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Evaluating the Effect of Environment Acidity on Stabilized Expansive Clay

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Abstract: In this article, the effects of environmental acidity on the mechanical and volumetric properties of cement-stabilized clay soils have been investigated through various tests on experimental scale. In this study, a problematic clay was chemically stabilized by cement under three treatment conditions including short term, medium term, and long term with different conditions varying from acid to alkaline environments, which were tested by different methods to evaluate their mechanical and volumetric behavior and properties. Mechanical characteristics assessment tests in this study include compaction tests, and unconfined compressive strength, which was conducted on samples under different conditions in terms of acidity and treatment time. The results of the study indicated that soil improvement by cement increases the mechanical strength and decreases the rate of soil swelling over time and treatment duration. However, the degree of acidity of the environment affects the chemical reactions of soil and cement, especially cement hydration, which causes changes in soil strength and volume variation due to swelling.

Keywords: Environment acidity; engineering properties; volumetric changes; clay; chemical stabilization.

1 Introduction

Soil as of the ground's surface coatings is the first and the most important part of any engineering project execution that engineers are faced with. Some of these soils cause problems in engineering projects, which are known as problematic soils. Most problematic soils are composed of clay minerals except for soils susceptible to liquefaction. These minerals have a very high capacity for water absorption and storage, which can create a lot of problems for existing structures on the ground. Among these problems are the changes in soil behavioral characteristics, that is, changes in volumetric, mechanical, and strength properties after water absorption, which can cause a lot of damage. So how to identify and deal with these types of soils is the subject of many studies and research in geotechnical engineering. The existence or creation of a resilient bed for the structure is one of the basics of construction in every civil project. Soil as the site of the structure distributes and transmits the loads efficiently, and if the strength and stability of the soil are insufficient, cracking and rupture will be inevitable due to the asymmetrical settlements of the structure. Clay soils are more exposed to this problem, therefore one of the solutions to this problem is the improvement of poor soils. Improving soils has numerous objectives including strength increase, settlement reduction, and increasing durability. Various studies have investigated different additives such as cement, lime, bitumen, fly ash, and so on, which have been used to improve soil behavioral properties (Lin et al., 2007; Munfakh, 1997; Hausmann, 1990; Chu and Rujikiatkamjorn, 2005; Lo and Wardani, 2002).

Fine-grained clay soils, which inherently have very low strength and high compatibility, are extensively found in coastal regions where major cities around the world are located at. Therefore, geotechnical engineers have always been looking for ways to improve and enhance the engineering properties of these soils with efficient methods at the surface or in depth. One of the common techniques of soil improvement is chemical stabilization using cement or lime. It should be noted that cement is more used than lime in Asia since it is more effective in practice (Alipoor R., 2010).

Generally, any soil free of chemicals such as sulfates and organic materials may be stabilized with cement (Neto et al., 2020). Portland cement type I or type II is used in most construction activities. In cases where the

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soil contains up to 10% sulfate or the consumed water contains more than 150 parts per million sulfate, type II cement shall be used (Dupas and Pecker, 1979). Based on a previous study, the cement used to efficiently stabilize clay soils that are low plastic clay based on a unified soil classification system should be between 5% and 12% of the soil weight (Mitchell and Freitag, 1961).

The degree of acidity or pH, which indicates the concentration of hydrogen ions is a logarithmic quantity that determines the acidity or alkalinity of the material. The range of pH is from zero (most acid environment) to 14 (most alkaline environment) at 25°C (298 K). At such temperature, any solution at pH of 7 is considered neutral, like pure water that is completely neutral at 25°C. Water quality is important in soil stabilization since the impurities present in it may affect the hydration and chemical reactions of the cement setting and cause some problems.

Water affects cement chemical reactions and soil chemical stabilization in three stages. The first stage of water is the initiation of the hydration and chemical reactions of cement slurry. The second is the effects of cement treatment (chemical reactions and hydration). The third stage occurs after hardening the cement in the long term. In this study, the environmental conditions are investigated after chemical stabilization, which is the second aforementioned stage and treatment. The effect of the degree of acidity of water on hardened concrete has been investigated by many researchers, but this has been less studied for cement-stabilized soils. This effect is also dependent on the degree of acidity of the soil. Soil pH is one of the outstanding physiological properties of the soil solution and has a significant impact on its physical, chemical, and biological properties.

Grachow et al. (2009) studied the behavior of fine-grained soils at different pH levels under cyclic loading and found that pH changes could affect the liquefaction potential of sandy soils. These changes are largely dependent on the plasticity properties of clay mineral compounds in that soil, as well as the degree of acidity. The best effect occurs at a moderate degree of acidity. In moderate acidity, the sand–kaolin composition will slightly increase the liquefaction resistance, while in sand–illite and sand–bentonite compounds, the liquefaction resistance will be reduced. Yang et al. (2013) examined the effect of mechanical properties of cemented soil at different pH levels and found that the strength of cement-stabilized soil could reach its peak in a neutral environment. The effect of changes in the acidity of the environment should be considered in practical applications and strength reduction factors should be considered. In addition, the use of special types of cement such as Pozzolanic and slag is recommended in alkaline environments. Kogbara et al. (2012) examined the soil divergence behavior under the influence of pH and other functional characteristics of garbage-contaminated and cement-stabilized soils and found that samples compacted in optimum moisture exhibit the best mechanical performance against divergence. Sariosseiri et al. (2009) examined the influence of cement on the geotechnical properties of some kind of clay in Washington and found that cement treatment resulted in a significant increase in unconfined compressive strength and stiffness of the soil so that the soils treated with cement demonstrated much more brittle behavior than untreated soils. Du et al. (2014) evaluated the impact of acid rain pH on the divergence behavior of cement-stabilized lead-contaminated soils. Their studies showed that with an increase in the amount of cement from 12% to 18%, the separation of lead and calcium will be decreased due to the influence of acid water. Kiad et al. (2015) examined the effect of cement composition and environmental pH on the strength of Portland and other cement pastes. The results of this study showed that a cement mixture containing micro silica and fly ash (with a weight ratio of 40%) performed better than all tested Portland cements. It was also found that the combination of 40% fly ash, 5% micro silica, and 8% slag provided good overall performance against sulfate attack and alkaline environments.

Several factors can cause soil contamination and create acid or alkaline environmental conditions. The urban waste landfill is one of the most cost-effective methods to dispose of waste from the human environment. In this method, waste is spread in layers of soil and compacted and will be covered with another layer of soil at the end. Waste dump with this technique leads to the leakage of leachate from it into the soil and environment, which, if not guided and collected appropriately, has harmful and irreparable effects on the environment and the surrounding soils (Popli et al., 2021). The chemicals derived from waste leachate will be absorbed by soil particles or imprisoned as an insoluble liquid between soil particles. Over time, chemical substances of the waste leachate, which have been absorbed by soil particles, will be spread in the soil texture and cause more soil contamination. On the other hand, surface currents, water from rainfall and snow, and groundwater, transport these materials to the areas far from the vicinity of the landfill, and in long term the pores between soil particles will be filled significantly or completely, which will have a considerable impact on the soil (Sunil et al., 2009).

Considering the increasing population growth, municipal solid waste is one of the most important factors in soil contamination. If waste burial is carried out in open deposits and without pre-reforming methods, where the rainfall rate is more than the rate of evaporation, water remains in the landfill and by combination with municipal waste leachate will be produced (Wang et al., 2008). The lack of leachate collection systems and final landfill coatings will lead to more waste leachate leakage into the surrounding soils. Penetration of waste leachate into the lands around the deposit site causes more soil pollution and may have a direct impact on geotechnical parameters of the soil, resulting in a change in volumetric changes, shear strength, and hydraulic behavior of the soil. To prevent further penetration of leachate into groundwater, clay or bentonite is used, which are more impermeable. Therefore, many researchers have investigated the effect of leachates existing in landfills or salt base chemical solutions or the metals in leachates on clay soil and bentonite, which is clay with 85% montmorillonite. They have tried to investigate the effects of leachate on clay soils due to the subject's importance (Ouria and Farsijani, 2019).

It should be noted that the hydraulic conductivity of clay soils strongly depends on the fluid in the soil pores. Extensive experimental studies have been carried out on the effects of leachate components on soils (Dutta and Mishra, 2016). Some researchers who have focused on the effects of alkaline waste leachate on clay soils have indicated that larger particles of leachate were deposited among small particles of clay and reduced its hydraulic conductivity (Gratchev and Sassa, 2009). Also, in the case of acid leachate (pH < 7), it was observed that the soil hydraulic conductivity was increased due to dissolving mineral materials by the leachate and porosity increase (Goswami and Choudhury, 2013).

As stated before, clay soils with less permeability are used to prevent leachate penetration into groundwater. Therefore, many researchers have investigated the effects of acid and alkaline environmental conditions on clay soils, which is why clay soil was selected in the present study. On the other hand, the increasing population growth and construction in the suburbs of large cities have led to construction and population settlement at many landfills. Therefore, the increasing chemical compounds from human waste and the lack of land needed for construction and accommodation of the growing population highlights the importance of assessing the impact of environmental conditions generated by human-generated waste on the soil.

In past research, it was found that the degree of acidity can affect the physical, mechanical, and volumetric properties of geotechnical materials. So, the novelty of this study is investigating the effect of environmental pH on the mechanical properties, chemical reactions, and volumetric changes of cement-stabilized soils.

2 Chemical stabilization of clay

Improving the properties of the soil using cement, lime, and other materials that require a chemical reaction is called chemical stabilization. In the chemical stabilization of soil, the physical and mechanical properties of the soil will be improved for specific engineering purposes, one of which is the chemical properties of clay with cement. The chemical reaction of clay and cement is important and various researchers have studied the beneficial effects of reactions (Chen et al., 2021; Manzoor and Yousuf, 2020). The reaction of clay and lime in cement includes short-term and long-term reactions. Short-term reactions include clotting, lime transfer, pH change, ion exchange reaction, and carbonation. These reactions affect soil physical properties such as Atterberg limits and grain distribution, whereas long-term pozzolanic reactions lead to the creation of new reaction products and will cause the growth and expansion of particles and affect the strength and compressibility of clay (Mahedi et al., 2020). The reaction of clay and cement depends on various factors such as type and amount of clay, type and amount of cement, environmental conditions, mixing method, initial moisture, and processing conditions. For example, if the amount of clay is small, the reaction will not take place, which is why there is enough clay to perform the reaction (Talluri et al., 2020).

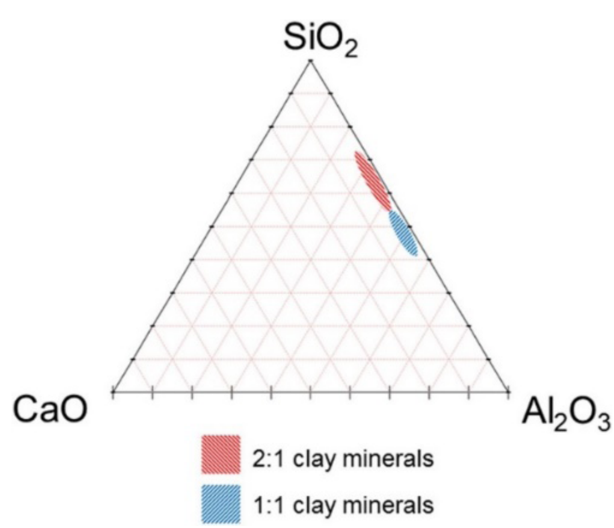

Figure 1: Compositional diagram showing the approximate composition range of clay minerals.

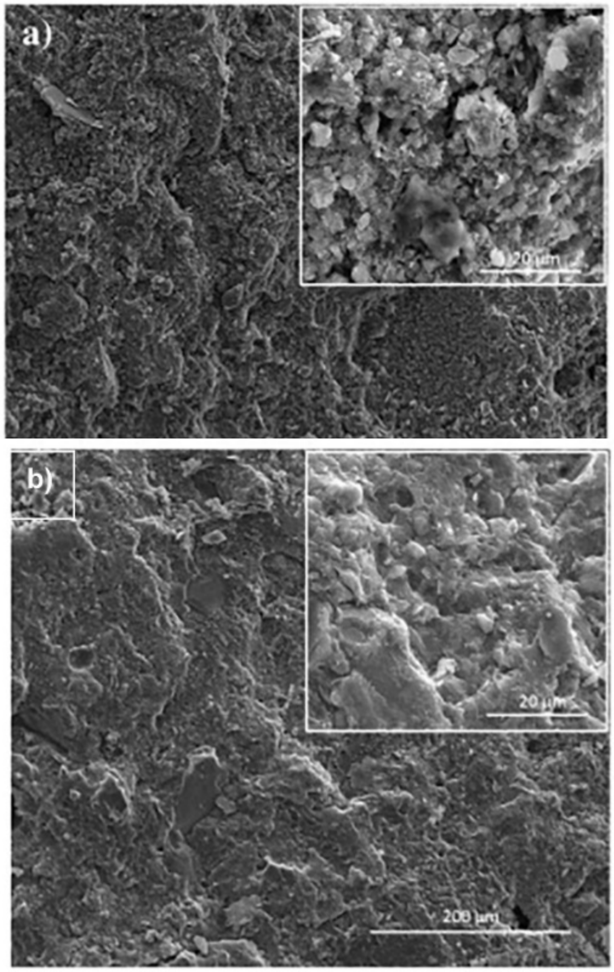

Figure 2: Micrographs of alkali-activated clay sediments showing that activation with NaOH (a) resulted in a more porous, less dense microstructure than activation with (b) Na-silicate solution (Ferone, et al., 2015).

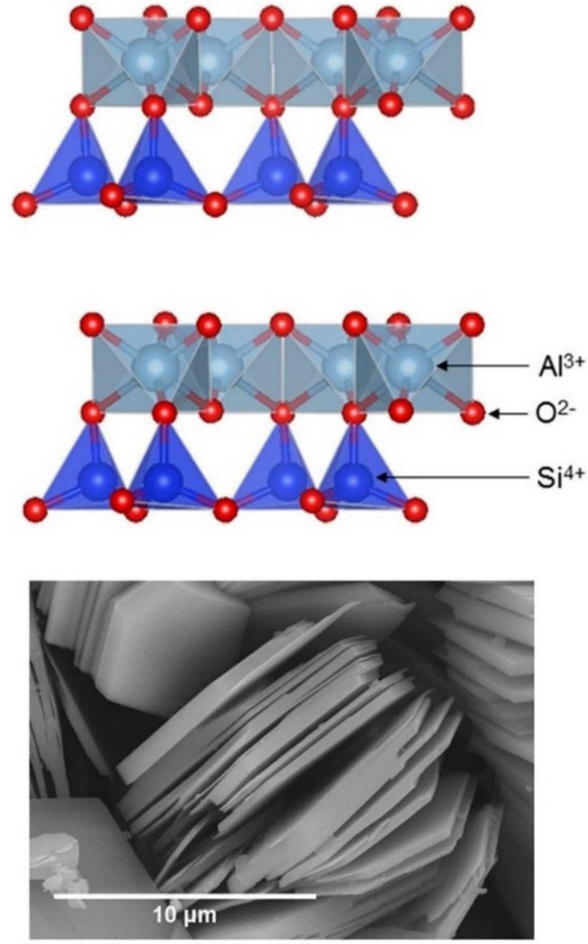

Figure 3: Atomic diagram of kaolinite (two layers), Image generated in VESTA (Larsen et al., 2017), using structural parameters from Bish (Bish, 1993).

Also, a pH of more than 10 is required to perform some reactions. The type and concentration of cations in soil moisture and pores as well as the type of clay mineralization are important in the reactions (Zhang et al., 2020). The addition of cement to clay in suitable conditions causes cation exchange reaction, pozzolanic reaction, integration, and carbonation (Li et al., 2020).

3 Cement–clay interaction

The interaction of cement and clay involves the process of hydration and hydrolysis in the short term, which results in the creation of hydrated cement and free lime, and increases the pH of the environment. High pH and high concentrations of portlandite or calcium hydroxide (Ca(OH)2) lead to the separation of silica and amorphous

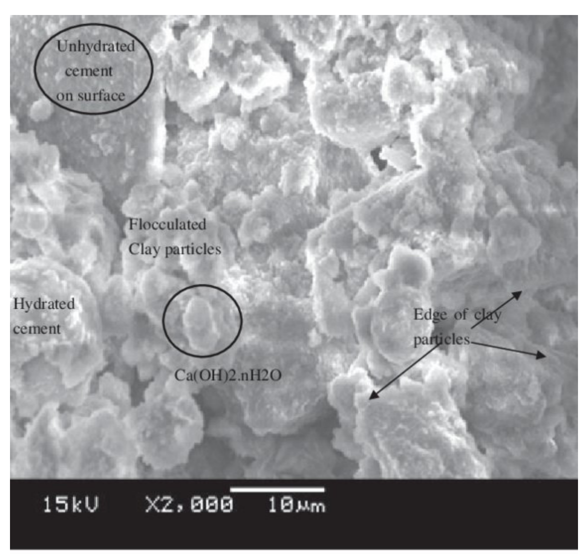

Figure 4: SEM image of cement-treated clay immediately after compaction (Zhao et al., 2016).

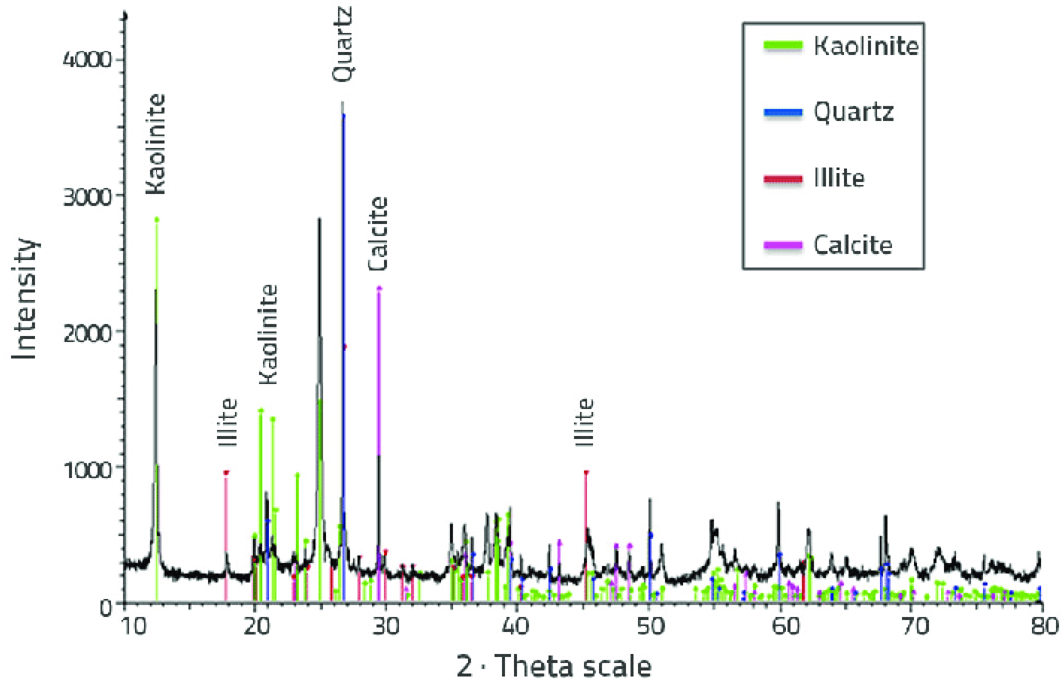

Figure 5: X-ray diffraction of clay sample. (Quartz, Illite, Kaolinite, and Calcite).

alumina, which combine with calcium to form a double cement compound. The pozzolanic properties of clay cause the portlandite (Ca(OH)2) produced during the hydration of the cement to react rapidly. The pH of the cement does not change during curing, but in the cement–clay composition, the pH of the composition decreases over time, which indicates the consumption of OH in the composition. Measurement of conductivity indicates that soluble salts formed during the hydration of cement due to clay particles becoming insoluble compounds. Alteration of clay mineral structure and amorphous compounds leads to the formation of double cementitious materials, which in addition to the usual hydrolysis and hydration in cement, is considered the initial stabilization reaction in the cement–clay composition. The results of studies show that after 12 weeks of hydration of the cement–clay composition, the amount of kaolinite decreases slightly and the amount of montmorillonite decreases significantly.

The cement–clay composition cannot be considered as a simple mixture of hydrated cement particles and unchanged clay particles, but as a new combination of hydrated clay and cement combined through double reactions.

In a high pH environment, there is the production of portlandite (Ca(OH)2) due to hydration of cement, so the dissolution of silica and aluminum from clay particles and amorphous compounds occurs. Dissolved materials can combine with calcium ions to produce double cementitious materials that can bond clay particles together (Zeng et al., 2021). The chemical reaction of clay and cement has three stages, which are described below.

3.1 Ion exchange reaction

Almost all fine-grained soils react with cation exchange in a short period when mixed with cement and water. In this exchange, clay cations are replaced with cement cations. In this case, the monovalent cations of the clay are replaced by the divalent ions of calcium or the polyvalent ions of the cement. Ion exchange can be described as follows (Visser, J.H.M., 2018):

$$Al^{3+} > Ca^{2+} > Mg^{2+} > NH^{4+} > K^{+} > Na^{+} > Li^{+}$$

Based on the above series, each cation replaces the ion on the right. For example, calcium ions can replace sodium and potassium ions in clay. Thus, the exchange between calcium-lime ions and different cations in the soil is considered a reaction and leads to the accumulation of calcium ions around the clay particles. This type of cation accumulation changes the concentration of electrons around clay particles.

This action is done immediately after adding water and cement to the soil and changing the soil structure will reduce plasticity, reduce soil swelling, reduce permeability, and increase mechanical strength. In fact, due to this type of reaction, the texture of clay changes physically and in practice, clay particles tend to bond with each other and form larger particles such as silt and sand (Barman and Dash, 2022).

3.2 Pozzolanic reactions

The increase in mechanical strength in soil and cement composition is due to the pozzolanic reaction. With the addition of cement to the soil, the pH of the mixture increases and sometimes reaches more than 12. Increasing the pH causes the dissolution and release of silicates and aluminates in the clay that can be combined with calcium lime and calcium silicate and calcium aluminates are formed (Zhao et al., 2016). These pozzolanic and crystalline materials are similar to cement. Pozzolanic reactions continue for as long as silicates and aluminates are present in the soil and new crystals form. These reactions are performed as follows:

$$CaO + SiO_2 + nH_2O \rightarrow CaSiO_3 + n\ HOH \text{ (calcium silicate)} \quad (4)$$

$$CaO + Al_2O_3 + nH_2O \rightarrow CaAl_2O_3 + n\ HOH \text{ (calcium aluminate)} \quad (5)$$

The basis of the work is that the lime in the cement, after being added to the wet soil, decomposes into calcium (Ca^{2+}) and hydroxide (OH2) ions. The higher the amount of lime, the higher the OH^- and the pH of the mixture will increase. When the pH of the soil reaches more than 12, the silicate and aluminate of the soil dissolve and the Si and Al ions in combination with OH ions produce $Al(OH)_3$ and $Si(OH)_2$. These hydroxides then combine with Ca^{2+} ions to form hydrated silicate-aluminum or aluminate-calcium.

Pozzolanic reactions depend on the amount and proportion of clay in the mixture, and previous research has shown that the amount of clay in the total sample mixture should not be less than 20% (Talluri et al., 2020). In addition to time, pozzolanic reactions also depend on temperature and humidity. At temperatures below 55°C, pozzolanic reactions slow down and at higher temperatures, these reactions accelerate (Mehdi et al., 2020).

3.3 Carbonation reactions

Carbonation is an undesirable phenomenon and is the result of not reacting properly with clay and lime in cement. In this reaction, lime combines with carbon dioxide in the air to form a weak adhesive (with high plastic properties) and return the lime to an inactive state:

$$CaO + CO_2 \rightarrow CaCO_3$$

Carbonation is done during the mixing of soil and lime and during construction and execution, so the mixing time should be short. Carbonation is considered a harmful reaction to the soil–cement mixture (Mehdi et al., 2020). Another type of carbonation reaction occurs when hydrated lime is used. The result of this reaction will be the production of carbonic acid and then its combination with calcium hydroxide, resulting in the formation of calcium carbonate.

$$H_2O + CO_2 \rightarrow H_2CO_3$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2\ H_2O$$

If the amount of clay is not enough and in other words, the ratio of cement to soil is too much, due to the formation of $CaCO_3$, stabilization, and improvement of soil will be inefficient. Therefore, it is necessary to determine the optimal percentage of cement and the optimal moisture of the mixing design by experimenting. The process of hydration of cement, the physical and chemical properties of clay, as well as the reaction of lime with clay lead to the hypothesis that in the mixing of clay and cement, the main reactions will increase the pH and create an alkaline environment and thus release lime.

An alkaline environment with a high pH and the presence of high calcium (OH concentration) can decompose silica and alumina by attacking clay particles. The combination of silica and alumina with calcium will create a double cementitious material that includes a cement matrix and a clay matrix. Mechanical experiments, X-ray evaluations, and electron microscope results, along with some chemical experiments on the combination of kaolinite and montmorillonite with Portland cement, have been confirmed by various researchers (Chen et al., 2022; Zhao and Khoshnazar, 2020; Latifi et al., 2018).

X-ray analysis shows that calcium hydroxide in the cement composition reacts rapidly with the clay. Also, the results of some researchers in evaluating the electrical conductivity of the mixture show that soluble salts formed by hydration of cement in the presence of clay are reduced

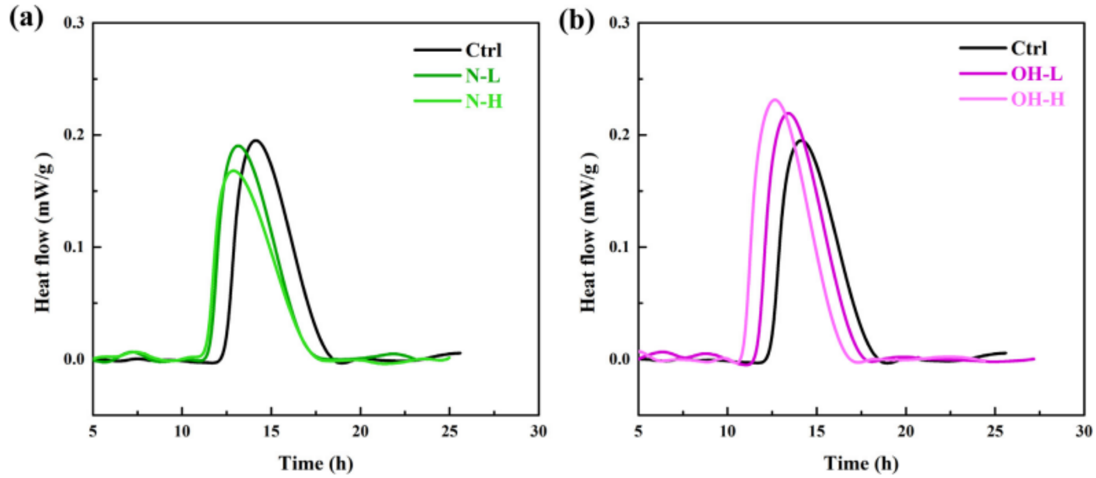

Figure 6: The determined heat flow curves of sulfate depletion peak in (a) N and (b) OH group (Chen et al., 2018).

to less soluble compounds (Zhang et al., 2022; Dubey and Gupta, 2020).

Therefore, cement-stabilized clay can not only be considered as a simple mixture of hydrated cement particles bonded to clay particles without change but also as a matrix in which both clay elements and hydrated cement are also combined through double (secondary) reactions.

4 The effect of environmental acidity on the process of mechanical properties

The alkaline environment has little effect on some Portland cements as well as some soils containing silica ores. Some research also shows that salts in water or soil can affect the setting time of cement and reduce the bond strength. An acidic environment can affect the setting of cement and convert some of the cementitious compounds to calcium compounds. That is, the chemical reaction converts calcium hydroxide to calcium silicate, and hydrated calcium aluminate changes to acidic calcium salts during this reaction. In acidic conditions, with the presence of CO2 or SO2 compounds, part of the cement structure decomposes and evaporates as gas and finally, by reducing the strength of the mixture, an environment with high porosity and high permeability is formed. The acidity of the environment and the amount of pH in the soil pores and the environment around the cementitious compounds can disrupt the process of increasing strength and curing. Therefore, the presence of an acidic and alkaline environment can affect the characteristics of cement-stabilized soil. And as general conclusion, it can be said that cement creates an alkaline environment around itself in the first stage of increasing resistance and curing, which lasts about two weeks.

The moisture and porous solution of the mixture provide the necessary conditions for the hydration of the cement. The concentration of hydroxyl (OH^-) in the pore solution directly determines the pH. In the porous solution, the calcium, silicon, and hydroxyl ions released by the dissolution of the cement clinker are converted into cement hydration products such as calcium silicate hydrates (CSH) and calcium hydroxide (CH). Calcium ions and pH of the solution has a great effect on the dissolution of cement clinker phases and the deposition of hydration phases such as CH and CSH. Also, the concentration of calcium and pH have a significant effect on the reaction between aluminate and silicate ions in the cement mixture (Nicoleau et al., 2014).

Owing to the importance of pH, the effect of this factor on the hydration of cement, especially in the early stages has been less considered by researchers. The results of studies by Ding et al. (2021) indicate a relationship between CSH phase growth orientation and CH concentration. Low concentrations of calcium hydroxide cause the CSH phase crystal to grow further in a direction parallel to the C_3S surface, and its high concentration accelerates the growth of CSH in the direction perpendicular to the surface. Therefore, it seems that increasing calcium ions and pH can accelerate the hydration of cement.

Chen et al. (2018) showed that the pH of the cement mixture affects the reaction of sulfate consumption. As shown in Figure 6, nitric acid (low pH) reduces the altitude

Table 1: Physical properties of the clay used in the study.

pH	G_s	Dry density	Natural moisture content	Soil classification (*USCS*)	Atterberg limits		
					PI	*PL*	*LL*
7.59	2.7	14.9 kN/m^3	20.9%	*CL*	19.7%	23.8%	43.5%

Table 2: Swelling rate and swelling pressure.

Soil type	Swelling pressure	Swelling rate	Swelling potential
CL	16.15 *kPa*	4.37%	Medium
	12.45 *kPa*	2.81%	Medium
	8.65 *kPa*	1.68%	Medium

and increases the peak time of the graph. In other words, the low pH of the cement mixture improves the process of chemical reaction and sulfate consumption and reduces the rate of this reaction. Potassium hydroxide (high pH) increases the altitude and decreases the peak time of the graph. The higher pH of the cement mixture improves the reaction process and sulfate consumption and increases the rate of this reaction. Therefore, it can be concluded that pH level affects the rate of chemical reaction and sulfate consumption and does not affect the reaction time.

Siler et al. (2018) evaluated the effect of environmental acidity in three phases of acidic (pH = 2), neutral (pH = 7), and alkaline (pH = 12) on the properties of concrete mix and cement. The results of this study showed that the 28-day compressive strength of the samples in alkaline curing conditions was slightly lower than the control sample. The reason for this result is the effect of pH on the hydration process of cement. To form portlandite (Ca(OH)2), the pH must be 12.4. Owing to the strong bonds of alkaline ions in the cement paste, the formation of portlandite decreases during the reaction and hydration process. However, the alkaline environment leads to the formation of the highest amount of portlandite in the cement mix owing to the higher concentration of calcium in the mix. Also, some studies show that increasing the pH causes a significant decrease in free water in the cement mixture and an increase in the CSH phase produced during hydration (Liu et al., 2022; Li et al., 2019). Therefore, it is inferred that increasing the pH increases the rate of hydration of cement and its chemical reaction. In the long term, lowering the pH will harm cement-setting process. The amount of CSH produced during the hydration process as an important component of concrete showed a significant decrease in samples with low pH during one year (Bach et al., 2012).

5 Material properties

The soil used in this study is a problematic expansive clay soil taken from Lashtu in Tonekabon County of Mazandaran Province. The superficial sediments of the Lashtu area are mainly composed of soft clay soils. To determine its physical characteristics, experiments were carried out on the basic soil sample according to *ASTM D-4318* and *ASTM D-854* standards, which are summarized in Table 1. According to the results, this soil was classified as CL according to the unified classification system. A direct method was used to identify and evaluate the soil swelling. Direct evaluation of swelling potential means direct measurement of swelling pressure and soil swelling rate. Table 2 shows the results of direct measurement of the swelling rate and pressure using the method in *ASTM D-4546* standard.

The cement used in this study was type II Portland, provided by Tehran Cement Company. This cement is produced according to the national standard of Iran (*ISIRI 389)*, and is a moderate hydration heat cement, the physical and chemical characteristics of which are presented in Tables 3 and 4. This type of cement has the same composition as type I Portland cement but is more resistant to attacking sulfates due to lower alumina (C_3A) content that is, less than 8%. Known as modified Portland cement, it produces less hydration heat and gets harder at a slower pace.

A buffer solution is a chemical solution with fixed and specific pH that is composed of a weak acid and its salt, or a weak alkaline and its salt. If this solution is exposed to air, it absorbs carbon dioxide (an acid anhydride) and gets more acid. If the solution is stored in a glass container, the alkaline impurities that are washed by the glass wetting may change the pH. While the buffer solution (tampon) has a somewhat stable acidity level, and its degree of acidity is preserved even when a small amount of acid or alkaline is added to them. In this study, a buffer solution was used to maintain the acidity degree of the environment where the samples are treated, as specified in Table 5.

Since purified water is used for cement hydration in practice, it was decided to use purified water to make cement slurry in samples. The purified water used in this study is free of harmful substances, such as acid or organic substances, with a degree of acidity of 7.3. Other chemical characteristics of the used water are shown in Table 6.

Table 3: Physical properties of cement.

Properties	Compressive strength		Setting time		Autoclave expansion	Specific surface area
	28 days	2 days	Final	Initial		
ASTM C150	more than 38.5 *kPa*	more than 7 *kPa*	less than 6 hours	more than 45 minutes	less than 0.8%	more than 2800 gr/cm^2

Table 4: Chemical properties of cement.

Properties	Loss on ignition	Remaining insoluble	C_3A	MgO	Fe_2O_3	AL_2O_3	SiO_2
ASTM C150	3%	0.75%	8%	5%	6%	6%	20%

Table 5: The used buffer specification.

Environmental condition	Degree of acidity
Acid	4
Neutral	7
Alkaline	10

Table 6: Specifications of water.

Chemical compounds existing in water	*Ppm*
HCO_3	329.4
CL	14.2
SO_4	9.6
Ca	92
Mg	14.4
Na	6.9
K	2.3

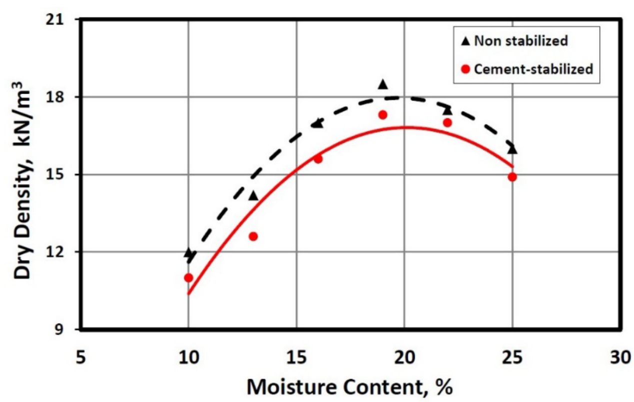

Figure 7: Density curve of cement-stabilized and unsterilized soil.

6 Fabrication of samples

To make samples on an experimental scale and determine their mechanical and volumetric characteristics due to the influence of the environmental degree of acidity in this study, the optimum moisture content and maximum dry density of the soil were determined using a compaction test according to *ASTM D698*, which is demonstrated in Figure 7. Based on this test, the optimum moisture content is 18.5% and the corresponding maximum dry density is 19%. Then, by selecting 5% cement (based on reference number 24), as the stabilizing material, the compaction curve for cement-stabilized soil was also calculated, the results of which are shown in Figure 7. For the improved soil with 5% cement, optimum moisture content of 21% and maximum dry density of 18 kN/m^3 can be estimated. A comparison of the two density curves shows that by adding cement, the optimum moisture content and the maximum dry density will change to 2.5% and 1 kN/m^3 respectively.

Mechanical properties of soil have been estimated by performing an unconfined compressive strength test in this study and volumetric characteristics were evaluated by swelling measurement in California bearing ratio test. An unconfined compressive strength test has been conducted according to *ASTM D2166*. The samples of these experiments were prepared at optimum moisture content, then treated and tested according to the following conditions.

7 Treatment procedure of samples

The treatment period of the samples in this study was selected as 3, 7, and 40 days (short term, medium term, and long term). In order to determine the effect of the environmental degree of acidity, samples were stored in different environmental conditions in terms of acidity,

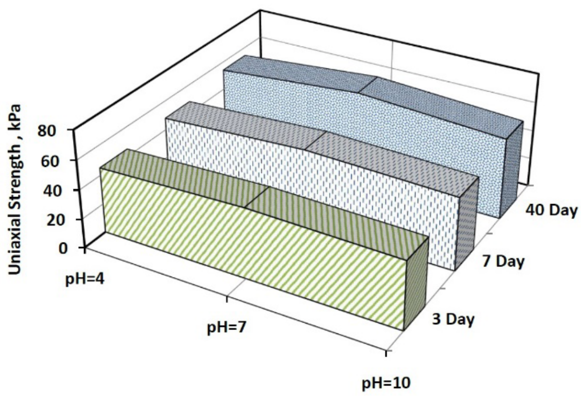

Figure 8: Unconfined compressive strength of nonstabilized samples in various environments in terms of acidity.

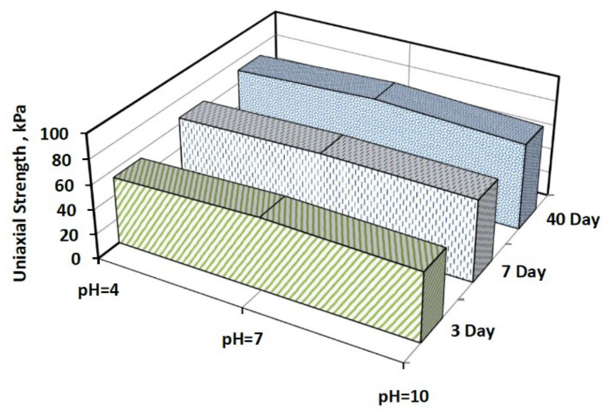

Figure 9: Unconfined compressive strength of samples stabilized by 5% cement in various environments in terms of acidity.

including pH of 4, 7, and 10. For this purpose, the samples were placed inside a cloth that was dipped in a buffer solution proportional to the acidity degree, and then placed in multilayer nylon during the treatment period to maintain the moisture content. To allow moisture availability to complete the chemical setting process of cement, the cloth around each sample (for the uniaxial test) was kept wet by spraying an appropriate buffer solution every three days. Therefore, it was experimentally decided to create some holes in the plastic tube that allowed penetration of the buffer solution. Samples were sprayed with the buffer solution every two days.

8 Analysis of the mechanical experimental results

Mechanical tests on samples were done using ASTM D2166 test methods (Standard Test Method for Unconfined Compressive Strength of Cohesive Soil). The maximum value of compressive stress or the compressive stress at 15% axial strain, whichever is secured first, is reported as the unconfined compressive strength. In this research, all samples below 15% axial strain reached the maximum load.

The results of unconfined compressive strength with different treatment periods are presented in Figures 8 and 9. A comparison of these results shows that in the acid environment, the strength of samples with cement after three days of treatment is greater than the strength of the corresponding samples without cement, which indicates the effect of cement on the strength increase of short-term samples, but over time and in long term, the strength of cement-contained samples will decrease and the samples without cement have more strength.

The failure strain of the specimen is defined as the strain corresponding to the maximum load in the unconfined compressive test. Figures 9 and 10 show the results of the failure strain comparison of samples in various treatment conditions. These results show that cement-stabilized samples in acid conditions have lower failure strains than in alkaline environmental conditions. Also, the process of changes in samples in alkaline and acid conditions is almost the same over time, which means the reduction of ductility and failure strain. Another result of this comparison is that nonstabilized samples exhibit higher ductility and failure strain in the acid environment compared to the cement-stabilized samples, while alkaline environmental conditions have less impact on the failure strain of samples.

9 Analysis of the volumetric experimental results

The compressibility of soil is measured in a laboratory oedometer device. The amount of vertical compression experienced by the soil as a result of the application of load is measured by a displacement transducer. The results obtained from the test may be presented as the vertical strain (ε) at the end of each load increment plotted against the vertical effective stress ($\sigma'v$). Clearly, the slope of the resulting curve is the one-dimensional or confined compressibility (mv) and as illustrated in Figure 11 the magnitude of mv decreases as the vertical effective stress increases.

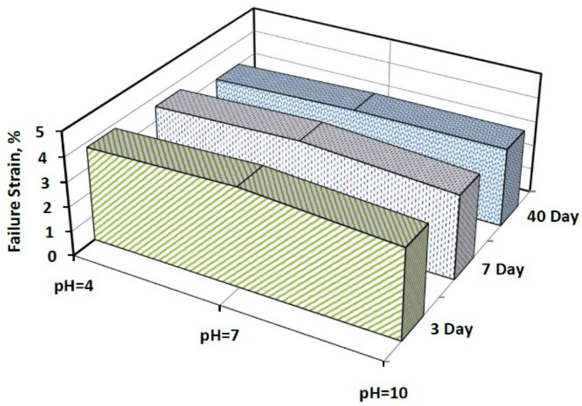

Figure 9: Failure strain of nonstabilized samples in various environments in terms of acidity.

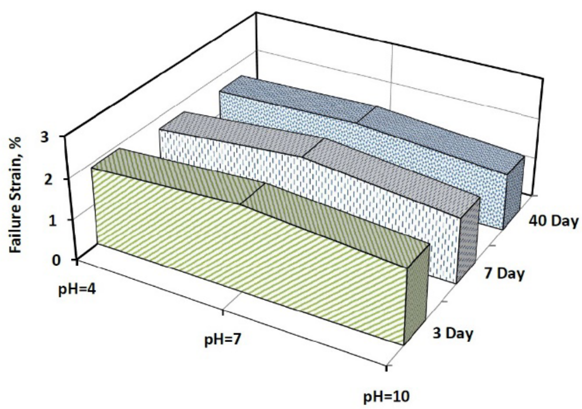

Figure 10: Failure strain of 5% cement-stabilized samples in various environments in terms of acidity.

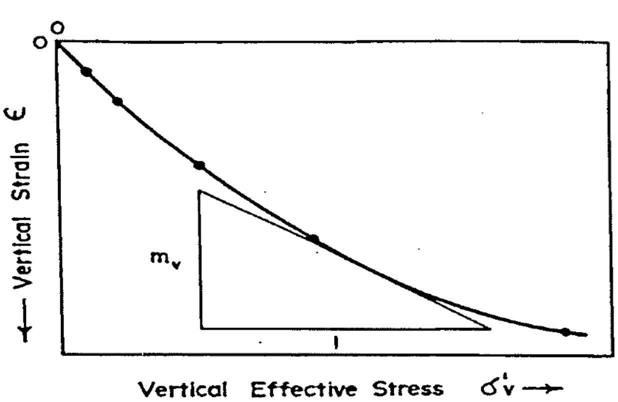

Figure 11: Stress–strain curve from an oedometer test.

This is similar to the comparison of the results for the coefficient of volume compressibility in Figures 12 and 13. So that the volume change coefficient in the neutral environment is less than in the alkaline and acidic environment. In an acidic and alkaline environment, the

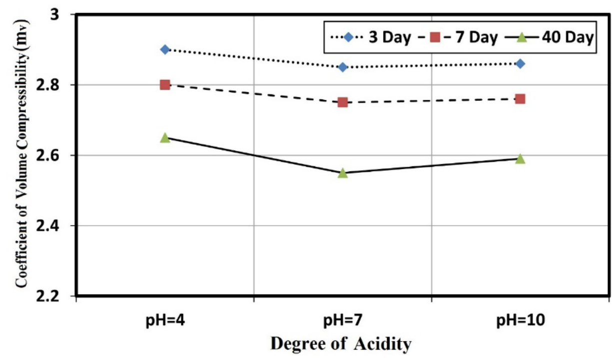

Figure 12: Volume change coefficient of nonstabilized samples in various environments in terms of acidity.

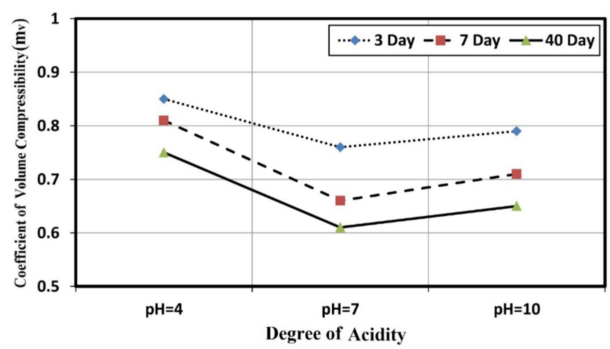

Figure 13: Volume change coefficient of 5% cement-stabilized samples in various environments in terms of acidity.

amount of swelling is always increased in comparison to the neutral environment, which indicates the effect of the environment on expansive chemical reactions in the soil. But it is important to note that adding cement has caused a significant drop in soil swelling.

10 Comparison result with another research

To verify and evaluate the results of this study, a case comparison was made with the studies of Yang et al. (2013). The effect of environmental pH with the presence of cement and treatment time on mechanical properties of soil was investigated in their study using an unconfined compressive strength test. The results of this comparison can be summarized in the fact that by increasing the amount of cement, the ability of cement-stabilized soil to resist the erosion of a contaminated environment will increase acid conditions with a long-term treatment time. The results of this article are consistent with the results of their study, whereby soil behavior is significantly affected by cement stabilization in acid or alkaline environments, increasing the cement content by more than 5%. Another result of comparing these two studies is the effect of a neutral environment on the completion of the chemical reactions of cement setting, leading to the peak strength and performance of cement-stabilized soil, while the acid or alkaline environments influence the intensity and rate of cement chemical reactions and reduce the strength.

In comparison, the results of this study are consistent with the findings of Koupai et al.'s (2020) research on the effect of pH degree on soil mechanical strength. The results of their research showed that the engineering properties of the soil greatly depend on the pH of pore water.

11 Conclusion

The impact of chemical stabilization with cement on expansive clay in acid and alkaline conditions was experimentally investigated in this study and the achieved results can be summarized as follows:

- Without the presence and effects of cement on the sample, the unconfined compressive strength and the bearing ratio of clay soils will not change significantly in the vicinity of water, over time, but soil cementation will increase slightly over time, proportional to which the failure strain is reduced but the swelling potential will not change.
- In neutral environmental conditions, the effect of cement on soil failure strain and swelling potential is very tangible. After completing the chemical reactions and cement hydration during the treatment period, the swelling potential and failure strain will decrease and the sample behavior will get brittle.
- Generally, acid environmental conditions have less impact on cement chemical reactions, compared to alkaline conditions and consequently have a lesser impact on the unconfined compressive strength. The reduction of swelling potential is also more tangible in acid environmental conditions than in alkaline environmental conditions.
- In general, it can be stated that with the passing of time and the treatment period, unconfined compressive strength will increase, while swelling potential and failure strain will decrease.
- The effects of environmental conditions on mechanical and volumetric properties of clay soils depend on environmental conditions and treatment time. The hydration reaction can be divided into three periods: the first 3 days, 7 days, and 40 days.

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