

EFFECT OF LIME TREATMENT ON SWELLING AND SOME GEOTECHNICAL PROPERTIES OF AN EXPANSIVE SOIL FROM MOSUL CITY

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Abstract

The cyclic swell and shrinkage behaviors of expansive soils due to environmental changes result in several structural problems. This study investigates the behavior of expansive soil under wetting-drying cycles for natural and lime-stabilized specimens. An experimental program was directed to evaluate the swelling potential, cyclic swell percent under wetting-drying conditions, wave velocity, pH, electrical conductivity, unconfined compressive strength, and soil-water characteristics curve for natural and lime treated expansive clay specimens. Soil specimens were treated with 4% lime and cured under 40 °C for different curing periods extended to 56 days. The results showed that lime addition causes a significant reduction in free swell potential. In addition, swelling percentages decrease markedly for specimens stabilized by lime and they were related to curing periods. swelling potential increases significantly at the end of the first cycle of wetting-drying, the amount of swelling increases in natural clay specimens is 5.75% and they are 0.8%, 0.6%, 0.16% for lime-treated specimens cured for 2, 7, 14 days, respectively. Furthermore, it was noted that after the first cycle, the highest reduction in free swell potential occurs, especially for the natural soil specimens. Unconfined compressive strength and wave velocity values of lime-treated soil specimens increased significantly with curing times, due to the cementing materials produced from the pozzolanic reaction. Electrical conductivity and pH values of lime stabilized soil specimens decreased rapidly during the first 7 days of curing, then decreased gradually. Increases in volumetric water content with curing periods were observed.

Keywords: Expansive clay, Lime stabilization, Swelling, Wetting-drying.

1. Introduction

The swelling of expansive soils considers one of the special problems that civil engineers are faced. This type of soil is widely distributed in many countries around the world. Expansive soils exhibit volume change due to their swelling and shrinkage responses resulting in many structural problems and damage hazards; especially, in infrastructures such as railways, motorways, and highways. On the other hand, expansive clay soils in nature under cyclic volume change (swelling and shrinkage) due to the change in the water content, this phenomenon has a significant effect on the expansive soil properties. In addition, the cyclic volume change leads to foundation movements and may result in cracking and structural damage. Several researchers investigated the influence of cyclic swelling and cyclic wetting-drying on the characteristics of expansive soils [1-7]. Some of them concluded that the swelling potential of expansive soils decreases with subjected cycles of wetting and drying [1, 3, 4, 7]. On the other hand, few of researches showed that the cycles of wetting-drying increase the swelling potentials of expansive clays [8,9].

Expansive soils were classified as problematic soils that have an adverse response and high swelling potential results in low bearing capacity and shear strength, especially in a saturated state. Therefore, geotechnical engineers directed their research to improve shear strength and mitigate the swelling amounts of the expansive clay to control the volume change and foundation movements. The improvements techniques are usually mechanical, chemical, and techniques were combined with both previous methods. In general, chemical stabilizations by cementing agents, such as cement, fly ash, lime, and salts were widely used in soil treatments [10-19]. Lime stabilization has been one of the important techniques for clayey soil stabilization. However, some researchers have focused their studies on the effect of lime on the swelling characteristics of expansive clays [20-23]. For example, Hamza [23] concluded that the addition of 5% lime decreases the plasticity and swelling potential of expansive soils. Bell [12] also indicated that mixing of the lime corresponding to optimum percentage with expansive soil, decreases the swelling percentages and he reported that further addition of lime does not change the swelling potentials while increasing the engineering properties of expansive soil.

The treatment of clayey soils with lime in the humid medium result in several reactions that make changes in soil properties [24]. Some of these reactions are short-term reactions and others are long-term reactions. The short-term reactions include cation exchange and flocculation. The chemical reaction that includes an exchange of similar cations is called cation exchange [11, 12, 25]. As mentioned by Mitchell and Soga [26], lime and water addition to clayey soil increase immediately pH values to 12.4 which results in the dissolution of alumina and silica. The exchangeable ions that are available around clay minerals like Na⁺ and K⁺ displace Ca⁺⁺ ions, in which Ca⁺⁺ has resulted from the dissolution of lime in water. The flocculation process occurs due to an increase in the concentration of Ca⁺⁺ ions around the clay particles which led to form of a floc.

In addition, this process made the clay particles to agglomerate. Short-term reactions modify soil properties by decreasing plasticity and increasing soil workability [27-30]. Long-term reactions include carbonation and pozzolanic reaction; due to lime addition to clayey soil in the presence of water, a highly

alkaline environment was generated. Then, the alumina and silica from the clay minerals react with calcium from lime. This reaction produces cementing material in the form of calcium silicates or calcium aluminates (calcium aluminosilicate hydrates, CASH; calcium aluminate hydrates, CAH; and calcium silicate hydrates, CSH), this reaction provides bonds between clay particles [11, 12, 27, 31].

The pozzolanic reaction is time-dependent and contributes to strength increases with time. In general, cementation results from lime stabilization processes, increase shear strength, reduce permeability, decrease swelling potentials, and modify the water retention ability of clayey soils [12, 20, 32]. The percentage of lime used for soil treatments depends on the type of treatments if its modification or stabilization. Therefore, some researchers suggested the amount of lime needs for lime modification is between 1% to 3%, while others found the optimum lime content for stabilization between 2%-8% [11, 12, 33].

The effect of lime stabilization considering curing periods and temperature on the physic-chemical and geotechnical properties of clay was studied by [30, 34]. For example, Boardman et al, [30] performed several tests for clay and lime mixtures cured in different periods ranging between 7 to 301 days. The curing process was conducted in a closed area and under 11.50° C temperature. They concluded that a curing period lower than 7 days did not result in significant cementation from the pozzolanic reaction, except for some short-term modifications that occur in clay properties. Bell [34] illustrated that the use of higher curing temperature made accretion in the curing process and increase the strength. While, delays in the soil modification occur when the curing process was conducted at a lower temperature.

This paper will direct the program of the experimental work to investigate the effect of wetting-drying cycles on the swelling potential of natural and lime treated expansive clay samples, which is the primary purpose of this study. On the other hand, secondary experimental studies were aimed to study the effect of the lime addition and curing time on unconfined compression strength, shear wave velocity through specimens, pH value, electrical conductivity, and water-retention behavior of the stabilized soil specimens.

2. Materials and Experimental Methods

2.1. Materials

Soil: The type of soil used during the experimental work was clay. Clay samples were quarried from the Al-Sedeeq region, Mosul city, Iraq. Clay samples were obtained from a depth varying between (0.5-1.0 m) under the ground surface. According to the grain size analyses of the clay (sieve analysis and hydrometer test). The grain size distribution curve for natural soil was presented in Fig. 1. Some index, chemical, and physical properties of natural clay were illustrated in Table 1. The clay soil was classified as high plasticity clay (CH) according to the unified soil classification system (USCS) based on the results of the grain size analyses and Atterberg limits values.

Lime: Hydrated lime was used as a stabilizing agent to treat clay soil in all tests during the laboratory work. The lime was obtained from Meshrag Sulphur factory, Mosul, Iraq. The lime powder was sieved through # 40 sieve, which has a 0.425 mm opening. The activity of hydrated lime was found to be 74%. Table 2 shows the chemical compositions of hydrated lime.

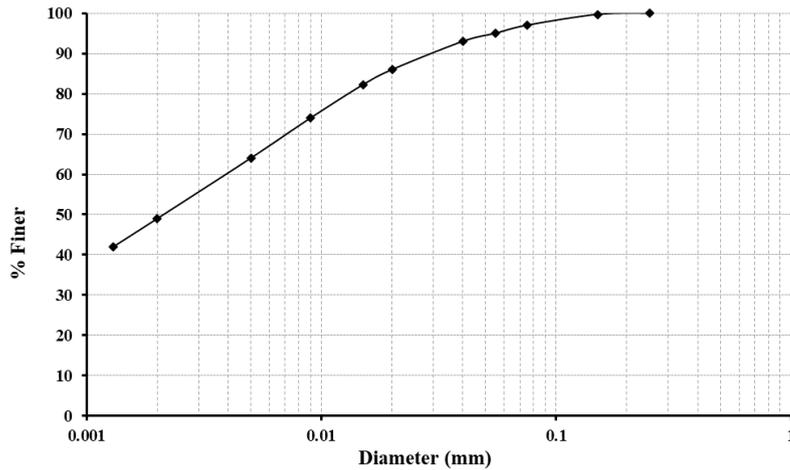


Fig. 1. Grain size distribution of natural soil.

Table 1. Index, chemical, and physical properties of natural soil.

Properties	Values
Liquid Limit (%)	86
Plastic Limit (%)	32
Plasticity Index (%)	54
Linear Shrinkage (LS) (%)	20
Total Soluble salts (%)	2.97
Gypsum (%)	1.39
Electrical Conductivity (mS/cm)	1.2
pH	7.97
Specific Gravity	2.75
CEC* (meq/100 gm of soil)	33
Activity (%)	1.1
Sand (%)	5
Silt (%)	46
Clay (%)	49
(USCS) Classification, Soil symbol	CH
Soil name	Fat Clay

*CEC is cation exchange capacity

Table 2. Lime properties and chemical compositions.

Composition	L.O.S*	H ₂ O	SiO ₂	MgO	Ca(OH) ₂	CaO	CaCO ₃	Al ₂ O ₃	Fe ₂ O ₃
Lime	1.09	0.07	8.41	4.3	74.0	6.5	5.4	0.2	0.03

*Loss of Ignition

2.2. Experimental work and testing apparatus

A series of mechanical, physical, and free swell tests were conducted in a soil mechanics laboratory on natural and lime stabilized expansive soils, these tests were directed to estimate some geotechnical properties and the effect of the wetting-drying

cycles (WDC) on the swelling potential of the natural and lime stabilized expansive soil specimens.

2.2.1. Sample preparation, pH value test.

Stabilized soil specimens were treated with 4% of lime which is corresponding to optimum lime percentages for this type of soil. This percentage was selected according to the pH value method that will discuss in detail in sections of results and analysis. The optimum lime percentage was obtained according to the method suggested by Eades and Grim and was recorded in ASTM (D6276) [35, 36]. At the beginning of the testing program, the soil specimen was prepared by drying it in a 60 °C oven for two days. The soil specimens were sieved using a 4.75 mm opening sieve. to obtain the compaction characteristics of the natural and lime stabilized soil, lime and clayey soil samples were mixed thoroughly in the dry state until the mixture become homogenous. Then, the required amount of the water was added to the mixture (water content equal to 5% of the dry weight), and thoroughly mixing is essential for better and uniform distribution of the water. The processes were repeated for samples with different water content (10, 15, 20, 25, and 30 % of the dry weight). Wet mixture samples were kept inside plastic bags for 24 hours for natural clay samples and 1 hour for lime stabilized clay samples as a mellowing period. Then, homogenous samples were placed inside compaction mold and compacted under standard compaction effort based on (ASTM D-698) [37] procedure.

2.2.2. Unconfined compressive strength and shear wave velocity tests

In order to obtain the shear strength response of the natural and lime stabilized clay and to correlate it with the shear wave velocity, unconfined compression test, and ultrasonic wave velocity test was conducted. Cylindrical samples having 50 mm diameter and 100 mm height were prepared using a specially designed mold. Samples of the natural and lime stabilized clay soil were compacted inside the mold using static compaction effort; the compaction effort was applied at the rate of 1mm/min. Soil samples were compacted in water content and dry density corresponding to maximum dry density and optimum moisture content.

Stabilized soil samples were kept in a closed medium by wrapping them with cling film and coating them with a thin layer of paraffin wax to eliminate the moisture loss. Stabilized soil specimens were cured for 2, 7, 14, 28, and 56 days at 40 °C temperatures (The temperature was selected at 40 °C due to this temperature is the maximum value before the wax melts to keep the specimens in a close medium). At least three trials were performed for each stabilization percent for repeatability checks. All soil samples were first tested to obtain the wave velocity and then tested in an unconfined compression machine based on the method recorded in (ASTM D-5102) [38].

The ultrasonic wave tests were conducted using a PUNDIT device under a frequency of 50 kHz. The direct transmission method was performed for measuring the wave velocity through soil specimens which is more sensitive than other methods [39]. Wave velocity was estimated from the travel distance and travel period of the wave. Then, specimens were tested in the unconfined compression device. The stabilized specimens were tested to obtain the electrical conductivity and their variations with the curing times. A small part of failed unconfined compression specimens was taken to determine the electrical conductivity (EC) of specimens.

2.2.3. Swelling test

The primary objective of this paper is to determine the free swell potential of natural and lime-stabilized clay and to study the influence of the wetting-drying cycles on the swelling potential in the two cases. Free swell tests were performed according to the procedure recorded in the ASTM standard (D-4546) [40]. A standard one-dimensional Oedometer device was used for swelling tests. Soil samples for natural and stabilized clay were statically compacted inside a rigid stainless-steel ring. In the beginning, samples of natural clay and samples of clay with lime were mixed with water in percentages corresponding to optimum moisture content (OMC) and thoroughly mixed until getting a homogenous mixture. Then, soil samples were pressed until the unit weight corresponds to Max. dry unit weight at a strain rate of 1 mm/min. The rings have a 63.5 mm diameter and 19 mm height. In addition, swelling test specimens of lime stabilized clay were cured in different curing periods (2, 7, 14, 28, and 56 days) in a closed area under a temperature of 40 °C. Specimens of natural clay were tested directly after their preparation, while the specimens of the lime stabilized clay was tested when curing times were completed.

Soil specimens were placed between two dried porous stones inside the Oedometer cell; then dial gauge was assembled on the top cap of the cell for vertical displacement measurement during the test. A contact pressure equals to (6.9 kPa, which is equivalent to the standard load of 1 Psi), was applied and then the initial reading was recorded. After that, the specimen was submerged with water and allowed to swell. The dial gauge readings were continuously recorded. The process was stopped, and the final reading was recorded when the specimen swelling was completed. In this study, the swelling period was fixed in 24 hours. The free swell potential of the specimens was estimated as (swell potential = $\Delta H/H * 100$, where ΔH is the vertical displacement and H is the initial height of the soil specimen).

The second part of the swelling tests was conducted on natural, and lime stabilized specimens (4% lime) after exposition to wetting-drying cycles. At the end of the curing periods (2, 7, 14, 28, and 56 days), the specimens were subjected to cycles of wetting-drying, this process was performed inside the oedometer cell. The number of wetting-drying cycles was five for natural and lime stabilized specimens. The wetting process consists of submerging the specimen for about 24 hours inside the cell, then the specimens were dried gradually at room temperature for 1 hour and then dried for 24 hours inside 60°C ovens. The specimens were dried gradually to save them from any damage. According to ASTM (D559) the wetting-drying cycle is completed within 48 hours.

2.2.4. Suction measurement

The effect of curing time of stabilization on soil water characteristics curve (SWCC) was investigated during the experimental work. In general, soil suction can be determined using a direct method or indirect method for SWCC construction. In this study, an indirect method was selected. This method includes three methods for a suction range of 0 to 1000000 kPa. These methods include tensiometric plates, vapor equilibrium technique, and osmotic membrane. Soil samples of natural clay and lime stabilized clay were compacted at dry density and moisture content correspond to maximum dry density and optimum moisture content, respectively. Then the compacted samples were cut and trimmed into pieces until they were 1 cm in

thickness. The pieces of stabilized clay specimens were kept for 7, 14, 28, and 56 days as a curing time and then tested for SWCC generation.

The first part of SWCC was measured using tensiometric plates method that covers a suction range of 10 to 20 kPa. The suction value of the soil specimen for this part was determined by calibrating the water column level in equilibrium with the air level inside the ceramic disk; the time required for each soil specimen to reach equilibrium was 21 days. Suction values in soil specimens are determined directly as a function of water height (for example 10 kPa suction amount has corresponded to 1 m water level in the column) [41]. While the suction range of 100 kPa and 1500 kPa (second part of SWCC) was estimated by the osmotic membrane method.

In this method, a soil specimen was covered by a semi-permeable membrane; after that, the soil specimen that was covered by a membrane was submerged in a solution of polyethylene glycol (PEG) with different concentrations for various values of suction determination (ranging between 100 to 1500 kPa). In this step, the time required for soil specimens to reach equilibrium was 28 days. The vapor equilibrium technique was followed in the determination of the high suction ranges of SWCC. In this method, the relative humidity in the airspace above a salt solution is determined. Therefore, chemical compositions unique and their concentration are important during this step. Then soil specimens were placed inside a closed medium (desiccator) and the chemical solution was calibrated with the correct target relative humidity. During this step, this solution will absorb or produce water vapor in the airspace until the system come to equilibrium.

The total suction using Kelvin's formula was calculated when the relative humidity was in equilibrium within the airspace. After that and during approximately 50 days, suction equilibrium was reached inside the closed medium due to soil specimens-moisture absorption and desorption. Finally, all previous methods and procedures were performed at room temperature (25°C) and under null pressure.

3. Results and Discussion

The results of this study are divided into two parts; the first part presents results related to the effect of the lime addition and wetting-drying cycles on the swelling properties of the expansive soils, which are the primary objectives of this work. The second part presents the results related to other geotechnical properties of expansive clay soil with lime and curing time, which are the secondary objectives of this research.

3.1. Estimation of lime stabilization percent using pH method

The optimum percentage of lime that was used to mitigate swelling potential and improve the shear strength response of expansive soil has been obtained according to [35-36]. Fig. 2 presents the variation of pH values with the lime content. It is clearly observed from the figure that pH values increase with the lime content and become in equilibrium as the lime percentage achieves 4%. Therefore, this amount of lime was taken as a stabilization percentage for the soil under study.

The changes in pH values with the curing period of stabilized specimens are presented in Fig. 3. It is clearly observed that there are significant reductions in the pH values as curing time increases until 14 days. After that, pH values gradually decrease and become in equilibrium with the curing period. The reason for this

behavior might be the lime consumption during cation exchange and pozzolanic reactions [30]. Similar results were obtained by Aldaood et al. [42] and they justified this behavior to the reaction between the lime and soil during the curing time which produces a new form of hydrated silicates.

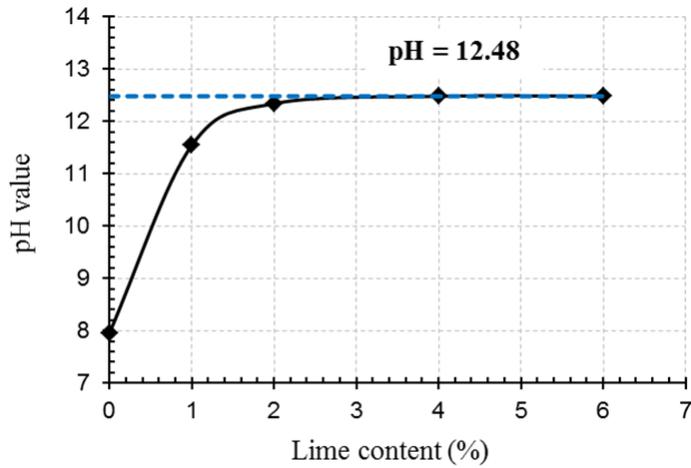


Fig. 2. pH values variation versus lime content.

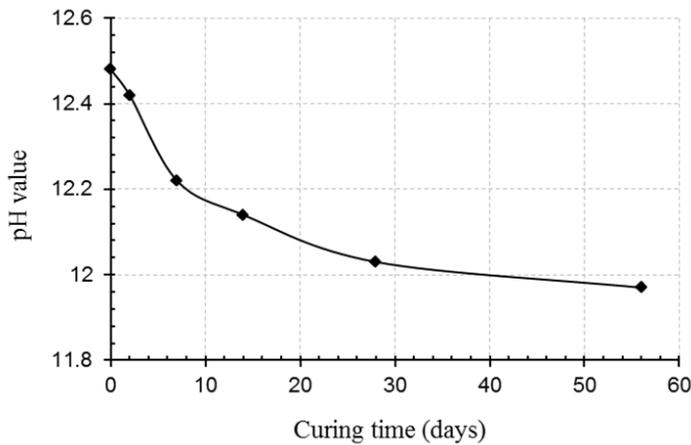


Fig. 3. Variation of pH values of stabilized specimens with curing period.

3.2. Electrical conductivity of stabilized clay specimens

The stabilized specimens were tested to evaluate the electrical conductivity and their variations with the curing times, in order to get a better observation of stabilized specimens. The addition of the lime increased the electrical conductivity from 1.2 to 8.82 and 9.66 mS/cm for stabilized specimens as lime content increased to 4 and 6 percent, respectively (see Fig. 4). The reason for this behavior might be the increase in the amount of calcium ions (Ca^{++}) and hydroxyl ions (OH^-) during lime addition. Also, it was noted that the electrical conductivity decreases

significantly as the curing time increase until 7 days curing period. While at higher curing periods the variation becomes gradually, and the electrical conductivity is near equilibrium with the curing time as shown in Fig. 5. This response can be attributed to the concentration of the exchangeable cations and lime-clay reactions which produce ettringite, which was affected by pozzolanic reaction continuity with time [42].

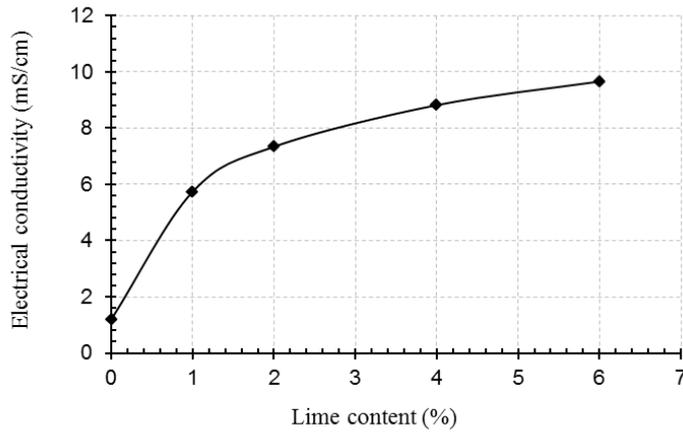


Fig. 4. Electrical conductivity variation with lime content.

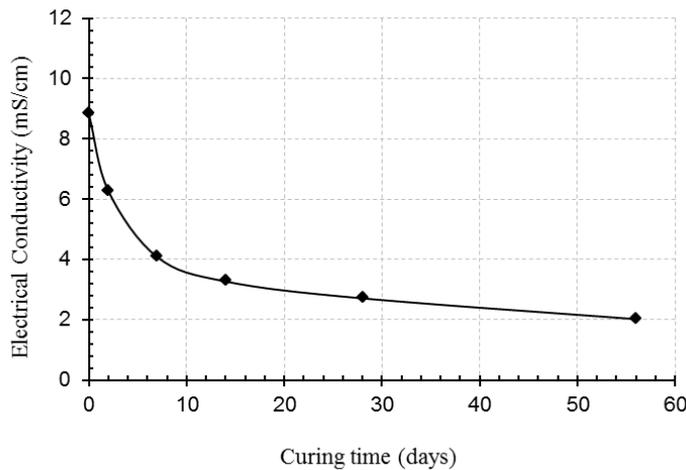


Fig. 5. Electrical conductivity variation with curing time of stabilized specimens.

3.3. Swelling potential variation with WDC

The variations of the swelling percentages versus elapsed time for specimens subjected to different wetting-drying cycles (WDC) are presented in Fig. 6. The swelling amount increased by about 5.75% during the first cycle. While the range of the increase in the swelling percentages becomes gradually lower as the wetting-

drying cycles increase. The swelling amount with the cycle number will be in equilibrium and close to the swelling percentages of clay specimens without wetting-drying cycles. The reason for this behavior might be the reduction in pore voids during the wetting-drying cycles which reduce the ability of soil particles to suck more water in the next cycles [43]. Also, the generation of the cracks as the wetting-drying cycles increase mitigates the swelling ability of the specimens. This finding is similar to the result obtained by Chu [44], in which swelling percentages increased with the wetting-drying cycles. On the other hand, Estabragh et al. [22] concluded in their study that the swelling amount decrease as the cycles of wetting-drying increase.

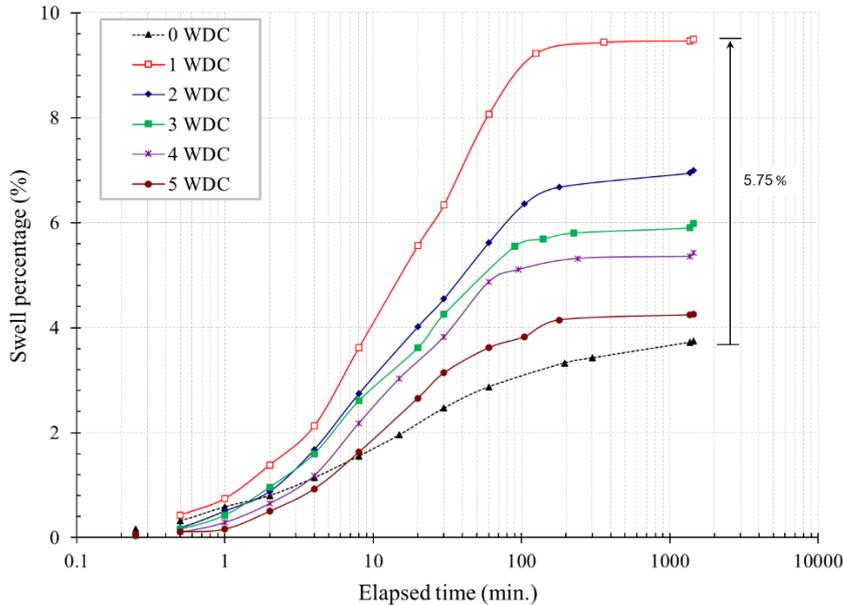


Fig. 6. Swelling percentages vs elapsed time for several wetting-drying cycles (WDC) of natural clay.

Variations of swelling amount versus elapsed time for different WDC of natural and lime stabilized specimens for different curing periods were presented in Figs. 7-9. Lime-treated specimens were cured for different curing periods. In general, swelling potential decrease as the soil stabilized with lime, this response is related to the curing periods, the swelling pressure decreases as the curing period increases. Also, swelling percentages for natural clayey soil and lime-treated soil specimens increase as the elapsed time increases. swelling percentages for untreated soils increase rapidly with elapsed time and become in the balance after approximately 100 minutes as presented in Fig. 6. While in the cases of treated specimens swelling percentages increase gradually and become in balance with time after 200-300 minutes (see figs. 7-9). The reason for this behavior is that the pozzolanic reaction of the lime produces cementing materials (calcite and calcium-silicate-hydrate "CSH") that make bonds between soil particles from one hand, Also, cementing materials gel that results from lime reactions covers soil particles and eliminates the water attach to these particles from other hands. These processes slow down the time of the swelling potential of the clay particles.

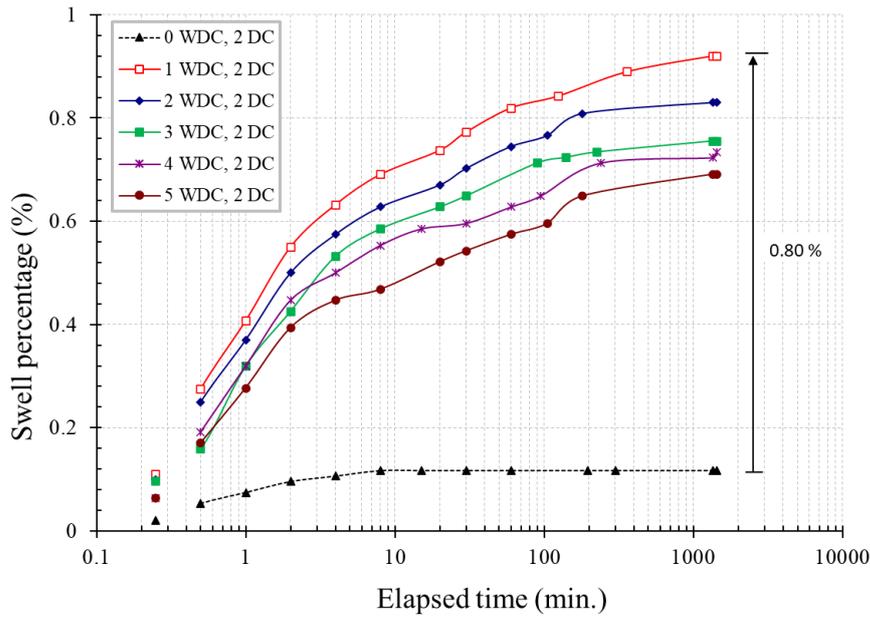


Fig. 7. Swelling percentages vs elapse time for several wetting-drying cycles (WDC) of stabilized clay and curried for 2 days (DC).

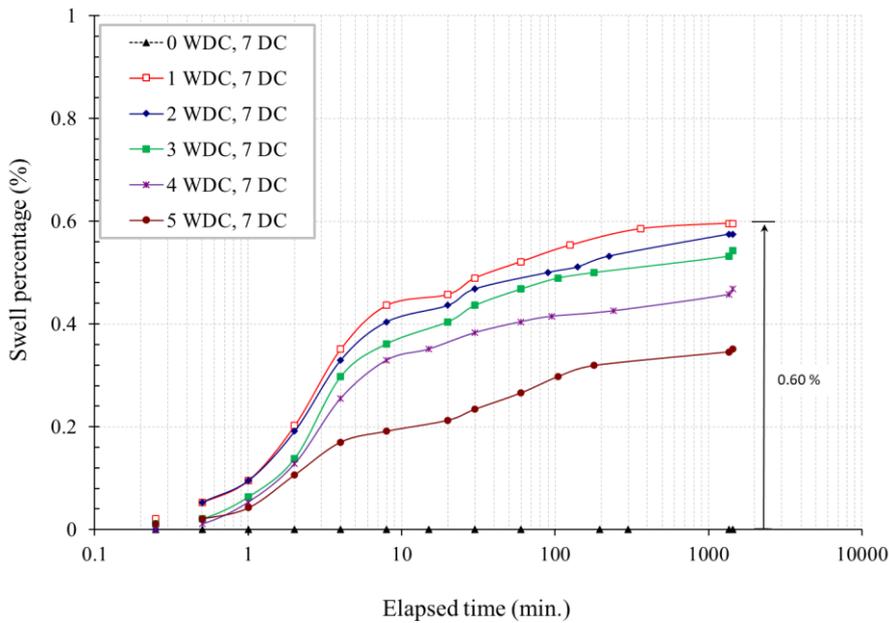


Fig. 8. Swelling percentages vs elapse time for several wetting-drying cycles (WDC) of stabilized clay and curried for 7 days (DC).

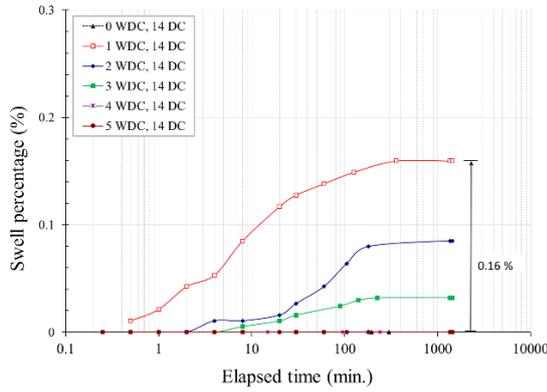


Fig. 9. Swelling percentages vs elapse time for several wetting-drying cycles (WDC) of stabilized clay and curried for 14 days (DC).

Variations of the swelling potential of natural clay and lime-treated specimens with the wetting-drying cycles are illustrated in Fig. 10. In general, swelling potential increases significantly during the first wetting-drying cycles, the amount of these increases is 5.75% for natural clay specimens and about 0.8%, 0.6%, 0.16%, and negligible value for lime treated values curried for 2, 7, 14, 28, 56 days, respectively (see Figs. 6-10). This behavior may be attributed to the reduction in voids volume of the specimen after the first wetting-drying cycle. While, after the first WDC, the swelling amount decreases gradually as the number of cycles increases. In addition, the figures show that amount of the swelling percent decrease significantly as the curing periods increase, this behavior might be due to the amount of the cementing material increasing with time. Also, cementing bonds resulting from lime reactions become stronger as the curing period increase. Similar results were obtained by Al-Daood [39]. This interpretation was supported by the results of the XRD analyses for a natural and lime-treated specimen for different curing periods, see Fig. 11. The amount of the calcite and CSH increase significantly in a treated specimen and especially in specimens that were cured for long curing periods.

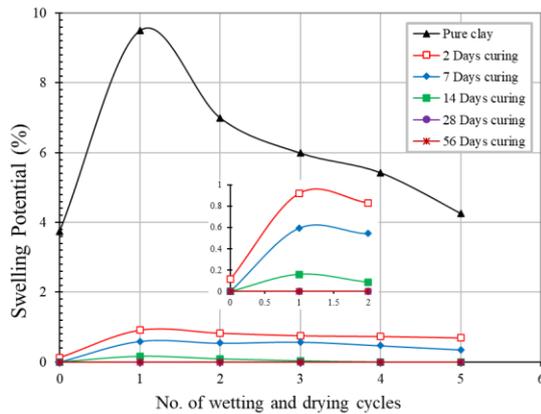


Fig. 10. Swelling potential variation with the wetting-drying cycles for different curing times.

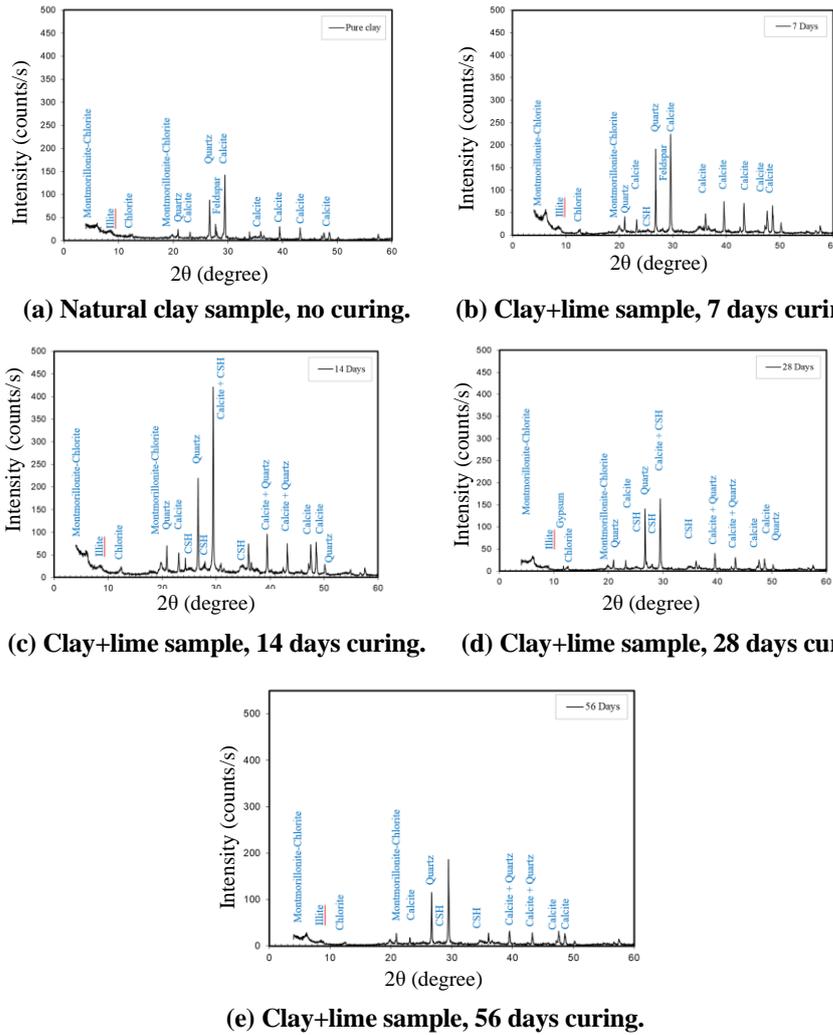


Fig. 11. XRD patterns of lime stabilized samples cured during different periods.

Figure 12 presents photos of specimens after tests. It is clearly observed that there is significant crack propagation in the natural soil specimens, while there are no cracks or micro-cracks shown in treated specimens for all curing periods. During drying cycles, cracks were resulted along weak planes within soil mass due to internal stresses, soil volume change, and mass decreases. During wetting, the specimen volume increases, the cracks are closed, and the swell was occurred [45]. Furthermore, soil structure collapse was resulted due to these cracks and especially at the initial stages of the wetting; this process closed the cracks and decrease soil volume. This problem was treated using lime stabilization that produces cementing material (calcite and calcium-silicate-hydrate “CSH”) [39]. The cementing material covers soil particles and makes bonds between them as can be seen using microscopic analyses for the treated samples (See Fig. 13).

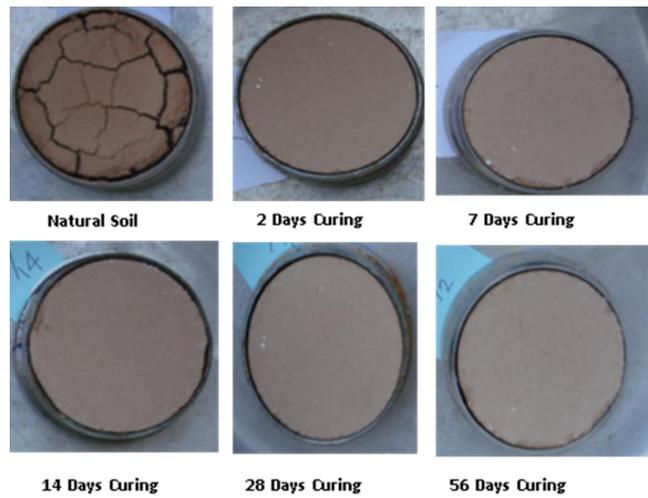


Fig. 12. Photos of the swelling samples for several curing periods.

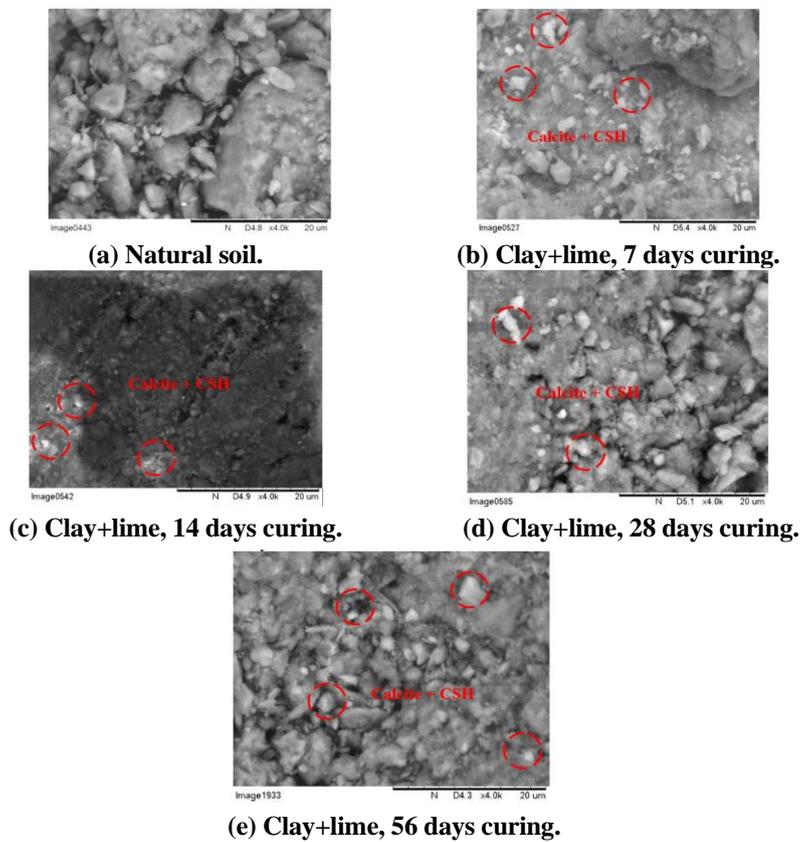


Fig. 13. Scanning electron microscopy pictures of lime stabilized clay samples for several curing periods.

3.4. Unconfined compressive strength and wave velocity of stabilized specimens

A series of unconfined compression tests and ultrasonic wave velocity tests were conducted for stabilized specimens with 4% lime, in order to get a better observation of the improvements in the strength response of soil specimens. These improvements have resulted from modifications in soil structure in which cementing materials make bonding between soil particles which mitigates soil swelling potential. The improvement in the unconfined compressive strength of the stabilized specimens with the curing period is presented in Fig. 14. It is observed from the analysis of this figure, that a significant increase in unconfined compressive strength as specimens cured for a long time until 14 days. Furthermore, the rate of increase in unconfined compressive strength becomes gradually and near to equilibrium. During high curing periods, it can be observed that unconfined compressive strength reaches 8.5 times the strength of natural clay specimens. Moreover, it is observed that the strength of the specimens was duplicated as the curing period increased from 2 to 56 days. This behavior may be due to an increase in the cementing material resulting from the pozzolanic reaction on one hand, in which the percentages of calcium silicate hydrate and calcium aluminate increase in the mixture of soil and lime. The strength of the cementing material itself improved and produces better bonding among soil particles on the other hand. Similar results were obtained by Calik and Sadoglu [17].

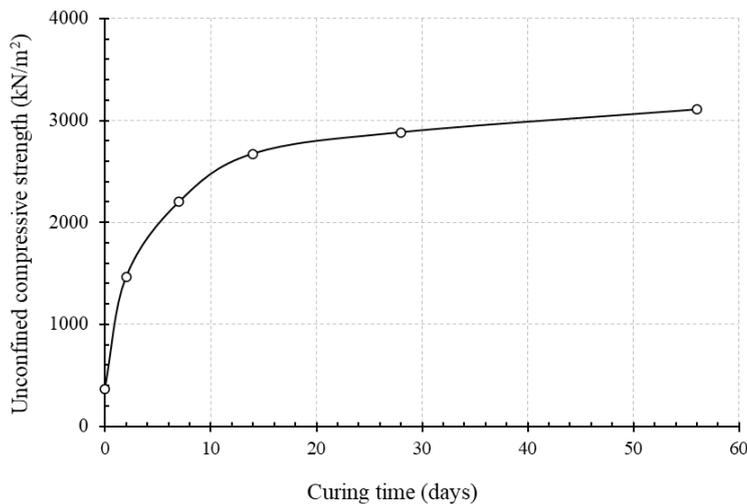


Fig. 14. Unconfined compressive strength variation versus curing times.

The wave velocity tests were conducted corresponding to unconfined compression tests. Fig. 15 presents the variation of wave velocity versus curing time for the stabilized specimens. In general, there is a pronounced increase in the wave velocity through specimens until 7 days. After that, the rate of increase in the velocity becomes gradually at times close to 56 days. Actually, the same trends were observed in the variation of the unconfined compression strength with curing time. Therefore, the same reasons may be result in these behaviors as mentioned above, the pozzolanic reaction produces cementing material that makes bonds

between soil grains. Better contact between soil grains and low voids resulted due to an increase in the amount of cementing material, which may facilitate wave propagation through stabilized specimens. Similar results were obtained by Yesiller et al. [39, 46]. They recorded that increases in the wave propagation through specimens with curing time are due to an increase in both specimen stiffness and cementing agent stiffness itself. Fig. 16 illustrates the correlation between the unconfined compressive strength and wave velocity. In general, wave propagation velocity increases as the strength become higher. In addition, it was clearly observed that there is a high-quality linear curve fit between them (with R^2 value of 0.99). However, a very small scatter in the relation has appeared, this might have resulted from the homogenizing process of soil and lime mixtures during the preparation of samples. Therefore, wave propagation velocity can be used as an indicator for the strength, cementation among particles, and other soil properties.

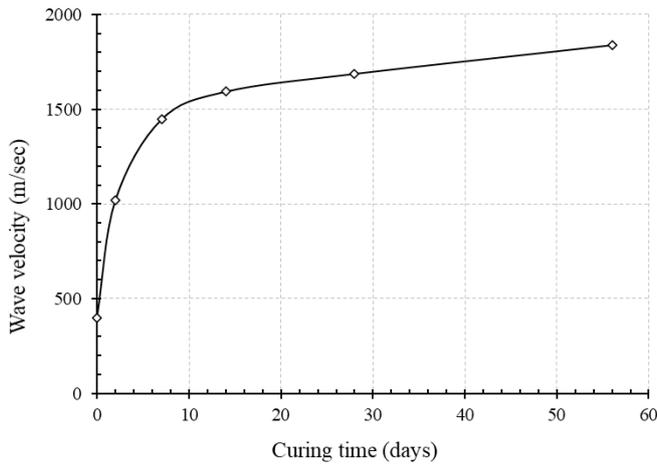


Fig. 15. Wave velocity through specimen variation versus curing times.

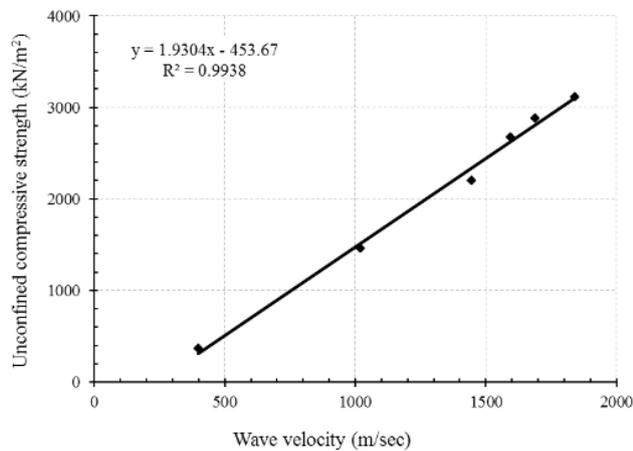


Fig. 16. Correlation between the unconfined compressive strength and wave velocity.

3.5. Soil-water characteristics curve for stabilized specimens

A series of tests were directed to investigate the influence of curing time on the soil-water characteristics curve SWCC of stabilized specimens, the results are presented in Fig. 17. The results of the soil-water characteristics curve were modeled using the software program suggested by Khattab and Al-Taie [20]. The constructed models produce a good correlation with R^2 values greater than 0.99 between the experimental and modeled SWCC curves. It was clearly observed, that in spite of similar trends in the results of lime-treated specimens that were cured for a different time, soil specimens of 56 curing period showed higher volumetric water content value than the specimens cured for other curing periods, and this value increase as curing period increases. In addition, the difference in the volumetric water content becomes close as suction pressure becomes higher. These behaviors may be that lime addition to clayey soil is associated with high moisture loss under curing temperature during the curing period. Furthermore, the results showed that air entry values (AEV) of treated soil specimens become higher as the curing period increase. The reason for this behavior might be the pozzolanic reaction of lime treatment during the curing period results in more cementing materials. The cementing materials fill the pores and capillary channels.

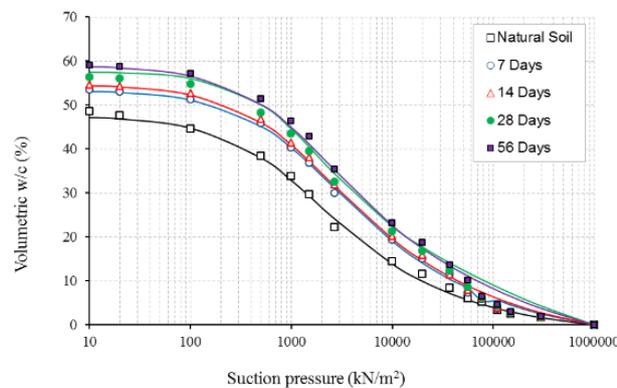


Fig. 17. Soil-water characteristics curves of soil samples with curing times (continuous lines represent the best fitting while the points represent the experimental data).

4. Conclusions

Based on the experimental work and analyses of tests results for the natural clay and lime treated specimens, the following conclusions can be drawn:

- The swelling potential increase significantly during the first cycles of wetting-drying, the amount of these increases is 5.75% for natural clay specimens and about 0.8%, 0.6%, 0.16%, and negligible value for lime treated values carried for 2, 7, 14, 28, 56 days, respectively. While the increase in the swelling percentages decreases gradually and becomes in equilibrium and close to swelling percentages of clay specimens without wetting-drying cycles.
- The swelling potential decrease as the soil stabilized with lime, this response is related to the curing periods, the swelling pressure decreases as the curing period increases.

- Significant crack propagation in the natural soil specimens were observed with wetting-drying cycles, while there are no cracks or micro-cracks shown in treated specimens for all curing periods.
- The addition of lime increased electrical conductivity and pH values of the soil to 4% and then become in equilibrium, while there is a significant reduction in these values as the curing periods increase.
- Significant improvements were observed in unconfined compression strength and wave velocity in lime-treated specimens and related to curing periods. In addition, a good correlation was observed between unconfined compression strength and wave velocity.
- The volumetric water content increases with curing periods and especially at a high curing period of 56 days.

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