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Stabilization of Meles Delta soils using cement and lime mixtures

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Abstract. İzmir Bay reserves high amount of residual alluvial deposits generated by Meles River at its stream mouth. These carried sediments with high water content and low bearing capacity are unsuitable in terms of engineering purposes. In-situ soil stabilization with deep soil mixing method is considered to improve properties of soil in this location. This method is widely used especially over Scandinavia, Japan and North America. Basically, the method covers mixing appropriate binder into the soil to improve soil profile according to the engineering needs. For this purpose, soil samples were initially provided from the site, classification tests were performed and optimum ratios of lime and cement binders were determined. Following, specimens representing the in-situ soil conditions were prepared and cured to be able to determine their engineering properties. Unconfined compression tests and vane shear tests were applied to evaluate the stabilization performance of binders on samples with different curing periods. Scanning electron microscope was used to observe time-dependent bonding progress of binders in order to validate the results. Utilization of 4% lime and 4% cement mixture for the long-term performance and 8% lime and 8% cement mixture for short term performance were suggested for the stabilization of Meles Delta soils. Development of CSH and CAH in a gel form as well as CSH crystals were clearly observed on SEM images of treated specimens.

Keywords: soil stabilization; deep soil mixing; lime-cement mixtures

1. Introduction

All types of engineering structures must transfer their loads to the load bearing soil strata by means of varying foundation designs. However, existing soil at a construction site may be unsuitable for supporting those structures. At this point, there are several solutions for load bearing problems to be preferred such as installing deep foundations, designing foundations according to characteristics of existing soil and replacing the soft soil by high-grade one. Applying soil improvement methods, especially using admixtures for the stabilization of existing soil by soil mixing, is another widely used method all around the world. Rather than the other methods, stabilization by use of various admixtures also helps improving hydraulic and mechanical features such as permeability and soil density as well as the strength parameters. Basically, the method covers mixing appropriate binder into the soil to improve soil profile according to the engineering needs.

Soil mixing is mainly divided into two categories as shallow mixing and deep mixing. Shallow mixing defines improving the upper soil parts up to approximately 5 meters depth from ground, by use of various mixing tools that can inject selected binder into the soil. On the other hand, deep soil mixing (DSM) uses the similar procedure with advanced mixing tools which are effective up to 30-40m depth.

DSM method is widely used especially over Scandinavia, Japan and North America since its first demonstration was seen in the USA in 1986 (Bruce *et al.* 1999). In the DSM method, binders are injected into the weak soil mass in two different ways of dry and wet mixing (Timoney *et al.* 2012). Wet mixing procedure is applied for the soils which are usually over the ground water level, so that the required amount of water for soil-binder reactions are also provided through injected binder slurry (Saberian *et al.* 2018). For the weak soils below ground water level and with high natural water content, dry mixing method is preferred. Dry mixing method, which covers injecting dry binder directly into the weak soil mass, also allows utilizing quicklime and that provides lowering the water content of target soil via exothermic hydration reactions.

İzmir Bay reserves high amount of residual alluvial deposits generated by Meles River at its stream mouth. These sediments with high water content and low bearing capacity are unsuitable in terms of engineering purposes. To overcome this problem, in situ soil stabilization with DSM method is planned to be implemented by İzmir Metropolitan Municipality, Department of Public Works and Engineering.

In this study, the laboratory representation of in-situ deep soil mixing implementation was performed to guide the stabilization works. In a similar manner with the literature, lime, cement and their mixtures were utilized in different proportions as the chemical binding agents. Soil samples were initially provided from the site, classification tests were performed and optimum ratios of lime and cement binders were determined. Subsequently, specimens representing the in-situ soil conditions were prepared and

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cured with the aim of determining their engineering properties. To do this, a special sample preparation technique has been adopted for the preparation of the samples, representing the deep soil mixing implementations. Unconfined compression test method was applied to evaluate unconfined compressive strengths (UCS) of specimens with different curing periods. Vane shear tests (VST) were also performed to precisely observe strength gain of specimens in time. For the microstructural analyses, scanning electron microscope (SEM) was used to observe time-dependent bonding progress of specimens.

1.1 Background

The most preferred stabilization agents for soft alluvial deposits are lime because of its overall economy and ease of use. Several research studies highlighted the beneficial effects of lime in improving soil performance (Dash and Huseyin 2012, Calik and Sadoglu 2014). But later than, cement became more popular due to providing greater strength increments. Nowadays, gypsum, ground granulated blast furnace slag, fly ash and various chemical binders are also used in addition to lime and cement for soil stabilization (Ferguson 1993, Cokca *et al.* 2009, Grubb *et al.* 2010, Mohanty *et al.* 2017, Rahmad and Ismail 2018).

Boardman *et al.* (2001) reported that lime, either in the form of quicklime [calcium oxide (CaO)] or as hydrated lime [calcium hydroxide ($Ca(OH)_2$)], has been added to clay soils to improve physical properties for centuries. When quick lime is mixed with soil, it reacts with the water in soil mass and initiates a highly exothermic hydration reaction. The water utilized in this hydration reaction can result in significant improvements in soil workability because of dewatering. In this case, an increase in pH of the soil is also experienced. The hydrated lime then reacts with the pozzolanic material in the soil and residual water to produce calcium silicate hydrate (CSH), which contributes to strength gain (Timoney *et al.*, 2012).

Apart from lime, cement is a hydraulic type stabilizing agent. Bergado *et al.* (1996) reported that there were two major chemical reactions between cement and clay minerals, which govern the soil cement stabilization process. The first one is the primary hydration reaction of the cement and water, and the second is pozzolanic reactions between the limes released by the cement and the clay minerals. Binding of soil particles during stabilization process is governed by calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) compounds, which are the binding gels formed throughout the hydraulic reactions.

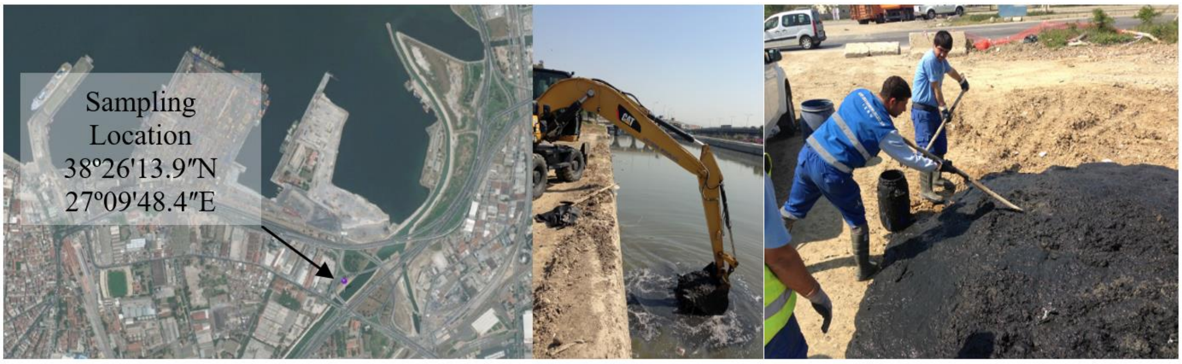
Soil stabilization in highly organic soils was analyzed in the studies of Timoney *et al.* (2012) and Yunus *et al.* (2016). As they reported, during the stabilization of organic soils, calcium hydroxide reacts with the humic acids to form insoluble products which coat the particles in the soil. Stabilization under highly organic soil conditions was also investigated by Hebib and Farrell (Hebib and Farrell, 2003) and Hernandez-Martinez and Al-Tabbaa (2005). These researchers were especially examined the stabilization process and stabilized organic soils under electron microscope. They concluded that there was little or no interaction between the strengthening products created during hydration and the organic material of the stabilized peat. Combining the results of mentioned investigations with the studies of Axelsson *et al.* (2002), it is easy to understand that there is a threshold below which no increase in strength will occur. It is suggested that once this threshold is passed, there is enough binder to cause the pH to increase, neutralizing the acids present.

To determine ideal amount of lime in soil stabilization works, Eades and Grim (1996) defined “initial consumption of lime (ICL)” as another governing term. ICL is the lime fixation point, which is the percentage quicklime addition required to produce a saturated solution of lime in a suspension of clay in water and thereby fully satisfy of ion exchange. Quicklime addition above this point is considered necessary to bring about the stabilization reactions. The test determines the pH of the solution and the ICL value is the quicklime percentage that produces a pH of 12.4. However, to avoid interpretation mistakes, it is recommended that the full ICL test curves should be examined, rather than concentrating on specific pH (12.4) values by Rogers *et al.* (1997).

Rogers *et al.* (1997) also worked on the plasticity alterations in lime stabilized soils. As the literature shows, a substantial reduction in plasticity (or plasticity index, PI) is seen for the clays mixed with lime. Generally, this reduction is caused by an increase in plastic limit (PL) and a small change in liquid limit (LL). They inferred that the LL altered with low lime contents, whereas the PL required greater lime addition to attain full change. So that, PL is a better indicator for tests. The results were in compliance with the literature and the PI values decreased with increasing lime contents. Effects of treatments with cement and lime on the consistency limits of marine sediments dredged from Dunkirk port were examined in the study of Wang *et al.* (2013). Also, a comprehensive study was conducted by Kim *et al.* (2018) on the laboratory samples of Korean marine clays. In this study, a series of laboratory experimental studies were conducted to obtain the static strengthening and dynamic behaviors and geotechnical engineering design parameters of cement-treated Korean marine clays.

A feasibility study was carried out by Grubb *et al.* (2010) to investigate usage of stabilized dredged materials as potential fill materials. Unconfined compression tests were performed to evaluate the improvement in stabilized samples. An initial moisture content of 132.5% was provided to represent deep soil mixing site conditions in the laboratory. As a result, authors concluded that dredged materials can be successfully stabilized through selecting right binders even they have high water contents.

Miura *et al.* (2001) also investigated the deep soil mixing implementations via laboratory representations. The authors especially focused on the relationship between binder ratio and strength development evaluated by UCS tests. In their study, cement was used as the stabilizing agent for improving Ariake-Saga and Hong Kong clays. Another research on stabilized dredge materials was carried out by Schlue *et al.* (2010), where peak and residual shear strengths were evaluated by vane shear testing using the dredged mud obtained from a harbor construction in Germany.



(a) (b) (c)

Fig. 1 Soil sampling location (a), soil removal (b) and sampling (c)

Rajasekaran *et al.* (1997) studied on the mineralogy of treated marine clays. Because of observing various foundation problems of offshore structures due to hostile wave conditions and climatic conditions, a need of soil improvement was occurred. To shed light on similar problems, representative soils were procured from the east coastal regions of India (from Madras and Nova ports) for improvement analyses. Lime and sodium hydroxide chemicals were utilized in scope of stabilization studies. Considering the results of SEM images, formation of aggregates/crumbs of different sizes were seen in all lime treated soils.

2. Materials and methods

2.1 Materials

2.1.1 Soil and in-situ sampling

Soil stabilization of Meles Delta soils with Deep Soil Mixing (DSM) method was primarily planned to be applied at Halkapınar/Konak, İzmir. This area is located close to the İzmir Port (Fig. 1a). Soil batches were taken out from the river base through an excavator bucket. After that, soil samples were filled into the lidded containers from accumulated river base sediments (Fig. 1b and 1c). Because of their soaked condition, the natural water content of removed soils could not be kept constant.

To examine the effect of drying conditions on Atterberg limits, the samples were dried at three different oven dry temperatures and air-dry conditions. Considering the Unified Soil Classification System (USCS), the liquid limits of dried samples were examined in terms of organic behavior. After observing a negligible difference between those results, all provided samples were dried at 105 ºC. Later, dried soils were crushed by use of a jaw crusher. All the pulverized soils were then stored in covered storage boxes in laboratory conditions.

2.1.2 Binders

Hydraulic or non-hydraulic binders may be selected for a soil improvement project with soil mixing. Hydraulic binders are self-curing in contact with water, while a nonhydraulic binder requires a catalyst (mostly air) to initiate curing. Jose (1989) reported, lime and cement were the most effective binders for marine clays among twenty different additives. For this study, the binder selection was completed with paying regard to in-situ soil conditions. Considering the in-situ soil mixing process, which is operated under water (soaked), the binders were chosen as hydraulic lime and cement.

In this study, high calcium quicklime (CaO) was used and it was donated by Turkish Lime Producers Association (TLPA). On the other hand, CEM-I 42.5 R type Portland cement according to TS EN 197-1 (2012) norms was provided from a local manufacturer for use in this research study.

2.2 Methods

2.2.1 Water content

Oven drying method was applied in accordance with ASTM D2216-10. For the drying process, small representative specimens were prepared from the stored bulk samples and dried at 105 ºC for 24 hours.

2.2.2 Atterberg limits

Plasticity of the soil samples were observed under four different drying conditions of 25ºC (air drying), 60ºC, 86ºC and 105ºC. By this means, liquid limits at each drying temperature was compared and it shed light to organic substances of soil samples as well as the effect of high temperature drying on Atterberg limits. Fall cone test method according to the BS 1377-2 was preferred for determination of liquid limits. On the other side, hand method in ASTM 4318-10 was practiced to determine plastic limits of samples.

2.2.3 Organic matter

In a soil stabilization with binder mixing project, organic content of the soil is highly significant in terms of binder dosages. Organic matter in soil body prevents the occurrence of required bonding reactions. Thus, this may result in overconsumption of lime to provide required pH conditions as it is defined by Eades and Grim (1996).

In the light of this information, organic matter determination of provided soil samples was completed by use of a muffle furnace in the laboratory. The ignition process was maintained at a temperature of 440 ºC as it is explained in ASTM D2974-07a.

Table 1 The implemented binder ratios

Cement (%)	Lime (%)	Total Binder (%)
0	2	2
2	2	4
0	4	4
4	0	4
4	4	8
0	8	8
8	0	8
8	8	16

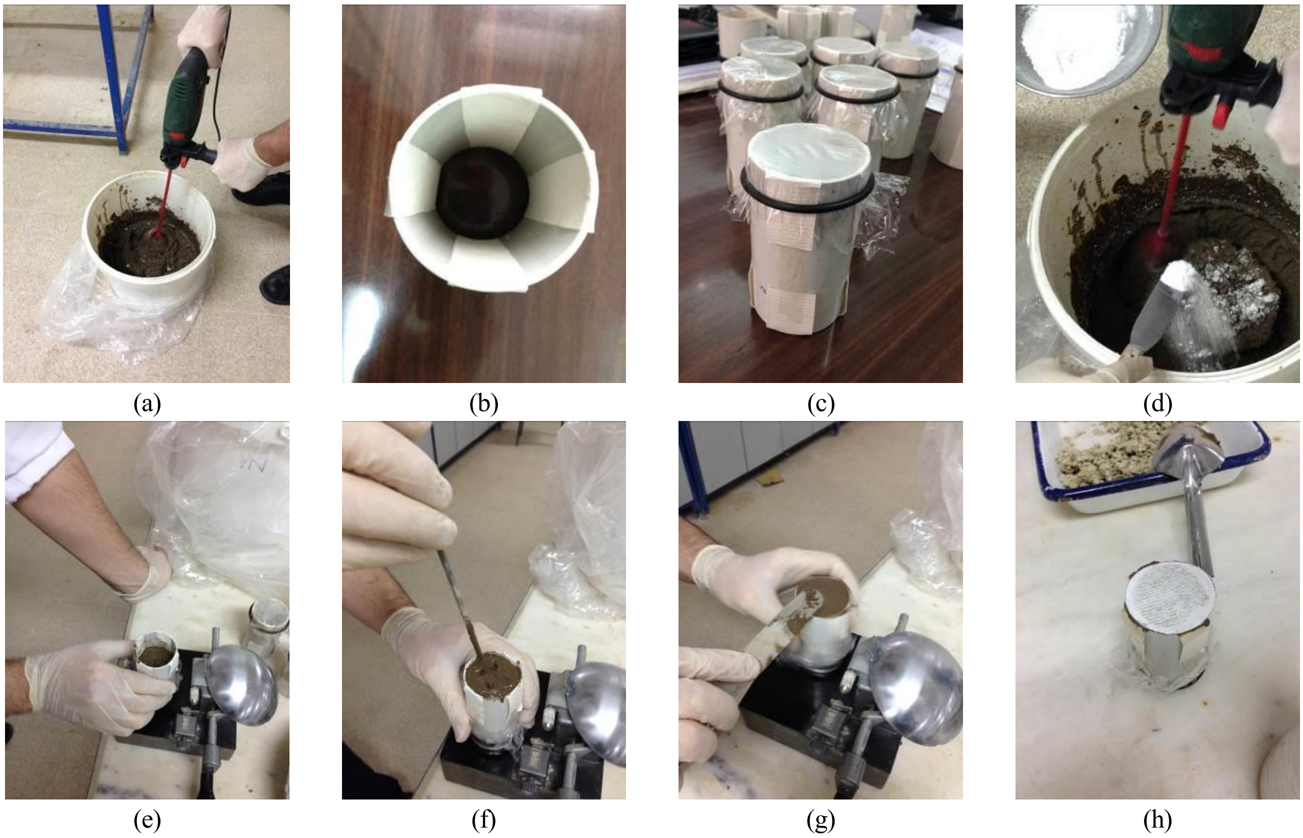


Fig. 2 Sample preparation steps (a-h)

2.2.4 Soil classification

Unified Soil Classification System was adopted in correspondence with ASTM D2487-11 to classify the Meles Delta soils. Samples dried in an oven at 105ºC were utilized after observing the negligible differences obtained from drying temperature effects.

2.2.5 pH evaluations

At the optimum lime content determination approach, Accumet XL-500 type bench top meter was used. Measurements were completed in compliance with ASTM D6276-99a. To be able to follow graphical variation in a wide scale, specimens with 7%, 8%, 9% and 10% of lime ratios were also tested in addition to defined specimens with lime ratios of 2%, 3%, 4%, 5% and 6%.

2.2.6 Unconfined compression tests

Unconfined compressive strengths (UCS) of specimens were determined as per ASTM D2166-13. Eccentric loading of specimens was precluded through hinged top connection of proving ring. The test apparatus used can provide the rate of loading in accordance with ASTM standards. To prevent moisture loss of soaked samples, the rate of strain was chosen so that the time to failure did not exceed about 15 minutes. This limitation was also important in terms of providing undrained test conditions.

2.2.7 Laboratory vane shear tests

To investigate the improvement in shear strength of samples, laboratory vane shear tests were applied in addition to unconfined compression tests. ASTM D4648-13 instructions were followed in line with this purpose. The vane blade used was having a diameter of 12.7 mm. The height of the blade was equal to its diameter (H=D type blade according to ASTM D4648-13). The torque was applied at a constant rate of 71.1°/min through a torque spring. Residual strengths of the samples were also evaluated as well as their peak strengths.

2.2.8 Scanning electron microscope (SEM) tests

SEM tests were one of the mineralogical investigations performed in scope of this study to understand development of specimen microstructures during stabilization process. The tests were performed in Electron Microscopy Laboratory of Dokuz Eylül University, Metallurgical and Materials Engineering Department. Investigations were done using JEOL - JSM6060 Scanning Electron Microscope which was operated at 10kV. Magnification level was adjusted to the lowest possible value for initial monitoring. Following this, analyses were completed using magnification levels of x5000 and x10000.

2.2.9 Sample preparation and binder ratios

Laboratory samples were prepared in a representative way to deep soil mixing application at the sea bottom, so that they were not compacted. Besides, reaching in situ moisture content and in-situ unit weight was intended. For the specimen preparation procedure, a method based on the study of Kitazume (2012) was developed special to this study. Specimens were placed in PVC molds through laying, tapping and poking, respectively. After the preparation of specimens, they were cured in a submerged condition for different periods to obtain the change on their moisture contents and unit weights. As a result of applied method, homogeneous, void-free and reproducible specimens were obtained.

Table 1 shows 8 different binder ratios implemented in this study. Mixture proportions were determined by dry weight of materials and it was intentionally preferred to use inadequate binder ratios for in-situ improvement conditions.

PVC sewage pipes were utilized as the laboratory molds for UCS and vane test specimens. Rigid PVC pipes having 50 mm outer diameter were provided and cut into required number of pieces for specimen preparation. Height of molds were arranged so that they will be equal to 2 times of specimen diameters (H/D=2). Filter papers were used in molds to help uniform wetting of specimens during curing process. To prevent undesirable swelling of specimens under curing conditions, rigid metal sheets were used as a mold cap to provide a flat surface for stone weight plates.

Initially, soil samples were mechanically mixed in liquid limit water content and left for mellowing process for at least two hours (Fig. 2(a)). Equally spaced filter paper strips were attached in the PVC molds and the bottom of the molds were sealed by use of stretch film and O-rings (Fig. 2(b)-2(c)).

Mellowed soil sample then thoroughly mixed with determined amount of binder/binder mixture and placed into the molds (Fig. 2(d)). Placement of mixed material was completed by means of three layers. Following placement of each single layer, 30 tapping, 15 poking and 30 tapping cycle was repeated to obtain void-free test specimens. Tapping jobs were completed on Casagrande test apparatus base plate to set a standard for this step (Fig. 2(e)-2(f)). Fully filled molds were then cleaned from the O-rings at the base and both ends of the specimens were smoothed with using laboratory spatula (Fig. 2(g)). Circular filter papers (Fig. 2(h)) were also placed at the leveled edges to provide uniform wetting during submerged curing. Those circular filter papers also helped movement of water between both ends of the specimens through filter paper strips at the internal walls of molds. To examine reproducibility of specimen preparation method, two identical specimens of each binder proportion and curing period were ensured.

2.2.10 Curing conditions

Curing periods were applied as 7, 14, 28 and 56 days to be able to determine and compare short and long-term stabilization behaviors. Following placement of materials into the molds, specimens were left soaking in curing baths with constant temperature. Curing baths were left in a humid room in 23°C at constant laboratory conditions. Swelling of specimens was prevented through applying an adequate pressure by use of adequate plates placed on rigid metal sheet caps. This pressure was kept constant during the curing. After completion of curing period, the specimens were removed from the baths, PVC molds are dismantled, dimensions were determined, weights were scaled, and water contents were measured.

3. Results and discussion

3.1 Classification of dredge material

Classification of the samples can be defined as low plasticity clay (CL). Soil samples were dark black colored and stinky regarding their visual description. However, the soil parts which had a contact with free air showed a color change that ended up as light brown.

Drying temperature effect on consistency limits due to organic content of soil was investigated, but the results showed there was a negligible difference between consistency limits of samples dried at different temperatures as shown in Table 2. By taking the measure of this behavior, all the stored soil batches were dried at 105 °C and pulverized.

3.2 Unit weights and water contents

Reproducibility of specimen preparation method was analyzed through determined unit weights and water contents of cured specimens. It was observed that the obtained results for two identical specimens were similar for each different curing period and binder ratio parameters. So that, it can be simply deduced that the method applied for specimen preparation was highly successful in terms of reproducibility. In Table 3, the average values of these parameters were shown.

An engineering drilling study by İzmir Metropolitan Municipality, Water and Sewerage Administration Office was conducted at a close point to sample procurement location. According to the results of that study, wet unit weight of soil at a 9.0m depth was found 17.85 kN/m^3 whereas the water content was found 43%. Previous studies in literature showed that a decrease in unit weight was observed for the stabilization works in which lime or lime-

Table 2 Effect of different drying temperatures on the consistency of soil samples

+No.4 (%)	-No. 200 (%)	Temp (°C)	LL (%)	PL (%)	IP (%)	Org. Cont. (%)	USCS Sym.
0.5	68.6	25	47.1	26.4	20.7	11	CL
		60	44.9	26.5	18.4		
		86	44.5	26.1	18.4		
		105	45.2	24.8	20.4		

Table 3 Unit weights and water content of cured specimens

Cement (%)	Lime (%)	Total Binder (%)	7 Days*	14 Days*	28 Days*	56 Days*
0	2	2	17.25/40.2	17.2/40.8	17.0/39.8	17.1/41.9
2	2	4	17.35/39.7	17.4/39.3	17.2/40.6	17.2/40.1
0	4	4	16.85/40.8	17.2/40.4	16.9/40.9	16.7/41.9
4	0	4	17.3/43.1	17.1/41.7	16.9/41.8	16.9/42.9
4	4	8	16.8/38.5	16.6/38.0	17.0/37.4	16.6/39.0
0	8	8	16.95/36.0	16.9/36.0	16.8/37.0	16.5/37.1
8	0	8	16.95/40.6	17.0/40.6	17.2/39.9	17.0/40.3
8	8	16	17.7/34.4	17.7/34.4	17.6/34.5	17.8/34.9

*Unit Weights (kN/m^3) / Water Content (%)

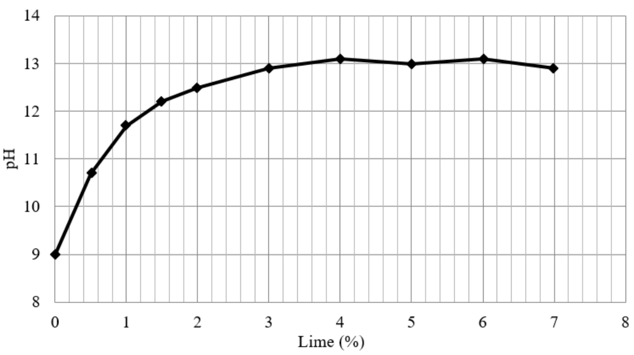


Fig. 3 pH test results

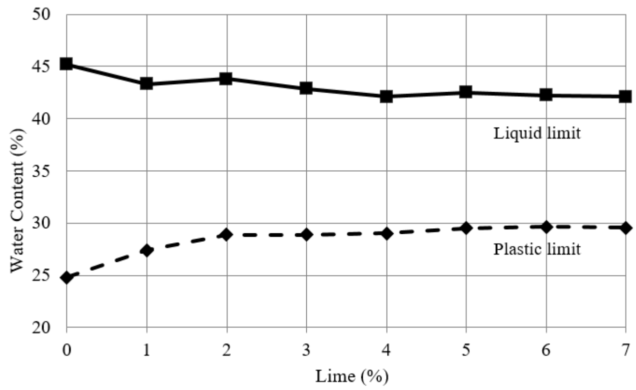


Fig. 4 Change in Atterberg limits with lime content

cement mixtures were utilized as the binder (Kavak and Akyarlı 2007, Moayed *et al.* 2011). Considering these all, the laboratory samples with decreasing unit weights and water contents represents the potential in situ conditions compatibly.

Table 4 UCS test results

Cement (%)	Lime (%)	Total Binder (%)	Unconfined Compressive Strength (kPa) 7 Days		14 Days		28 Days		56 Days	
0	2	2	33	36	41	43	51	54	42	50
2	2	4	77	83	99	90	101	109	112	102
0	4	4	40	34	67	61	59	67	72	77
4	0	4	29	32	31	29	27	30	30	31
4	4	8	75	80	109	97	171	198	200	182
0	8	8	63	69	82	107	107	104	104	104
8	0	8	186	184	193	198	236	233	239	248
8	8	16	137	173	273	272	376	449	520	475

The relationship between binder ratio and water content of cured specimens can be followed in Table 3. Simply, a decrease in water content can be seen with increased binder ratio. It is undoubtedly a result arises out of the reactions between binder and pore water as well as more dry material added. However, this tendency is more obvious for lime dosage increments rather than increased cement ratios due to the exothermic reactions of lime in its hydration process.

3.3 pH

To be able to determine the minimum percentage of lime requirement for stabilization works, pH tests in laboratory conditions were performed. Results of pH test were recorded after reaching stable readings of second decimals for each step. The tests were not terminated after reaching 12.40 pH value as it was defined by Eades and Grim (1996). It was aimed to observe a clear asymptote of diagram as shown in Fig. 3. The ICL, corresponding to 12.4 pH value of solution, was observed at 2% lime addition, however, increasing lime percentages were utilized to observe variations on pH values.

3.4 Variation in Atterberg limits with lime content

Variation in Atterberg limits of specimens with different lime contents were examined to determine the optimum lime content for stabilization works. As it is seen from Fig. 4, liquid limit (LL) of samples consistently decreases with increasing lime content whereas the behavior of plastic limit (PL) is exact the opposite. As a consequence of liquid and plastic limit changes, plasticity index (PI) of samples persistently decreases with lime addition. This improvement is substantial until a definite point of 4% lime content, which is called "lime fixation point" by Eades and Grim (1996).

It is also notable to report that there is little or no change in liquid and plastic limits of samples after 4% lime addition. Considering this result, 4% addition of lime was decided to be applied as a design ratio, however inadequate and overdose ratios were also utilized to present a reference study.

3.5 Unconfined compressive strength (UCS)

UCS test results of provided test specimens are shown

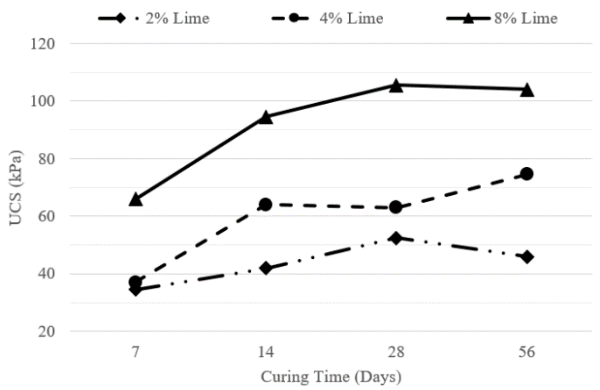


Fig. 5 Effect of lime content on UCS test results

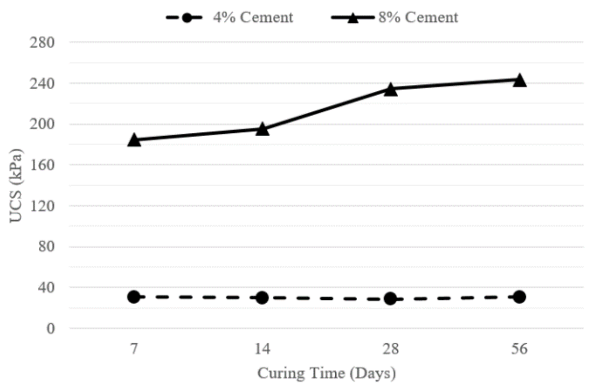


Fig. 6 Effect of cement content on UCS strengths

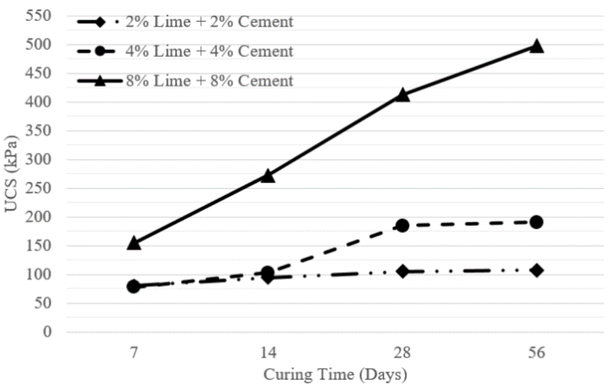


Fig. 7 Effect of lime and cement content on UCS strengths

in Table 4 for varying binder ratios as well as different curing periods. In total, 64 UCS tests were conducted in laboratory conditions.

The effect of lime content on unconfined compressive strength of stabilized specimens in terms of curing periods can be seen in Fig. 5. Average strengths of identical specimens were calculated and those were used to draw resulting graphics. As it is seen on the figure, specimens with 2% lime content gained some strength in the short period (from 34.5 kPa to 52.5 kPa). However, this improvement was not sustained and a decrease in the long-term outcomes was shown up. The main reason of this result was the inability to provide necessary alkali medium for long term pozzolanic reactions.

On the other hand, relatively high compressive strengths were obtained for 4% lime (74.5 kPa) and 8% lime (104.0 kPa) contents for longer curing periods. Especially for 8% lime content, it can be said that the compressive strengths of specimens reached a stable level and remained similar after a curing period of 28 days (Fig. 5).

Effect of cement addition on UCS is shown in Fig. 6. Considering the similar studies in literature as well as previous site reports, 2% of cement addition solely was disregarded as it was a real low dosage in terms of stabilizing weak soils. For this reason, only 4% and 8% of cement addition by dry weight of soil was applied and the results were drawn. As Fig. 6 illustrates, addition of 4% cement by dry weight made almost no change in UCS of specimens with curing periods. By this result, a deduction can be made as utilizing 4% cement without adding any lime in the mixture is not enough to improve strength characteristics of Meles Delta soils. So that, these results verify the binder ratio design of this study, especially for cement percentages. However, 8% addition of cement, which resulted in 243.5 kPa in strength, is prominently effective in terms of stabilizing riverbed soils. Reaching stability in UCS of specimens was also observable after 28 days.

Another comparison of UCS values with changing binder contents and curing periods were made in Fig. 7. In this figure, the UCS values of designs for lime and cement mixtures were presented. This graphic primarily shows the effect of cement addition on UCS, when it is compared to lime only designs as shown in Fig. 5. As one can see that the cement addition has a significant effect on UCS of dredge material.

It is definite that the 8% lime and 8% cement mixture gave the highest compressive strengths up to 500 kPa when all the mixture designs in Fig. 7 is considered. Even 4% lime and 4% cement mixture are seen adequate for the short-term improvement of Meles Delta soils, 16% binder in total (8% lime + 8% cement) seemed to be resulted with greater long-term strength developments. It may also be said that the UCS gain over time did not complete yet for 8% lime + 8% cement specimens, considering the gradual increase tendency of the bar graphic. The same tendency may not be valid for the cement only mixtures considering the average slopes of the UCS graphics in Fig. 6.

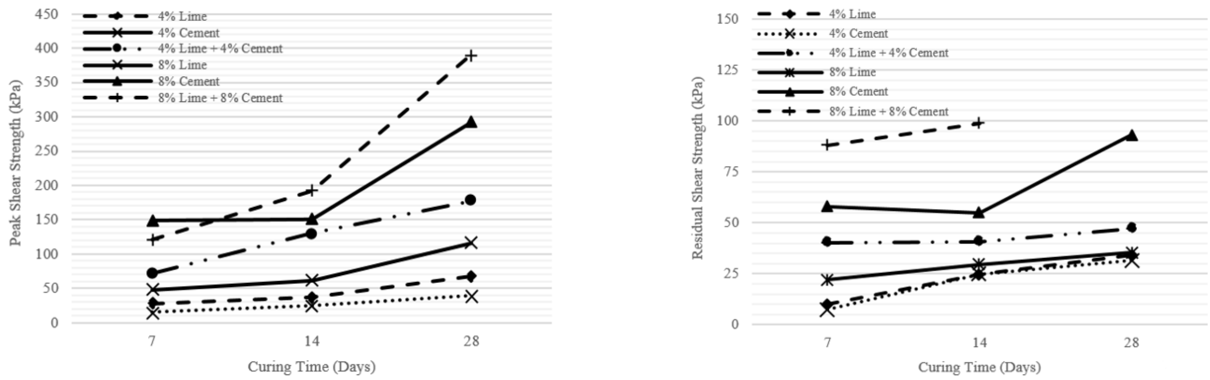
Japanese references reported extreme improvements in site up to 30 meters depth and 500 kPa of compressive strength by use of relatively strong heavy-duty equipment. For highly organic soils of Nordic countries, 200 kPa of compressive strengths could be achieved with their techniques (Bruce *et al.*, 1999). In general, total binder ratio for deep mixing site implementations changes between 8% and 12%, which corresponds to a dosage of 150-200 kg/m^3 (Puppala *et al.*, 2008). Similarly, Massarsch and Topolnicki (2005) reports these values as 80-200 kg/m^3. Considering these all, utilizing 4% lime and 4% cement mixture for a necessity of the long-term performances and 8% lime and 8% cement mixture for short term performances may be suggested for the stabilization of Meles Delta soils.

3.6 Vane shear test results

Vane shear tests were performed on six different types of specimens in terms of their binder proportions (Table 5).

Table 5 Vane shear test results

			Shear Strength (kPa)					
			7 Days		14 Days		28 Days	
Cement (%)	Lime (%)	Total Binder (%)	Peak	Residual	Peak	Residual	Peak	Residual
0	4	4	27.79	10.09	36.98	24.65	67.46	34.07
4	0	4	15.24	7.40	24.43	24.88	39.22	31.60
4	4	8	71.05	40.12	129.99	40.79	177.73	47.07
0	8	8	47.52	21.96	61.41	29.58	116.32	35.41
8	0	8	148.60	58.05	150.61	54.91	292.49	93.24
8	8	16	121.70	87.86	191.85	98.84	390.43	N/A



(a) (b)

Fig. 8 Peak (a) and residual (b) shear strengths versus curing time

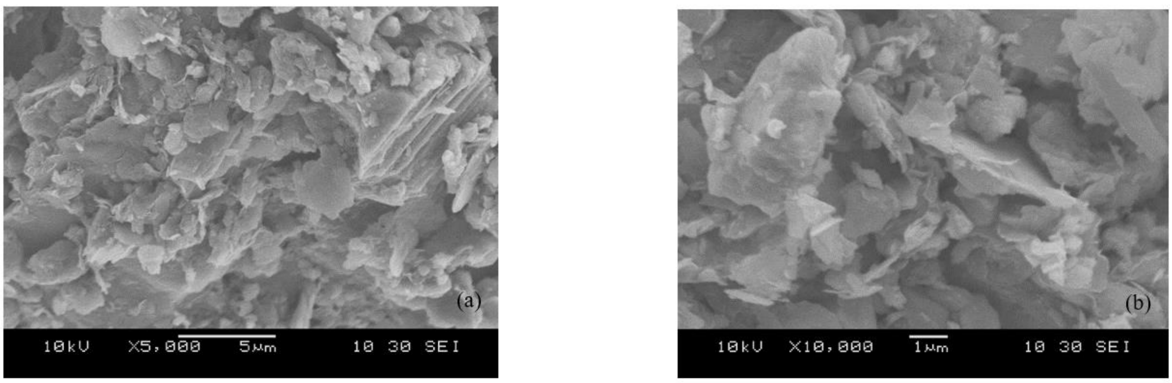


Fig. 9 SEM images of untreated soil at different magnification levels

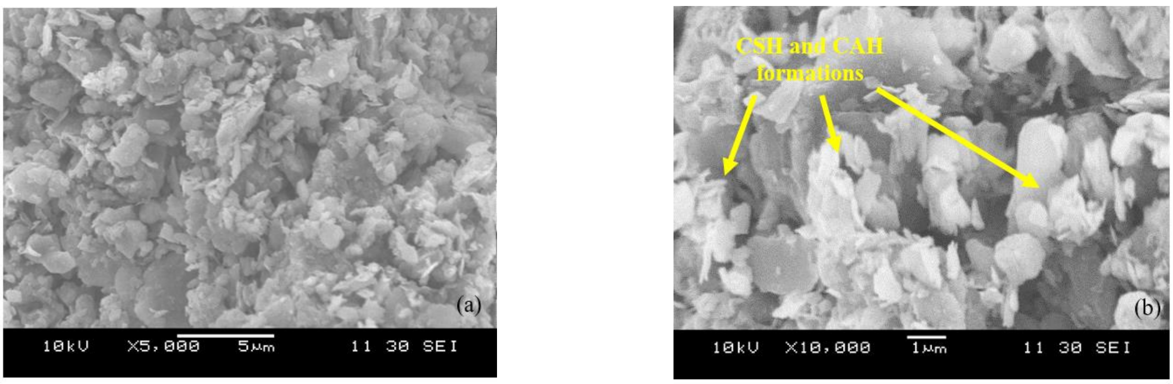


Fig. 10 SEM images of 7 days cured specimens with 8% lime

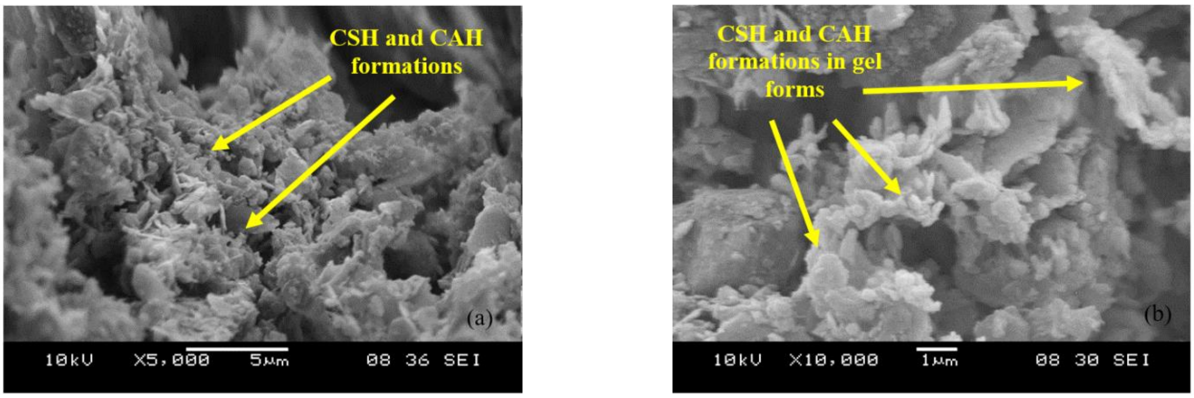


Fig. 11 SEM images of 28 days cured specimens with 8% lime

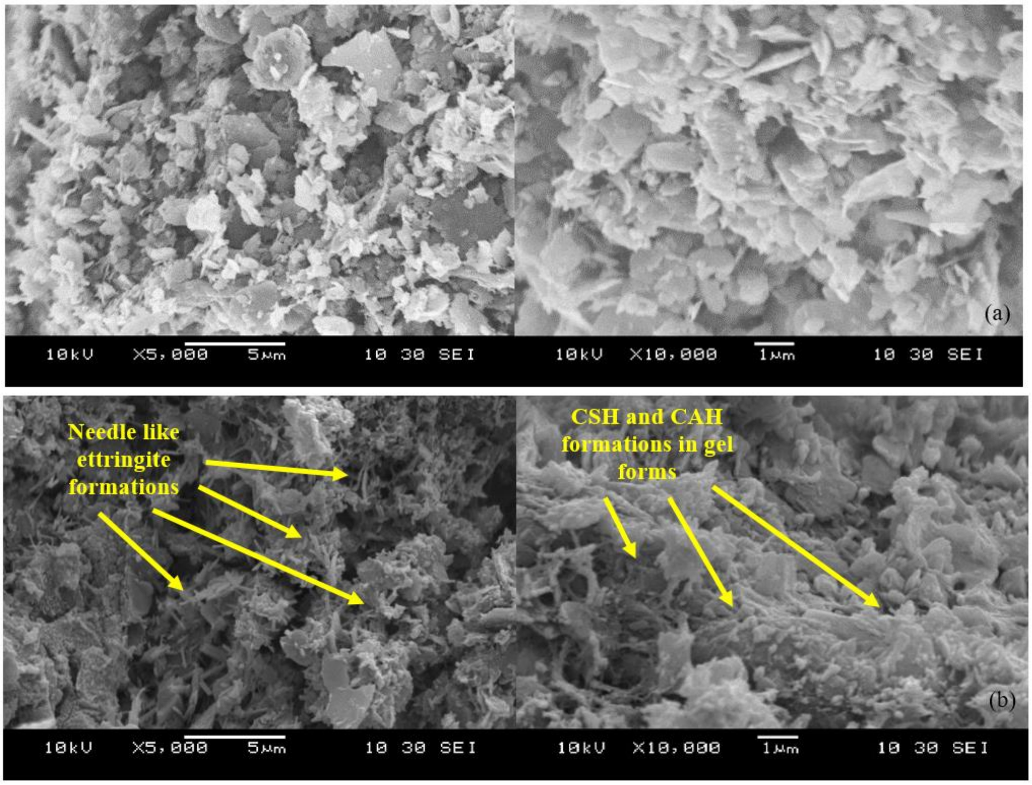


Fig. 12 SEM images of (a) 7 and (b) 28 days cured specimens with 8% lime and 8% cement mixture for x5000 and x10000 magnification

For the test design, addition of 2% lime as well as 2% lime and 2% cement mixture were neglected during the preparation of VST specimens. This proportions were found to be insufficient (i.e., under doses) due to achieving inadequate performances in UCS tests.

Results obtained from VST are very similar to those obtained from UCS tests and they are presented in Table 5. The specimens treated with only 4% lime or only 4% cement showed quite a little improvement in shear strengths. These unsuccessful improvements indicate that the binder added for those specimens were insufficient for the full potential of chemical interactions. However, on treatment with 8% or 16% binder in total, significant increases up to 400 kPa was observed in shear strengths.

Another important observation can be reported by looking at the strength gains of pure lime or pure cement added specimens. In case of unmixed binder addition, the specimens had negligible changes in their peak shear strengths until 14 days of curing. The strength gain process began after two weeks of curing and major improvements continued until 28 days. The development of peak and residual shear strengths in time were shown in Fig. 8.

However, most of the residual strength improvements were completed in 14 days except from the design with 8% cement addition. Following 14 days of curing period, there was almost no changes determined for residual strengths but the peak strengths rapidly increased. Due to the vane blade failure in the peak strength determination of specimen with 8% lime and 8% cement mixture, the remolded strength of this design could not be evaluated. The ratio of peak strengths to residual strengths approximately varies from 2 to 4 for all specimens tested.

3.7 Scanning electron microscope (SEM) micrographs

Changes in soil fabric by means of the binder reactions were properly detected by SEM results. Although SEM images were acquired for all binder contents, only SEM images of 8% lime, 8% lime and 8% cement were shown in this paper, where the cementation compounds are evident, however, interpretations were made based on all SEM images. The details about the SEM of other binder contents can be found in Sariavci (2016). Fig. 9(a) and 9(b) shows the SEM images of untreated soil at magnification levels of 5.000 times and 10.000 times, respectively.

It is obvious that the untreated clay soil is in a laminated state and has a discontinuous structure. Due to lack of hydration reaction products, voids are clearly visible, and the porous fabric can be easily determined.

In Fig. 10, development of weak soil with the help of admixed lime can be followed for 7 days curing period. Presented SEM images with 8% lime content are magnified 5.000 and 10.000 times. It is clear that the untreated soil fabric changed from particle-based orientation to an integrated structure by lime addition. Cementitious reactions were resulted with a bonded structure of existing particles. Cementation products can be distinctly seen on 8% lime added specimen’s 10.000 times magnified image and quantity of those have a tendency to increase with increasing lime percentage. However, there is almost no change visualized for the specimen with a lime content of 2% (Sarıavci 2016). The SEM image was very similar to that of the untreated soil sample. This is due to the insufficient amount of added lime, which was already submitted as the under dose considering the UCS test results, to promote stabilization needs.

Developments in soil fabric due to lime stabilization can be seen more specifically in Fig. 11. Here is shown the soil-lime reaction products for 28 day cured specimens with the same binder quantities as in previous figure.

The presence of calcium silicate hydrate (CSH) in a gel form, which coats fine particles provides greater aggregates with a spongy appearance, as well as calcium aluminate hydrate (CAH) is clearly seen for 28 day cured specimens. CSH crystals are also noticeable especially for the specimen with 8% lime content. Observing much more reaction products with increasing lime content is another conclusion can be drawn.

Fig. 12(a) and 12(b) illustrates the SEM images of the specimens with 8% lime and 8% cement mixtures for 7 days and 28 days of curing periods, respectively, for two magnification levels. In addition to previously presented lime treated specimens, appreciable formations such as needle like ettringite crystals are also visible after 28 days of curing. This figure also shows that the cement addition not only enhanced the shear strength of the material as previously reported but also decreased the pore spaces in soil structure.

By looking at obtained SEM images, homogeneously improved soil partitions were provided throughout this study. This is most probably due to providing correct mixing procedures and providing homogeneous soil-binder mixtures. Another important point is that the soaked curing procedure played a big role to ensure necessary wet environment for binder reactions. However, it is also thought that soaked curing only would not be successful unless utilizing filter papers to provide evenly wetted specimens as in this study.

The SEM test results are all in compliance with previously obtained strength test results. Even the obtained images are not absolute answers for strength gains of specimens, the visual assessments represent the strength test results by examining types and amounts of reaction products formed.

4. Conclusions

In the scope of this study, a laboratory representation of previously planned deep soil mixing implementation at the stream mouth of İzmir Bay was completed. The tests were performed by use of the soil samples that initially provided from the site. Considering the reserved residual alluvial deposits, lime, cement and their mixtures were utilized in different proportions as the chemical binding agent for stabilization works.

The conclusions that were derived from this study are presented as follows:

• When the relationship between binder ratio and water content of cured specimens is examined, a decrease in water content can be seen with increased binder ratio. It is undoubtedly a result arises out of the reactions between binder and pore water and as a result of increased quantity of dry material. However, this tendency is more obvious for lime dosage increments rather than increased cement ratios due to the exothermic reactions of lime in its hydration process.

• Increment in the lime content of specimens resulted with a decrease in their liquid limit. However, plastic limit values increased with increasing lime content. The lime fixation point was found to be 4% as it was defined by Eades and Grim (1966).

• Considering the unconfined compression test results, specimens with 2% lime content gained some strength in short period. However, this improvement was not sustained and a decrease in long term outcomes was shown up. The main reason of this result was the inability to provide necessary alkali medium for long term pozzolanic reactions.

• Relatively high compressive strengths were obtained for 4% and 8% lime contents for longer curing periods. Especially for 8% lime content, it can be said that the compressive strengths of specimens reached a stable level and remained similar after a curing period of 28 days.

• Addition of 4% cement by dry weight made almost no change in UCS test results of specimens with proceeded curing periods. By this result, a deduction can be made as utilizing 4% cement without adding any lime in the mixture is not enough to improve strength characteristics of Meles Delta soils.

• Specimens treated with lime-cement mixtures were resulted with the highest UCS’s when they are compared to those with pure lime or pure cement addition.

• Utilization of 4% lime and 4% cement mixture for the long-term performance and 8% lime and 8% cement mixture for short term performance were suggested for the stabilization of Meles Delta soils.

• Vane shear test specimens treated with only 4% lime or only 4% cement showed quite a little improvement in their shear strengths. These unsuccessful improvements indicate that the binder added for those specimens were insufficient for the full potential of chemical interactions. However, on treatment with 8% or 16% binder in total, significant increases up to 400 kPa was observed in shear strengths.

• According to the vane shear test results, the specimens had no big alterations in their peak shear strengths until 14 days of curing periods in case of unmixed binder addition. The strength gain process began after two weeks of curing and major improvements continued until the day 28.

• According to the SEM analyses, untreated clay soil was found to be in a laminated state and had a discontinuous structure. It was determined that the untreated soil fabric changed from particle-based orientation to an integrated structure by lime addition. However, there was almost no change determined for the specimen with a lime content of 2%. The reason of this was thought to be the insufficient amount of added lime, which was previously submitted as the under dose considering the UCS test results, to promote stabilization needs.

• Development of CSH and CAH in a gel form as well as CSH crystals were clearly observed on SEM images of treated specimens. Another conclusion that can be drawn was the observation of much more reaction products with increasing lime content.

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References

Axelsson, K., Johansson, S.E. and Andersson, R. (2002), “Stabilization of organic soils by cement and puzzolanic reactions–Feasibility study”, Linkoping, Swedish Deep Stabilization Research Centre c/o Swedish Geotechnical Institute. Linkoping, Report 3, 44.

Bergado, D.T., Anderson, L.R., Miura, N. and Balasubramaniam, A.S. (1996), *Soft Ground Improvement in Lowland and Other Environments*, ASCE Press, New York, U.S.A.

Boardman, D.I., Glendinning, S. and Rogers, C.D.F. (2001), “Development of stabilisation and solidification in lime-clay mixes”, *Geotechnique*, **50**(6), 533-543. https://doi.org/10.1680/geot.2001.51.6.533

Bruce, D.A., Bruce, M.E.C. and DiMillio, A.F. (1999), “Dry mix methods: A brief overview of international practice”, *Proceedings of the International Conference on Dry Deep Mix Methods for Deep Soil Stabilization*, Stockholm, Sweden, October.

Calik, U. and Sadoglu, E. (2014), “Engineering properties of expansive clayey soil stabilized with lime and perlite”, *Geomech. Eng.*, **6**(4), 403-418. https://doi.org/10.12989/gae.2014.6.4.403.

Cokca, E., Yazici, V. and Ozaydin, V. (2009), “Stabilization of expansive clays using granulated blast furnace slag (GBFS) and GBFS-cement”, *Geotech. Geol. Eng.*, **27**(4), 489. https://doi.org/10.1007/s10706-008-9250-z.

Dash, S. and Hussain, M. (2012), “Lime stabilization of soils: Reappraisal”, *J. Mater. Civ. Eng.*, **24**(6), 707-714. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000431.

Eades, J.L. and Grim, R.E. (1966), “A quick test to determine lime requirements of lime stabilization”, Highway Research Record 139, Highway Research Board, National Research Council, Washington, D.C., U.S.A., 61-72.

Ferguson, G. (1993), “Use of self-cementing fly ashes as a soil stabilization agent. Fly Ash for Soil Improvement”, ASCE Geotechnical Special Publication No. 36.

Grubb, D., Chrysochoou, M., Smith, C. and Malasavage, N. (2010), “Stabilized dredged material. I: Parametric study”, *J. Geotech. Geoenviron. Eng.*, **136**(8), 1011-1024. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000254.

Hebib, S. and Farrell, E.R. (2003), “Some experiences on the stabilisation of Irish peats”, *Can. Geotech. J.*, **40**(1), 107-120. https://doi.org/10.1139/t02-091.

Hernandez-Martinez, F.G. and Al Tabbaa, A. (2005), “Strength properties of stabilised peat”, *Proceedings of the International Conference on Deep Mixing–Best Practice and Recent Advances*, Swedish Deep Stabilisation Research Centre, Stockholm, Sweden

Jose, B.T. (1989), “A study of the physical and engineering behaviour of Cochin marine clays”, Ph.D. Thesis, Cochin University of Science and Technology, Cochin, India.

Kavak, A. and Akyarlı, A. (2007), “A field application for lime stabilization”, *Environ. Geol.*, **51**(6), 987-997. https://doi.org/10.1007/s00254-006-0368-0.

Kim, A.R., Chang, I., Cho, G.C. and Shim, S.H. (2018), “Strength and dynamic properties of cement-mixed Korean marine clays”, *KSCE J. Civ. Eng.*, **22**(4), 1150-1161. https://doi.org/10.1007/s12205-017-1686-3.

Kitazume, M. (2012), “Laboratory testing on stabilized soil for ground reinforcement”, *Joint Conference Proceedings. 6-8 March 2012. Tokyo: Tokyo Institute of Technology, 2012*. Web. 23 Mar. 2012

Massarsch, K. and Topolnicki, M. (2005), “Regional Report: European practice of soil mixing technology.”, *Proceedings of the International Conference on Deep Mixing—Best Practice and Recent Advances; Deep mixing’05*, Stockholm, Sweden.

Miura, K., Horpibulsuk, S. and Nagaraj, T.S. (2001), “Engineering behavior of cement stabilized clay at high water content”, *Soils Found. Jap. Geotech. Soc.*, **41**(5), 33-45. https://doi.org/10.3208/sandf.41.5_33.

Moayed, R.Z., Haratian, M. and Izadi, E. (2011), “Improvement of volume change characteristics of saline clayey soils”, *J. Appl. Sci.*, **11**(1), 76-85. https://doi.org/10.3923/jas.2011.76.85.

Mohanty, S.K., Pradhan, P.K. and Mohanty, C.R. (2017). “Stabilization of expansive soil using industrial wastes”, *Geomech. Eng.*, **12**(1), 111-125. https://doi.org/10.12989/gae.2017.12.1.111.

Puppala, A.J., Madhyannapu, R.S., Nazarian, S., Yuan, D. and Hoyos, L. (2008), “Deep soil mixing technology for mitigation of pavement roughness”, Technical Report, No. FHWA/TX-08/0-5179-1.

Rahmat, M.N. and Ismail, N. (2018), “Effect of optimum compaction moisture content formulations on the strength and durability of sustainable stabilised materials”, *Appl. Clay Sci.*, **157**, 257-266. https://doi.org/10.1016/j.clay.2018.02.036.

Rajasekaran, G., Murali, K. and Srinivasaraghavan, R. (1997), “Fabric and mineralogical studies on lime treated marine clays”, *Ocean Eng.*, **24**(3), 227-234. https://doi.org/10.1016/S0029-8018(96)00010-8.

Rogers, C.D.F., Glendinning, S. and Roff, T.E.J. (1997), “Lime modification of clay soils for construction expediency”, *Proc.*

Inst. Civ. Eng. Geotech. Eng., **125**(4), 242-249. https://doi.org/10.1680/igeng.1997.29660.
Saberian, M., Moradi, M., Vali, R. and Li, J. (2018). “Stabilized marine and desert sands with deep mixing of cement and sodium bentonite”, *Geomech. Eng.*, **14**(6), 553-562. https://doi.org/10.12989/gae.2018.14.6.553.
Sarıavcı, C. (2016), “Stabilizing Meles Delta soils and monitoring the bonding structures using SEM and XRD analyses”, Master Thesis, Dokuz Eylül University Graduate School of Natural and Applied Sciences, İzmir, Turkey.
Schlue, B.F., Moerz, T. and Kreiter, S. (2010), “Influence of shear rate on undrained vane shear strength of organic harbor mud”, *J. Geotech. Geoenviron. Eng.*, **136**(10), 1437-1447. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000356.
Timoney, M.J., McCabe, B.A. and Bell, A.L. (2012), “Experiences of dry soil mixing in highly organic soils”, *Proceedings of the ICE - Ground Improvement*, February.
Wang, D., Abriak, N.E., Zentar, R. and Chen, W. (2013), “Effect of lime treatment on geotechnical properties of Dunkirk sediments in France”, *Road Mater. Pavement Des.*, **14**(3), 485-503. https://doi.org/10.1080/14680629.2012.755935.
Yunus, N.Z.M., Wanatowski, D., Hassan, N.A. and Marto, A. (2016), “Shear strength and compressibility behaviour of lime-treated organic clay”, *KSCE J. Civ. Eng.*, **20**(5), 1721-1727. https://doi.org/10.1007/s12205-015-0438-5.

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