA15010375

Abhishek, Sharma RK, Bhardwaj A (2018) Effect of construction demolition and glass waste on stabilization of clayey soil. Lect Notes Civ Eng 21 LNCE:87–94. https://doi.org/10.1007/978-3-030-02707-0_12

Adeyanju E, Okeke CA, Akinwumi I, Busari A (2020) Subgrade stabilization using rice husk ash-based geopolymer (GRHA) and cement kiln dust (CKD). Case Stud Constr Mater 13:e00388. https://doi.org/10.1016/j.cscm.2020.e00388

Al-Homidy AA, Dahim MH, Abd El Aal AK (2017) Improvement of geotechnical properties of sabkha soil utilizing cement kiln dust. J Rock Mech Geotech Eng 9:749–760. https://doi.org/10.1016/J.JRMGE.2016.11.012

Al-Malack MH, Abdullah GM, Al-Amoudi OSB, Bukhari AA (2016) Stabilization of indigenous Saudi Arabian soils using fuel oil fly-ash. J King Saud Univ Eng Sci 28:165–173. https://doi.org/10.1016/j.jksues.2014.04.005

Al-Taie A, Disfani MM, Evans R et al (2016) Swell-shrink cycles of lime stabilized expansive subgrade. Procedia Eng 143:615–622. https://doi.org/10.1016/J.PROENG.2016.06.083

ASTM D (1988) Standard test methods for one-dimensional swell or collapse of soils. ASTM International, West Conshohocken, PA, USA; ASTM (1988c) D-4546:

ASTM D (2000) Standard test methods for liquid limit, plastic limit, and plasticity index of soils. 4318-00; Annual Book of ASTM Standards, Vol. 04.01, pp 1–14

ASTM D (2011) In standard test method for direct shear test of soils under consolidated drained conditions; D3080/D3080M; ASTM: West Conshohocken, PA, USA, 2011.

ASTM D (2016) Standard test method for unconfined compressive strength of cohesive soil, ASTM International, West Conshohocken, Pennsylvania, U.S.A. ASTM D2166/D2166M-16

Azam M, Usmani MA, Junaid M, Student BT (2020) Stabilisation of clayey soil by using lime. Int J Innov Res Sci Eng Technol 9:7783

Babu N, Poulose E (2008) Effect of lime on soil properties: a review. Int Res J Eng Technol

Baruah D, Goel S, Gupta C, Sahu AK (2020) Ground improvement using municipal solid waste ash. Lect Notes Civ Eng 35:271–280. https://doi.org/10.1007/978-981-13-7480-7_25

Behnood A (2018) Soil and clay stabilization with calcium- and non-calcium-based additives: a state-of-the-art review of challenges, approaches and techniques. Transp Geotech 17:14–32. https://doi.org/10.1016/J.TRGEO.2018.08.002

Bell FG (1996) Lime stabilization of clay minerals and soils. Eng Geol 42:223–237. https://doi.org/10.1016/0013-7952(96)00028-2

Ben Haha M, Le Saout G, Winnefeld F, Lothenbach B (2011) Influence of activator type on hydration kinetics, hydrate assemblage and microstructural development of alkali activated blast-furnace slags. Cem Concr Res 41:301–310. https://doi.org/10.1016/J.CEMCONRES.2010.11.016

Blayi RA, Sherwani AFH, Ibrahim HH et al (2020) Strength improvement of expansive soil by utilizing waste glass powder. Case Stud Constr Mater 13:e00427. https://doi.org/10.1016/j.cscm.2020.e00427

Chittoori BCS, Mishra D, Islam KM (2018) Forensic investigations into recurrent pavement heave from underlying expansive soil deposits. Transp Res Rec J Transp Res Board 2672:118–128. https://doi.org/10.1177/0361198118758625

Consoli NC, Rotta GV, Prietto PDM (2000) Influence of curing under stress on the triaxial response of cemented soils. Geotechnique 50:99–105. https://doi.org/10.1680/GEOT.2000.50.1.99

Dang LC, Fatahi B, Khabbaz H (2016) Behaviour of expansive soils stabilized with hydrated lime and bagasse fibres. Procedia Eng 143:658–665. https://doi.org/10.1016/J.PROENG.2016.06.093

Daraei A, Herki BMA, Far A, Shokrollah HS (2018) Slope stability in swelling soils using cement grout : a case study. Int J Geosynth Gr Eng 4:1–10. https://doi.org/10.1007/s40891-018-0127-9

Daraei A, Far Haji Sherwani A, Faraj RH et al (2019) Stabilization of problematic soil by utilizing cementitious materials. Innov Infrastruct Solut 4:33. https://doi.org/10.1007/s41062-019-0220-5

Daraei A, Sherwani AFH, Faraj RH et al (2019b) Stabilization of problematic soil by utilizing cementitious materials. Innov Infrastruct Solut 4. https://doi.org/10.1007/s41062-019-0220-5

Darvishi A, Vosoughifar H, Saeidijam S et al (2020) An experimental and prediction study on the compaction and swell–expansion behavior of bentonite clay containing various percentages of two different synthetic fibers. Innov Infrastruct Solut 5:31. https://doi.org/10.1007/s41062-020-0280-6

Du YJ, Jiang NJ, Liu SY et al (2016) Field evaluation of soft highway subgrade soil stabilized with calcium carbide residue. Soils Found 56:301–314. https://doi.org/10.1016/j.sandf.2016.02.012

Escalante-García JI, Fuentes AF, Gorokhovsky A et al (2003) Hydration products and reactivity of blast-furnace slag activated by various alkalis. J Am Ceram Soc 86:2148–2153. https://doi.org/10.1111/J.1151-2916.2003.TB03623.X

Fares R, Santisid′Avila MP, Deschamps A (2019) Soil-structure interaction analysis using a 1DT-3C wave propagation model. Soil Dyn Earthq Eng 120:200–213. https://doi.org/10.1016/j.soildyn.2019.02.011

Goñi S, Guerrero A, Luxán MP, Macías A (2003) Activation of the fly ash pozzolanic reaction by hydrothermal conditions. Cem Concr Res 33:1399–1405. https://doi.org/10.1016/S0008-8846(03)00085-1

Granizo ML, Alonso S, Blanco-Varela MT, Palomo A (2002) Alkaline activation of metakaolin: effect of calcium hydroxide in the products of reaction. J Am Ceram Soc 85:225–231. https://doi.org/10.1111/J.1151-2916.2002.TB00070.X

Horpibulsuk S, Miura N, Bergado DT (2004) Undrained shear behavior of cement admixed clay at high water content. J Geotech Geoenvironmental Eng 130:1096–1105. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:10(1096)

Horpibulsuk S, Phetchuay C, Chinkulkijniwat A, Cholaphatsorn A (2013) Strength development in silty clay stabilized with calcium carbide residue and fly ash. Soils Found 53:477–486. https://doi.org/10.1016/j.sandf.2013.06.001

Horpibulsuk S, Munsrakest V, Udomchai A et al (2014) Strength of sustainable non-bearing masonry units manufactured from calcium carbide residue and fly ash. Constr Build Mater 71:210–215. https://doi.org/10.1016/j.conbuildmat.2014.08.033

Ikeagwuani CC, Nwonu DC (2019) Emerging trends in expansive soil stabilisation: a review. J Rock Mech Geotech Eng 11:423–440. https://doi.org/10.1016/J.JRMGE.2018.08.013

Ismail AIM, Belal ZL (2016) Use of cement kiln dust on the engineering modification of soil materials, Nile Delta. Egypt Geotech Geol Eng 34:463–469. https://doi.org/10.1007/S10706-015-9957-6/TABLES/4

Ismeik M, Shaqour F, Hasan SE (2021) Geotechnical evaluation of clayey soils amended with cement kiln dust during freeze-thaw cycling. Arab J Geosci 14:1–14. https://doi.org/10.1007/S12517-021-08144-6/FIGURES/15

Ito A, Wagai R (2017) Data descriptor: global distribution of clay-size minerals on land surface for biogeochemical and climatological studies. Sci Data 4:1–11. https://doi.org/10.1038/sdata.2017.1031

Jiang NJ, Du YJ, Liu SY, et al (2015) Multi-scale laboratory evaluation of the physical, mechanical, and microstructural properties of soft highway subgrade soil stabilized with calcium carbide residue. 101139/cgj-2015–0245 53:373–383. https://doi.org/10.1139/CGJ-2015-0245

Kasama K, Ochıaı H, Yasufuku N (2000) On the stress-strain behaviour of lightly cemented clay based on an extended critical state concept. Soils Found 40:37–47. https://doi.org/10.3208/SANDF.40.5_37

Khadka SD, Jayawickrama PW, Senadheera S, Segvic B (2020) Stabilization of highly expansive soils containing sulfate using metakaolin and fly ash based geopolymer modified with lime and gypsum. Transp Geotech 23:100327. https://doi.org/10.1016/J.TRGEO.2020.100327

Kolay PK, Ramesh KC (2016) Reduction of expansive index, swelling and compression behavior of kaolinite and bentonite clay with sand and class C fly ash. Geotech Geol Eng 34:87–101. https://doi.org/10.1007/S10706-015-9930-4/TABLES/14

Krammart P, Tangtermsirikul S (2004) Properties of cement made by partially replacing cement raw materials with municipal solid waste ashes and calcium carbide waste. Constr Build Mater 18:579–583. https://doi.org/10.1016/J.CONBUILDMAT.2004.04.014

Li W, Yi Y, Puppala AJ (2019) Utilization of carbide slag-activated ground granulated blast furnace slag to treat gypseous soil. Soils Found 59:1496–1507. https://doi.org/10.1016/j.sandf.2019.06.002

Li Y, Li J, Cui J et al (2021) Experimental study on calcium carbide residue as a combined activator for coal gangue geopolymer and feasibility for soil stabilization. Constr Build Mater 312:125465. https://doi.org/10.1016/J.CONBUILDMAT.2021.125465

Li Z, Liu S, Ren W et al (2020) Multiscale laboratory study and numerical analysis of water-weakening effect on shale. Adv Mater Sci Eng 2020. https://doi.org/10.1155/2020/5263431

Liu Y, Chang CW, Namdar A et al (2019) Stabilization of expansive soil using cementing material from rice husk ash and calcium carbide residue. Constr Build Mater 221:1–11. https://doi.org/10.1016/j.conbuildmat.2019.05.157

M T (1979) Engineering properties of lime-treated marine soils and D. M. M. Method. Proc 6th Asian Reg Conf SMFE, 1979 1:191–194

Mahmudi M, Eskisar T (2022) Altun S (2022) The effects of electric arc furnace (EAF) slag on engineering properties of clay–slag mixtures. Arab J Geosci 152(15):1–12. https://doi.org/10.1007/S12517-022-09494-5

Mıura N, Horpıbulsuk S, Nagaraj TS (2001) Engineering behavior of cement stabilized clay at high water content. Soils Found 41:33–45. https://doi.org/10.3208/SANDF.41.5_33

Moayedi H, Kazemian S, Huat BBK (2013) Shear strength parameters of improved peat by chemical stabilizer. Geotech Geol Eng 31:1089–1106. https://doi.org/10.1007/S10706-013-9635-5/FIGURES/19

Mosa AM, Taher AH, Al-Jaberi LA (2017) Improvement of poor subgrade soils using cement kiln dust. Case Stud Constr Mater 7:138–143. https://doi.org/10.1016/j.cscm.2017.06.005

Nicholson PG (2015) Soil improvement and ground modification methods. Elsevier Inc

Parthiban D, Vijayan DS, Kausik J et al (2020) Performance study on clayey soil stabilized by lime and geopolymer with partial replacement of sodium bentonite as an additive. AIP Conf Proc 2271:030003. https://doi.org/10.1063/5.0025073

Ramos MR, Melo VF, Uhlmann A et al (2015) Clay mineralogy and genesis of fragipan in soils from Southeast Brazil. CATENA 135:22–28. https://doi.org/10.1016/j.catena.2015.06.016

Rimal S, Poudel RK, Gautam D (2019) Experimental study on properties of natural soils treated with cement kiln dust. Case Stud Constr Mater 10:e00223. https://doi.org/10.1016/J.CSCM.2019.E00223

Salimi M, Ilkhani M, Vakili AH (2018) Stabilization treatment of Na-montmorillonite with binary mixtures of lime and steelmaking slag. 101080/1938636220181439294 14:295–301. https://doi.org/10.1080/19386362.2018.1439294

Siddiqua S, Barreto PNM (2018) Chemical stabilization of rammed earth using calcium carbide residue and fly ash. Constr Build Mater 169:364–371. https://doi.org/10.1016/J.CONBUILDMAT.2018.02.209

Taher A, Rabb Z, Kuwano J et al (2011) Effect of curing stress and period on the mechanical properties of cement-mixed sand. Soils Found 51:651–661. https://doi.org/10.3208/SANDF.51.651

Tangpagasit J, Cheerarot R, Jaturapitakkul C, Kiattikomol K (2005) Packing effect and pozzolanic reaction of fly ash in mortar. Cem Concr Res 35:1145–1151. https://doi.org/10.1016/J.CEMCONRES.2004.09.030

Tatsuoka F (1983) Triaxial strength characteristics of cement-treated soft clay

Thomas A, Tripathi RK (2018) Yadu LK (2018) A laboratory investigation of soil stabilization using enzyme and alkali-activated ground granulated blast-furnace slag. Arab J Sci Eng 4310(43):5193–5202. https://doi.org/10.1007/S13369-017-3033-X

TokgözHozatlıoğlu D, Yılmaz I (2022) Şişen Zeminlerdeki Kireç Kolonu Uygulamalarında İyon Göçü Mekanizması. Jeol Mühendisliği Derg 45:245–260. https://doi.org/10.24232/jmd.1049677

Yang L, Deng X, Hussein AF et al (2018) Research on pavement performance of mixed filler with alkaline residue-expansive soil. IOP Conf Ser Earth Environ Sci 170:022148. https://doi.org/10.1088/1755-1315/170/2/022148

Yang H-P, Zheng J-L (2006) The new engineering treatment techniques of expansive soils subgrade for GuangXi Nanning-Youyi Guan Expressway. 439–450. https://doi.org/10.1061/40802(189)32

Yılmaz F, Sadoğlu E, Kamiloğlu HA (2022) Evaluation of the effect of waste zeolite on the strength and micro-macrostructure of a high plasticity clayey soil stabilized with lime-waste zeolite mixtures subjected to freezing–thawing cycles. Arab J Geosci 156(15):1–12. https://doi.org/10.1007/S12517-022-09767-Z

Yin J, La CK (1998) Strength and stiffness of Hong Kong marine deposits mixed with cement — the Hong Kong Polytechnic University. Geotech Eng 29(1):29–44

Zheng J-L, Zhang R, Yang H-P (2009) Highway subgrade construction in expansive soil areas. J Mater Civ Eng 21:154–162. https://doi.org/10.1061/(ASCE)0899-1561(2009)21:4(154)