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Individual and combined effect of Portland cement and chemical agents on unconfined compressive strength for high plasticity clayey soils

Yuksel Yilmaz[1a], Jongwan Eun[*2] and Aysegul Goren[1b]

[1]*Deptartment of Civil Engineering, Gazi University, 06570 Maltepe, Ankara, Turkey*
[2]*Deptartment of Civil Engineering, University of Nebraska-Lincoln, Lincoln, Nebraska, U.S.A.*

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Abstract. Unconfined compressive strength (UCS) of high plasticity clayey soil mixed with 5 and 10 % of Portland cement and four chemical agents such as sodium hexametaphosphate, aluminum sulfate, sodium carbonate, and sodium silicate with 0, 5, 10, and 20% concentrations was comparatively evaluated. The individual and combined effects of the cement and chemical agents on the UCS of the soil mixture were investigated. The strength of the soil-cement mixture generally increases with increasing the cement content. However, if the chemical agent is added to the mixture, the strength of the cement-chemical agent-soil mixture tends to vary depending on the type and the amount of the chemical agent. At low concentrations of 5% of aluminum sulfate and 5% and 10% of sodium carbonate, the average UCS of the cement-chemical agent-soil mixture slightly increased compared to pure clay due to increasing the flocculation of the clay in the mixture. However, at high concentrations (20%) of all chemical agents, the UCS significantly decreased compared to the pure clay and clay-cement mixtures. In the case of high cement content, the rate of UCS reduction is the highest among all cement-chemical agent-soil mixtures, which is more than three times higher in comparison to the soil-chemical agent mixtures without cement. Therefore, in the mixture with high cement (> 10%), the reduction of the USC is very sensitive when the chemical agent is added.

Keywords: clay; cement; chemical-based agent; unconfined compressive strength; soil-cement-chemical interaction

1. Introduction

Soil stabilization through mechanical and chemical processes are commonly used to enhance soil properties such as increasing the shear strength of the soil and decreasing the compressibility under consistent loading condition. Soil can be improved by combining mechanical and chemical methods. For instance, compaction with various additives (e.g., cement, lime, fly ash, synthetic polymers, chemical agents, etc.) is used for pavement stabilization, waterproof enhancement in dam or reservoirs, construction of lightweight foundations, and solid waste storage facilities (Falamaki *et al.* 2008, Goren 2013, Anagnostopoulos 2015, Canakci *et al.* 2015, Shooshpasha and Shirvani 2015, Rica *et al.* 2016, Suganya *et al.* 2016, Vakili *et al.* 2016, Güllü and Fedakar 2017). In particular, cement and chemical-based agents as additives are beneficial for reducing the swelling potential of expansive soils, decreasing the plasticity index of highly plastic clays, and increasing the bearing capacity of soils (Bergado 1996, Falamaki *et al.* 2008, Goren 2013, Yilmaz and Ozaydin 2013, Arasan and Nasirpur 2015, Rica *et al.* 2016).

Portland cement is widely used in soil improvement because it has the advantage of obtaining the high strength easily, and it is cheaper than other chemical agents. The soil-cement becomes a hard and durable structural material as the cement hydrates and develops the strength. It is known that cement can interact with the silt and clay fractions and reduce their affinity for water. This increases the strength. However, it takes a relatively long time to apply the cement until the soil settles down and shows satisfactory strength (El-Rawi and Al-Samadi 1995, Balasingam and Farid 2008, Sen and Dixit 2011, Horpibulsuk *et al.* 2012, Saride *et al.* 2013, Anagnostopoulos 2015). To reduce the curing time and fully generate the satisfied strength of the mixture, the compaction characteristics associated with a cement content of the mixture have been investigated. Although the compaction characteristic of cement-soil mixture is different from that of pure clay, it is a common practice to use optimum moisture content and maximum dry unit weight of the pure soil for cement-soil mixtures, with up to 10% cement content. (El-Rawi and Al-Samadi 1995, Balasingam and Farid 2008, Le Runigo *et al.* 2009, Sen and Dixit 2011). However, for cement contents higher than 10%, it is necessary to properly use the specific compaction characteristics of the mixture for desired soil improvement.

Chemical based agents have been known to help formulate a binder-additive combination with cement (Moayedi *et al.* 2011, Abood *et al.* 2007, Huan and Chang 2008, Suganya and Sivapullaiah 2013, Anagnostopoulos 2015, Canakci *et al.* 2015, Kalıpcılar *et al.* 2016, Vakili *et al.* 2016) to control the curing time and the strength of the

∗Corresponding author, Ph.D.
E-mail: jeun2@unl.edu
[a]Professor
E-mail: yyuksel@gazi.edu.tr
[b]M.Sc.
E-mail: a.goren85@gmail.com

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mixture during hydration. Although mixing of the soil with the chemical agents is commonly used for soil stabilizing practice, it induces unexpected changes in the chemical properties and results in a loss of soil strength. Several previous researches have figured out that soluble minerals in the clay such as phosphates, nitrates, and chloride might cause some disadvantage to the engineering properties such as swelling and losing strength (Wang 2002, Wang *et al.* 2003, Saussaye *et al.* 2011, 2013, 2014, Le Borgne *et al.* 2009).

In the past decades, there have been many studies based on the usage of cement and chemical agents on the stabilization of clayey soils. Based on the literature, the strength of a soil mixed with cement generally increases, while the strength of a soil mixed with chemical agents varies depending on the agents and clay minerals (Wang 2002, Wang *et al.* 2003, Le Borgne *et al.* 2009, Saussaye *et al.* 2013, 2014, 2015, Rica *et al.* 2016, Suganya *et al.* 2016, Vakili *et al.* 2016). However, there are only a few existing researches for the combined effect of a soil mixed with chemical agents and cement on the soil stabilization (Vakili *et al.* 2016, Güllü and Fedakar 2017). In regards to the geotechnical properties, the combined effects of chemical agents and cement in the mixture on the geotechnical properties is still not understood.

Hence, the objective of this study is to investigate the individual and combined effects of a clayey soil mixed with different chemical agents and cement on the behavior of the soil mixture. To evaluate the variation of the strength of the soil mixture quantitatively, unconfined compressive strength (UCS) of high plasticity clayey soil with respect to ordinary Portland cement and four representative chemical agents such as sodium hexametaphosphate, aluminum sulfate, sodium carbonate, and sodium silicate in different concentration with 0, 5, 10, and 20% were systematically assessed. Further, chemical formulas were analyzed to account for and support the experimental results. Based on the results, the effectiveness of the soil mixture combined with cement and chemical agents were confirmed.

2. Stabilization of clayey soil with cement and chemical agent

Numerous studies have been conducted to evaluate the strength of soil-cement mixtures used for soil stabilization. Typically, as the cement content increases in the mixture, the strength of the mixture increases due to cement hydration in the mixture (El-Rawi and Al-Samadi 1995, Balasingam and Farid 2008, Sen and Dixit 2011). Nontananandh *et al.* (2005) studied how the curing time of cement in the soil-cement mixture influences the strength of the mixture. The unconfined compressive strength (UCS) of clay-cement mixtures after 3, 7, 14, 28, and 90-days curing period were evaluated. The UCS quickly increased in the first two weeks and the rate of the increase decreased slowly for a longer time (1 to 3 months). Saadeldin *et al.* (2011) also reported similar results that the UCS quickly increased up to 28 days and did not change significantly after a month.

Many applications of a chemical agent for soil stabilization have been studied. El-Rawi and Al-Samadi (1995) investigated the effects of two chemical agents such as sodium hydroxide (NaOH) and sodium carbonate (Na_2CO_3) on the UCS of three different soils. Normality was used for the study to quantify the effect, which is a measure of concentration equal to the gram equivalent weight per liter of solution. The normality for the concentrations of chemical agents was varied from 0.25 to 2.0. The test results indicated that the use of NaOH or Na_2CO_3 solutions at a 0.5 normality was found to be beneficial to improve the UCS of silty clay and clayey silt soils. The effect of chemicals on the strength of marly clay was not significant. Additionally, Rica *et al.* (2016) found that sulfate, chloride, and phosphate salts in the mixture induce significant swelling and some loss of strength.

Abood *et al.* (2007) examined the effect of adding different chloride compounds including sodium chloride (NaCl), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$) on the engineering properties of a clayey soil. They prepared highly plastic clay, which is CH per the Unified Soil Classification System, mixed with 2, 4, and 8% dissolved solution of chloride compounds. The UCS of the mixture increased with the addition of $CaCl_2$ yielded approximately 720 kPa. As the amount of the chloride compounds increased, the maximum dry density increased while the optimum moisture content decreased.

Falamaki *et al.* (2008) experimentally investigated the effect of using hexametaphosphate on the strength of clayey soils. The ratios of the hexametaphosphate to the soil were chosen as 1, 2, and 3% by weight. The strength of the soil-hexametaphosphate mixture was measured by unconfined compression test after 3, 7, 28, and 56-days curing period. The variation of UCS of the clayey soil associated with time and different hexametaphosphate contents were analyzed. For pure clay without hexametaphosphate, the UCS increased from 60 kPa to 80 kPa at the end of 4 weeks. However, the UCSs of all soil-hexametaphosphate mixtures were lower than that of the pure soil.

Maaitah (2012) investigated clay stabilization used for sub-base with lime and sodium silicate. The shear strength of the clay mixture was the highest when 5% of lime and 2% of sodium silicate were properly mixed. The reaction time was a significant parameter where the strength improved with time. Moayedi *et al.* (2011) also evaluated the change in the engineering properties of a soft clayey soil, of which the dominant mineral was kaolinite when treated with sodium silicate. The samples used in the experiments were prepared by mixing soft soil with a solution of sodium silicate at three different molarities of 1, 3, and 5 mol/L. The unconfined compression tests were conducted at 1, 7, and 14-day curing periods. The maximum UCS was approximately 160 kPa obtained for 1-day cured specimens, which were treated with 5 mol/L sodium silicate. The reported UCS value for the treated soil was nearly three-fold of pure clay.

Mardani *et al.* (2016) evaluated the effect of sulfate on cement stabilized swelling soils. When the sulfate is mixed with the soil, the UCS of montmorillonite is decreased. The results showed that sulfate resistance cement instead of normal Portland cement is more plausible for soils under the threat of sulfate attack. Recently, Güllü and Fedakar

(2017) proposed the prediction of UCS mixed with soils and additives based on artificial intelligence techniques. Even though, that current effort, the combined effect of a clayey soil mixed with different chemical agents and cement on the behavior of the soil mixture is still unknown.

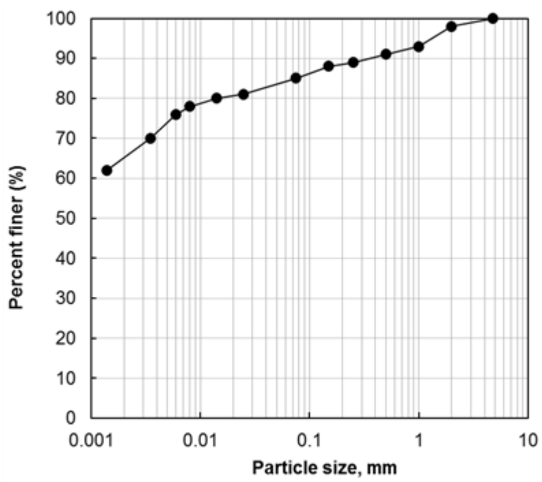

Fig. 1 Particle size distribution curve of the clayey soil used in the study

Table 1 Basic properties of clay

Basic characteristics and descriptions	Values
Specific gravity	2.62±0.03
Passing No. 200 sieve (<0.075 mm) (%)	86.5±1.6
Liquid limit (%)	74
Plastic limit (%)	29
Plasticity index (%)	45
USCS soil class	CH
pH	8.07
Organic material (%)	1.45
Solubility in acid (%)	26.74

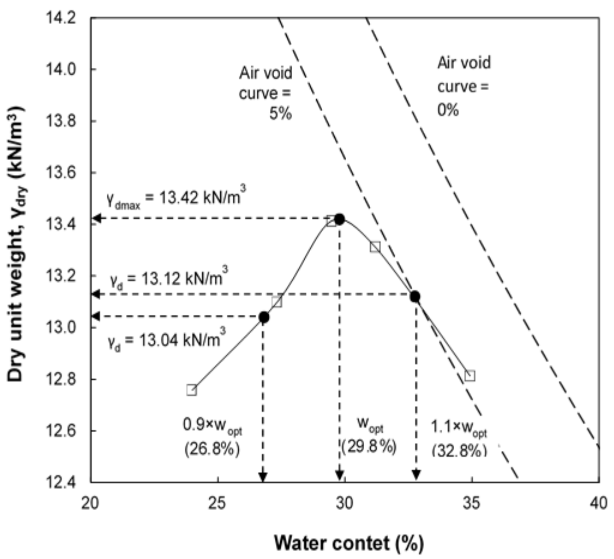

Fig. 2 Standard Proctor compaction curve of the clay used in the study

Table 2 Chemical compositions as well as physical and mechanical properties of the cement used in the study (Yilmaz and Ozaydin 2013)

Basic characteristics and descriptions	Values
SiO_2 (%)	18.5
Al_2O_3 (%)	5.41
Fe_2O_3 (%)	6.23
CaO (%)	59.47
MgO (%)	1.65
Cl^- (%)	0.012
SO_3 (%)	2.71
Loss of ignition (%)	1.91
Unsolubletrace (%)	0.99
Total Alkalinity (%)	1.04
Amount of clinker (%)	95.8
R (Gypsum) (%)	1.18
Specific gravity	3.15
Blaine (cm^2/g)	3696
Retaining on 45 μm sieve (%)	20.22
Retaining on 90 μm sieve (%)	1.3
7 day strength (N/mm^2)	37.9
28 day strength (N/mm^2)	50.2

3. Materials and method

3.1 Soil

The soil that was tested was obtained from an excavation pit opened for a new building in Gazi University Central Campus. The particle size distribution curve, consistency limits and specific gravity of the clayey soil used in the study were determined in accordance with ASTM D 422, ASTM D 4318, and ASTM D 854, respectively. The particle size distribution curves of the clay are shown in Fig. 1. The soil is the high plasticity clay (CH) classified by Unified Soil Classification System (USCS) (ASTM D 2487). Table 1 describes the basic properties of the clay.

Standard Proctor test on the soil (ASTM D 698) was carried out to obtain the maximum dry unit weight and optimum water content of the clay. The maximum dry unit weight and optimum water content were 13.42 kN/m^3 and 29.81%, respectively. To demonstrate the effect of air void on the compaction, the air content curves at air void = 0% and air void = 5% (G_s = 2.62) are also plotted in the figure. Air content is defined as the ratio of the volume of air to the volume of soil. Furthermore, water contents at $1.10\times w_{opt}$ and $0.90\times w_{opt}$, and corresponding dry unit weights, were also shown in Fig. 2.

3.2 Cement

CEM I 42.5 R type ordinary Portland cement (OPC) was used in this study. The chemical compositions, physical, and mechanical properties of the cement are charted in Table 2

(Yilmaz and Ozaydin 2013).

3.3 Chemical agents

Four chemical-based agents were used in the study: sodium hexametaphosphate [$(NaPO_3)_6$], aluminum sulfate [$Al_2(SO\ )_3$], sodium carbonate (Na_2CO_3), and sodium silicate (Na_2SiO_3). Those chemical agents were selected because the agents are widely used for soil enhancement related to geotechnical and geoenvironmental applications.

$(NaPO_3)_6$ is a white granule chemical material which is a water-insoluble resistant. It is used to disperse the silt and clay-size fraction of the soil. $Al_2(SO_4)_3$ is highly soluble in water. It is mainly used as a flocculating agent in the purification of drinking water. It is also used for dispersive soil treatment. Na_2CO_3 commonly occurs as a crystalline heptahydrate, which readily effloresces the monohydrate to form a white powder. Pure Na_2CO_3 is a white, odorless powder that is hygroscopic (absorbs moisture from the air). It is effective when used as a chemical agent in cement or lime stabilization. Na_2SiO_3 is available in aqueous solution and in solid form. The pure compositions are colorless or white and it shows high solubility in water. It is also capable of producing an alkaline solution. Na_2SiO_3 is often used to supply moisture for dust control at the low standard of road construction.

3.4 Unconfined compression test

Unconfined compression tests are commonly used to evaluate the shear strengths of soils from a site quickly and cost-effectively, and to compare the strength characteristics of cement-soil mixtures. The specimen of the mixture can be maintained without confinement during the test because the mixture has much higher strength than pure soil (Yilmaz and Ozaydin 2013). The samples were prepared at standard Proctor compaction effort followed by previous researches (Saride *et al.* 2013, Anagnostopoulos 2015, Vakili *et al.* 2016, Güllü and Fedakar 2017). This experimental study aims to quantitatively investigate how the combination of cement and chemical agents mixed in soil influences the strength characteristics of the mixture. For this purpose, a series of unconfined compression tests were carried out on the soil specimens treated with different amounts of cement and chemical agents. The mixtures were categorized as cement-soil, chemical agent-soil, and cement-chemical agent-soil and tested in triplicate in all cases. For control test, only clayey soil compacted without cement and the chemical agent was also tested. Depending on the variation of cement, chemical type, and concentration, a total of 87 sets (3 identical samples in each set), unconfined compressive tests were conducted. The systematic program of the test is described in Table 3. The soil specimen was prepared as 50 mm in diameter and 100.5 mm in height in the mold of unconfined compression test. Most samples were compacted with the optimum water content and maximum dry unit weight of soil obtained from standard Proctor tests.

For cement, 0, 5, and 10% of cement in terms of total dry weight of the mixture were added for the preparation of the specimen. The cement was added to the soil and mixed thoroughly. The cement contents (%) is defined as the ratio of the weight of Portland Cement over weight of a dry soil. The specimen was allowed to cure for 28 days in an airtight moisture-proof desiccator maintained at a relative humidity higher than 95% (ASTM D 5102).

Table 3 The number of set for cement-chemical agent-soil mixture conducted in the study

Chemical agent	Amount (%)	Cement		
		0	5	10
$(NaPO_3)_6$	0	5*	5	5
	5	2**	2	2
	10	2	2	2
	20	2	2	2
$Al_2(SO_4)_3$	5	2	2	2
	10	2	2	2
	20	2	2	2
Na_2CO_3	5	2	2	2
	10	2	2	2
	20	2	2	2
Na_2SiO_3	5	2	2	2
	10	2	2	2
	20	2	2	2

*At $0.9\times w_{opt}$, $0.95\times w_{opt}$, $1.0\times w_{opt}$, $1.05\times w_{opt}$ and $1.0\times w_{opt}$

**At $0.9\times w_{opt}$ and $1.0\times w_{opt}$

Chemical agents were not directly added to soil or cement-soil mixtures but diluted solutions of chemicals were used as the mixture liquid. This is because the agent should be mixed homogeneously in the specimen. The solution was counted as the water to prepare the optimum water content of each specimen. Four different concentrations of the chemical agents were prepared in 0, 5, 10, and 20% of the chemicals over water by weight percentage. To prepare the specimen of the cement-chemical and agent-clay mixtures, clay was mixed with cement first and then, chemical solutions were added to the mixture as mixing liquid. The chemical agents (%) is defined as the ratio of the weight of a chemical agent over weight of the solution in a soil.

The water content and dry unit weight of a soil specimen can significantly influence the strength of compacted soils (Moayedi *et al.* 2011, Abood *et al.* 2007). It is a common practice to select a specified interval on the water content, which is near the optimum water content of ±10% and corresponding dry unit weights. Generally, it is very hard to apply the same optimum water content and maximum dry unit weight values obtained from a standard Proctor test in the field due to the nature of the compression process and material heterogeneity. Therefore, to observe the effect of water content on the strength, additional unconfined compression tests were carried out for the compacted samples only for clayey soils, as well as for mixtures with 10% on the wet side of the optimum water content (= $1.10\times w_{opt}$) and 10% on the dry side of optimum water content (= $0.90\times w_{opt}$). Therefore, in this study, the specimens were prepared per the compaction curve as shown in Fig. 2 as compacted at five water contents, which were at 1.10, 1.05, 1.0, 0.95, and 0.90 of the w_{opt}.

Unconfined compression tests were performed using strain-controlled procedure (ASTM D 2166). The strain rate was kept constant at 0.5 mm/min for all tests.

4. Unconfined compressive strength of clay mixed with cement or chemical agent

4.1 Effect of initial water content on UCS of clay

Unconfined compressive strengths (UCSs) of the clay specimens with different relative water contents are plotted in Fig. 3. This specimen does not contain any cement or chemical agents. The relative water content is the ratio of initial water content ($w_{initial}$) to optimum water content (w_{opt}). The average of the USCs from triplicate tests was also described in the figure as white square symbols. The dotted line shows the trend line of the average USCs. The specimens were prepared according to the compaction curve as compacted at five water contents, of 1.10, 1.05, 1.0, 0.95, and 0.90 of the w_{opt}.

The UCSs at the w_{opt} show higher strength compared to those at the dry and wet sides of the water contents, which is similar to the trend of the dry unit weight as shown in Fig. 2. The flocculated particles of clay at the w_{opt} have higher strength than dispersed particles. The average UCS at the optimum water content is higher by 16.7% to 83.3% compared to those at the 0.9 and 1.1 of w_{opt}, respectively. The UCS compacted at the 1.1 of w_{opt} in the wet side shows 118.5 kPa, which is the lowest UCS among tested specimens.

4.2 UCS of cement-clay mixtures

The UCSs of soil specimen mixed with 0, 5, and 10% of cement by weight at different water contents are plotted in Fig. 4. The water contents were measured from the specimen after the unconfined compression test. The UCS significantly increased with increasing the amount of cement in the specimen. However, the UCS decreased with increasing the water content. The reduced rate of the UCS with the water contents varies depending on the cement content. With higher cement contents, the reduction of the UCS is less sensitive, which was presented by the slope of the power function. This means that the reduced rate decreased with increasing the cement contents.

As more cement was mixed with the soil, the variation of the UCS became more significant compared to only soil. The UCS values of 10% cement-soil mixture were ranged from 796 kPa to 2140 kPa, while those of only soil were in the range of 487.8 kPa and 918 kPa.

The change of the water content before and after the test was less for soil-cement mixture than the soil-only specimen. For the soil specimen without cement prepared at the optimum moisture content and 29.8% compaction, the water content at the end of the test was measured in the range of 22.5% and 29.7%. However, for 10% cement-soil mixtures, the end water content obtained was between

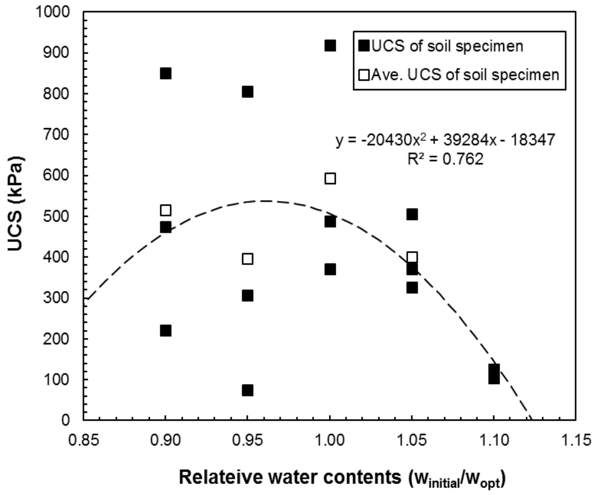

Fig. 3 Variation of UCS for soil alone specimens with relative water content at the initial condition of unconfined compressive tests

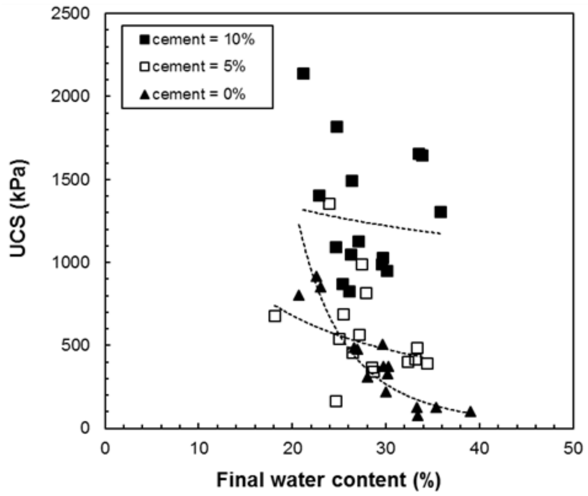

Fig. 4 Variation of UCS for soil-cement mixtures containing 0, 5, and 10% cement by weight with final water contents after unconfined compression tests

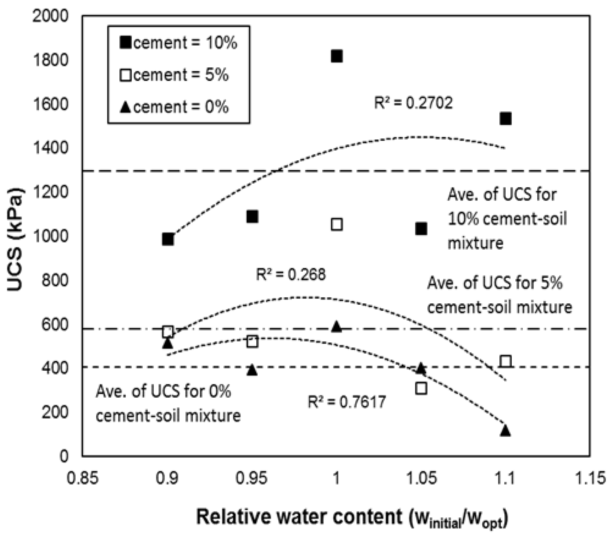

Fig. 5 Variation of average UCS for soil-cement mixtures containing 0, 5, and 10% cement by weight with relative water contents after unconfined compression tests

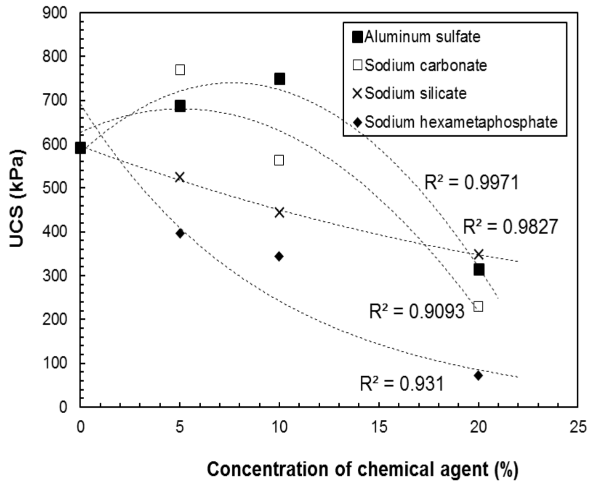

Fig. 6 Variation of average UCS for soil-chemical agent mixtures containing 0, 5, 10, and 20% concentration of the agents by weight

21.2% and 26.3%. The hydration heat of the cement and curing period of 28 days might result in the wide range of the UCS and less fluctuation of the water content.

Fig. 5 clearly demonstrates the effect of water content with different amounts of cement on the variation of the USC. In Fig. 5, the relationship between the average of UCSs for different amounts of the cement and the relative water content (which is initial water content over the optimum water content) is plotted. With increasing the amount of cement in the specimen, the UCS increases remarkably. The average of UCSs for 0, 5, and 10% of the specimens were 404.7, 578.9, and 1294.3 kPa, respectively. The UCS is the largest around the optimum water content. The excessive water content reduces the strength of the cement-clay mixture. This might be because excessive water might change the arrangement of clay to be dispersive. The UCSs of the soil-cement mixture is varied more significantly than those of the pure soil, which is consistent with the result described in Fig. 4. For instance, the R^2 value of the UCSs for the soil-cement mixture is much smaller than that for pure soil.

On the other hand, the UCS increased remarkably at the low concentration ranged from 0 to 10% for aluminum sulfate and ranged from 0 to 5% for sodium carbonate as shown in Fig. 6. However, at the high solution concentrations of the agents (> 10%), the UCS for these two agents significantly decreased like other agents. It was found that the UCSs of soils mixed with each chemical agent at higher concentration were lower than the average UCS of pure clay. The increase of the USC at the lower contents resulted from the formation of iron and aluminum with the agents to produce cementations materials such as strengite and sulfate precipitation and the particles become flocculated (Ouhadi and Goodarzi 2006, Rica *et al.* 2016). Similar to previous cases, the reduction of UCSs occurred because the chemical interaction between the chemical solution and clay particles induced the precipitation of the metal cations and dispersion of the fine contents after exceeding the threshold of the agents' concentration (Falamaki *et al.* 2008).

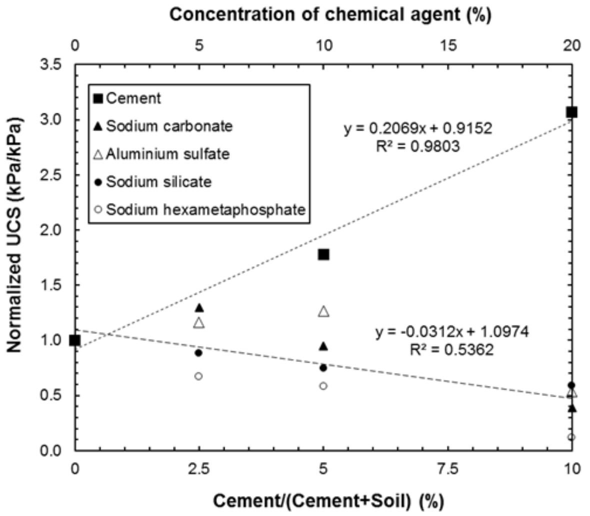

Fig. 7 Normalized UCSs of soil-cement mixtures by adding the different amount of cement by weight in the specimen, and of soil-chemical agent mixtures as adding the different concentration of the agents in the specimen

4.3 Normalized UCS with cement and chemical agents

The variation of the average UCS with respect to cement contents and concentrations of chemical agent in the specimen was plotted in Fig. 7. According to the trend of increasing UCS with increasing cement contents as shown in Fig. 5, there is a strong-positive linear correlation with $R^2 = 0.98$ between the average UCS and cement content of the mixture. With a 1% increase of the cement content in the mixture, the strength increased by 20.6%. The UCS of the specimens compacted at the optimum water content and at the dry side of the optimum water content varies within a wide range. However, the strengths of the specimens obtained were very close to each other on the wet side of the optimum water content. The reason is that more water added to the wet specimen might help the soil mix homogenously.

On the other hand, there is a negative linear correlation with $R^2 = 0.54$ between the average UCS and chemical agents of the mixture. With a 1% increase in the concentration of the chemical agent in the mixture, the strength decreased by 3.1%. The average UCS for most specimens with the chemical agents typically decreased with increasing amounts of chemical agents. However, the UCSs of the soil mixture with aluminum sulfate and sodium carbonate at the low concentration slightly increased.

5. Combined effect of cement-chemical agent on strength of clay mixture

5.1 UCS of clay mixtures combined with cement-chemical agent

Fig. 8 shows the UCS behavior of the cement-chemical agent-clay mixtures. The four chemical agents such as sodium hexametaphosphate, aluminum sulfate, sodium carbonate, and sodium silicate were added to the mixture as a solution. Similar to the results of the unconfined compression test for the chemical agent-clay mixture without cement (Fig. 6), the UCS of the cement-chemical agent-clay mixtures increased with increasing cement content. On the contrary, the UCS mostly decreased as the concentration of the chemical agents increased.

For the mixtures containing 10% of the cement and 20% of the chemical agent, as a black square shown in Fig. 8, the UCSs were 25, 7, 10, and 2 times smaller compared to the average UCS of pure clay (= 592.7 kPa) for sodium hexametaphosphate, aluminum sulfate, sodium carbonate, and sodium silicate, respectively. Similarly, for the mixtures containing 5% of cement and 20% of the chemical agents, the UCSs were 20, 2, 5, and 1.5 times compared to the average UCS of pure clay, for sodium hexametaphosphate, aluminum sulfate, sodium carbonate, and sodium silicate, respectively.

As the concentration of the chemical agent increased from 0% to 20% in the mixture, the UCS markedly decreased. The reduction of UCS with increasing the concentration of the chemical agent was matched well with the exponential function, for the mixture of soil and sodium hexametaphosphate, aluminum sulfate, and sodium carbonate with high cement content (> 5%) (R2 > 0.90). However, for aluminum sulfate and sodium carbonate, the UCS of the soil without cement content increased slightly with increasing the agents at the low concentration (< 10%). With high cement contents in the cement-chemical agent-clay mixtures, the UCS decreased dramatically. The reducing UCS of the mixture containing sodium hexametaphosphate, aluminum sulfate, and sodium carbonate stabilized when the concentration of the agents was higher than 20%. Regardless of the cement content, the UCSs containing over 20% of those agents were similar except for sodium silicate.

Accordingly, the UCS of the mixture with the chemical agents is highly influenced by the cement content. It was also found that the effect of cement content on the UCS is much greater at low concentrations of the agent. However, at higher concentration of the chemical agents, the effect of cement on the UCS becomes smaller.

5.2 Chemical reaction in clay mixtures combined with cement-chemical agent

The reduction of UCS for the clay mixture containing the chemical agents and cement can be explained by the chemical reaction of the mineral compounds consisting of the mixture. For instance, sodium hexametaphosphate [$(NaPO_3)_6$] solution in the mixture typically generates sodium phosphate cements which have the lower compressive strength (see Fig. 8(a)) than cement hydrated by water or sodium phosphate dibasic (Na_2HPO_4) solutions. This is because sodium hexametaphosphate inhibited the growth of apatite crystals during soaking of the cement in the solution (Levy *et al.* 1999, Falamaki *et al.* 2008, Hesaraki *et al.* 2009).

$$(NaPO_3)_6 + CaCO_3 + 6H_2O \rightarrow Ca10(PO_4)_6(OH,F,Cl)_2 \quad (1)$$

However, Ghazali *et al.* (1991) reported that phosphoric acid generated from phosphate increases cohesion and internal angle of friction of kaolinite clay. Therefore, the strength might be varied depending on the chemical characteristics influenced by the presence of a multitude of metal cations, organic, and inorganic anions in the mixture.

For aluminum sulfate [$Al_2(SO_4)_3$], the UCS increased slightly at lower concentrations of the agent from 0 to 10% without cement (see Fig. 8(b)). This might be because the soil structure changes from a dispersive structure to a more flocculated non-dispersive structure by adding aluminum cations. The effects of aluminum sulfate on the dispersivity of clay soils could be due to a pH effect:

$$\begin{aligned} &Al_2(SO_4)_3 + \mathrm{Clay} \rightarrow Al[\mathrm{clay}] + 3(H_2SO_4)\!: \mathrm{reduction\ in\ pH} \\ &Al^{3+} + OH^- \rightarrow Al(OH)^{++}\!: \mathrm{reduction\ in\ pH} \\ &Al(OH)^{++} + OH^- \rightarrow Al(OH)_2{}^{+}\!: \mathrm{reduction\ in\ pH} \end{aligned} \quad (2)$$

Additionally, some of the aluminum hydroxyl ions are adsorbed and act as exchangeable cations (Brady 1974). Such a reduction in pH is an appropriate condition for enhancing the interaction of clay particles and electrolytes, and causing a decrease in soil dispersivity (Chorom *et al.* 1994, Ouhadi and Goodarzi 2006). Sodium cations may be replaced by aluminum ions that have higher valences, causing a decrease in the thickness of the double layer, which leads to a decrease in the repulsive forces of clay particles, and reduced dispersivity potential of soils (Ouhadi and Goodarzi 2006). Ouhadi and Goodarzi (2006) found that with the addition of 1.5% aluminum, the dispersivity ratio decreases below 40 %, which increases the strength of the mixture.

Sodium carbonate (Na_2CO_3) is an effective accelerator of hydration and settling in the cement paste. During the hydration, $Na_2SiO_3 \cdot nH_2O$ (where n = 5, 6, 8, 9) generates from the reaction of Na_2CO_3 with $SiO_2(OH)^{22-}$ in the mixture, which is a discrete, approximately tetrahedral anion (Huan and Chang 2008, Ivanov and Chu 2008). The aqueous Na_2CO_3 enhances the self-settling of tricalcium silicate cement (Ca_3SiO_5) and generates Ca_2SiO_5-$NaCO_3$. At the low contents of Na_2CO_3 less than 10%, the strength of the mixture increases due to increasing Ca_2SiO_5-$NaCO_3$ paste in the mixture (see Fig. 8(c)).

Sodium silicate (Na_2SiO_3) treated with cement generates calcium silicate hydrate (CSH) in the cement admixed soil samples. The addition of sodium silicate is expected to have some influence on the soil microstructure and on the settling process of the cement itself. According to Sugaya and Sivapullaiah (2016), the clayey soil with cement as a primary binder has identified CSH as a predominant compound, resulting in cement hydration. The main reactions responsible for its formation are as follows:

$$\begin{aligned} &2(3CaO\ SiO_2) + 6H_2O \\ &\qquad \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2 \\ &2(2CaO\ SiO_2) + 4H_2O \\ &\qquad \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2 \end{aligned} \quad (3)$$

However, the equations also show that OH^- and Ca^{2+} ions are released into the pore solution. In contrast to aluminum cations, such an increase in pH is a proper condition for diminishing the interaction of clay particles and electrolyte, causing an increase in soil dispersivity. The sodium silicate added would dissociate and supply silicate ions, which are expected to be adsorbed on the clay

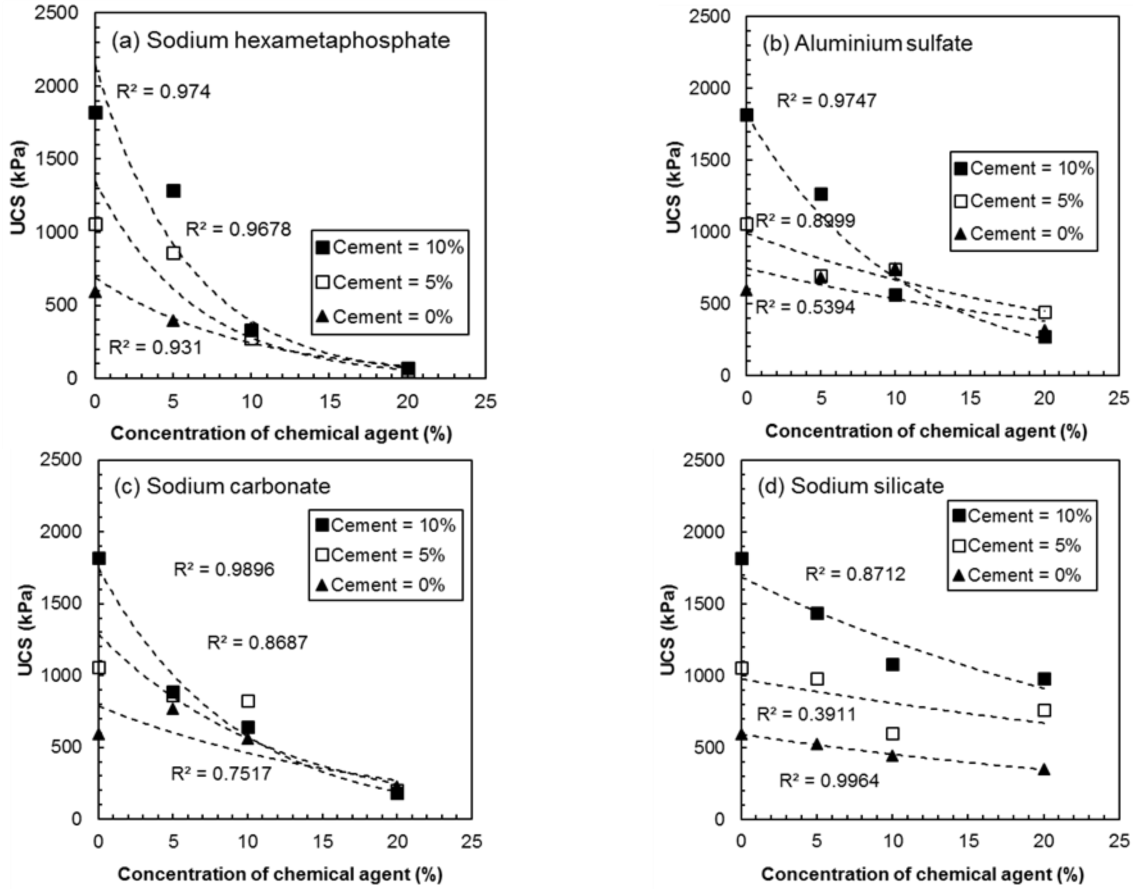

Fig. 8 Average UCS of soil-cement mixtures containing 0, 5, 10, and 20% concentration of the chemical agents by weight: (a) Sodium hexametaphosphate, (b) Aluminum sulfate, (c) Sodium carbonate and (d) Sodium silicate

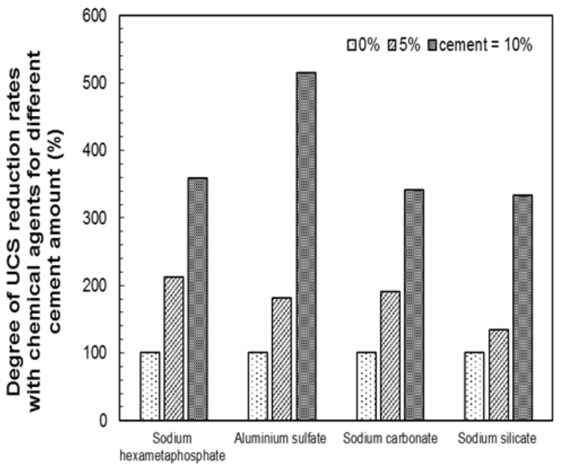

Fig. 9 The degree of UCS reduction rates of soil mixture when chemical agents increase from 0 to 20% of the solution at 0, 5, and 10% of cement

minerals (Brykov *et al.* 2002). The reaction between the monomeric silicate anions from sodium silicate, the lime (liberated during cement hydration), can be given by

$$\mathrm{Ca(OH)_2 + 2NaH_3SiO_4 \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2} \quad (4)$$

While studying the effect of hydrated sodium silicates on cement paste hardening, an increase of the OH^- and the cations results in a reduction of the flocculated potential of soils and decreased strength. Hence, the UCS of the mixture containing sufficient Na_2SiO_3 is more diverse than the mixture containing other chemical agents (see Fig. 8(d)).

5.3 Comparison of UCS reduction with varied amount of cement-chemical agent

Fig. 9 shows the degree of UCS reduction rates of the soil-cement-chemical agents mixtures when the chemical agents increase from 0 to 20% at 0, 5, and 10% of cement. The degree of the UCS reduction rate was obtained by the linear fit of the average UCSs of the soil-cement mixture with different amounts of the solution of the chemical agents. The fitted line for each agent was also classified with different amounts of cement for 0, 10 and 20%. In Fig. 9, the value of the slope was presented as a percentage of average UCS reduction rate over the reduction rate of UCS for the soil mixture without cement. With increasing the cement content from 0 to 10% in the mixture, the degree of the UCS reduction remarkably increased. For example, the reduction rates of the UCS for the soil mixtures with sodium hexametaphosphate and 10% of the cement presents approximately 350% in comparison to that for the soil mixtures without cement. Further, for 10% of cement, the UCS reduction is the highest for all soil mixtures containing chemical agent-cement, which is more than three times higher compared to that for the soil mixtures without cement.

Therefore, the combined effect of cement-chemical is significant on the UCS of the mixture in that the reduction of the UCS is much higher when the soil is mixed with the high amount of cement and the lower concentration of the chemical agent together. The soil mineral mixed with the chemical agents and cement generated various chemical reaction as described in the previous section, which led to the change of soil microstructure and the precipitation from the reaction. This procedure might reduce the interlocking frictional resistance among clay-cement particles physically and cause the variation of the mechanical properties of cement-chemical agent-soil mixtures to occur.

6. Conclusions

In this study, the unconfined compressive strength (UCS) of highly plastic clayey soil mixed with various amounts of cement and four chemical agents (i.e., sodium hegzametafosfat, aluminum sulfate, sodium carbonate and sodium silicate) were evaluated to investigate the combined effect of the chemical agents and cement on soil stabilization. The UCS significantly increased with increasing amount of cement in the specimen. However, the UCS mostly decreased with increasing chemical agents. There is a strong-positive linear correlation (R^2 = 0.98) between the average UCS and cement content of the mixture, while a negative linear correlation occurred between the average UCS and chemical agents of the mixture. With 1% increase of the cement content in the mixture, the strength increased by 20.6%.

For the soil-cement mixtures containing the chemical agents, the strength of the cement-chemical agent-soil mixture tends to vary depending on the type and the amount of the chemical agent. For example, at low concentrations of aluminum sulfate (5%) and sodium carbonate (5% and 10%), the average UCS slightly increased compared to that of pure clay. At high concentrations (20%) of all chemical agents, the UCS decreased considerably. Regardless of the cement content, the UCS of soil-cement mixtures containing over 20% of those agents is similar except for sodium silicate. Hence, the UCS of the mixture with the chemical agents is highly influenced by the cement content. It was also found that the effect of cement content on the UCS is much greater at low agent concentrations.

With an increase in cement content from 0 to 10% in the mixture, the degree of the UCS reduction remarkably increased. In the case of high cement content, the rate of UCS reduction is the highest among all cement-chemical agent-soil mixtures, which is more than three times higher in comparison to the soil-chemical agent mixtures without cement. Therefore, in the mixture with high cement (> 10%), the reduction of the USC becomes sensitive when the chemical agent is added. The results of the study can be applied to the effective improvement of the soil-cement-chemical mixture used in soil stabilization.

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