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# Geotechnical and other characteristics of cement-treated low plasticity clay

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Article

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Clay soil
Cement stabilization
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**Abstract**

This research work examines the utilization of cement in order to improve low plasticity clay soil. The soil samples treated with 2, 4 and 6% cement percents and cured for different curing times extended to 90 days. Laboratory investigations include unconfined compression, indirect tensile, gas permeability and microstructural tests, which were conducted on the tested samples. The soil-water retention behavior has been also investigated. The test results showed that the cement addition improved both the compressive and tensile strength properties of soil specimens. These strength properties were also increased with curing times. pH and electrical conductivity values were good indicators for the enhancement in the strengths properties. The results of micro structural tests illustrated that the natural soil specimens contain voids and the open structure. Further, these tests showed the cementation of soil grains and filling the voids among soil grains with cementing compounds. Gas permeability and soil-water retention behavior of soil specimens are strongly related to the variations in the soil structures. Further examination illustrated that in the case of low cement content, the pore size distribution (PSD) and the efficiency of gas permeability are more sensitive to curing times.

## 1. Introduction and past studies

The successive urban development in various parts of the world necessitated further improvement of the infrastructure accompanying the constructed facilities. Compacted fine-grained soils are used in the infrastructure earthworks such as the construction embankment of roads, highways, road foundations. Fine-grained soils (especially clayey soils) consider as a problematic soil and can induce damages to roads founded on them, due to their volume changes, higher water content and/or low bearing capacity. The use of ordinary Portland cement; its components or residues; has been widely used in stabilizing cohesionless and some types of problematic soils like clayey soil. Studies conducted in this field may be classified into three main categories: use byproduct from cement production operations, direct use of cement alone or mixed with other materials, and recycling of cement as concrete waste. The use of cement byproduct, especially cement kiln dust to stabilize or improve clay soil was cover by many studies (Adeyanju & Okeke, 2019; Amadi & Osu, 2018; Miller & Azad, 2000; Naseem et al., 2019). The mixing of cement with fly ash become commonly used to reduce the amount of cement used or improve specific geotechnical properties of soil (Amu et al., 2008; Chenari et al., 2018; Khemissa & Mahamedi, 2014). Portland cement was also used with other stabilizing materials to improve the soil engineering properties. Lime is used with cement to improve the soil strength and reduce the swelling and settlement (Amu et al., 2008; Joel & Agbede, 2010; Lemaire et al., 2013; Mousavi & Leong Sing, 2015; Riaz et al., 2014; Saeed et al., 2015; Sharma et al., 2018; Umesha et al., 2009; Wei et al., 2014). Nayak & Sarvade (2012) used cement and quarry dust to improve the shear strength and hydraulic features of lithomarge clay. Ayeldeen & Kitazume (2017) utilized fiber, and liquid polymer to enhance the strength of cement-soft clay blends. The fibers and liquid polymers displayed a notable mechanically, economically and environmentally prospects to be used as an additive to cement in improving the soft clay. Also, organic soils have become the target of many studies that have addressed improving the properties of these soils by adding cement and other materials (Kalantari & Huat, 2008; Kalantari & Prasad, 2014). Moreover, Osinubi et al. (2011) used ordinary Portland cement –Locust bean waste ash mixture to enhance the engineering properties such as (UCS) and California bearing ratio (CBR) for black cotton clayey soil. Crushed concrete waste, which represents the last form of cement used, has been used in many studies to improve the properties of clay soils (Abdulnafaa et al., 2019;

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Cabalar et al., 2016, 2017, 2019a, b; İşbuğa et al., 2019). The main purpose of adding ordinary Portland cement to cohesionless soils is to provide strong bonds between soil particles (Consoli et al., 2011, 2017). Al-Aghbari et al. (2009) used cement and cement dust to stabilize desert sands. The results showed that the cement and cement by-pass dust could be used to improve the compressibility and shear strength characteristics of desert sands. Also, Saberian et al. (2018) studied the stabilization of marine and desert sands with deep mixing of cement and sodium bentonite and found an improvement in the geotechnical properties of these soils. Shooshpasha & Shirvani (2015) reported that the use of cement to stabilize sandy soils resulting in increased strength parameters, reduced strain at failure, and changed soil behavior to a noticeable brittle behavior. Iravanian & Bilsel (2016) studied the sand-bentonite landfill barrier material with and without cement additive, at different periods of aging. The strength characterization of mixtures was a marked improvement with cement inclusion and that the effect of aging has been very effective.

The clay-cement reaction produce primary and secondary cementations materials in the soil-cement matrix (chew et al., 2004). Cement has two chemical reactions; the first one begins at the time of adding the water to the fine soil-cement mixture and the second one is the secondary reaction occurs as the calcium ions diffuse through the soil (Chen & Wang, 2006; Chew et al., 2004). These chemical reactions are responsible for the strength development in cement-treated soils. The geotechnical properties of cement-treated clay soils have been investigated by different researchers (Consoli et al., 2010; Goodary et al., 2012; Kalıpcılar et al., 2016; Kasama et al., 2000; Kenai et al., 2006; Lorenzo & Bergado, 2004; Okyay & Dias, 2010; Park, 2011; Petchgate et al., 2001; Saadeldin & Siddiqua, 2013; Zhang et al., 2014). Common Portland cement was used to improve shear resistance and durability of clay soils. The unsaturated properties of cement-treated clay soils were observed by different studies (Attom et al., 2000; Azam & Cameron, 2013; Nahlawi et al., 2004). Horpibulsuk et al. (2012) found that the strength of clay is governed by the clay-water/cement ratio. The strength increases with the decrease in the clay-water/cement ratio. (Horpibulsuk et al., 2012) studied the microstructural characteristics of cement-stabilized soils and found that soil behavior enhanced significantly. The optimum dosages of cement added to clay soil to improve some geotechnical properties were investigated by Rojas-Suárez et al. (2019a, b). Korf et al. (2017) observed the hydraulic and diffusive behavior of compact clay soil, with and without cement addition. The results of the reactive behavior analysis showed that the retention by adsorption increased with the increase of pH, but it was not affected by the applied static load.

In summary, many interesting results indicating the potential of the use of ordinary Portland cement to improve clayey soils have been reported. This study aims to extend and increase the knowledge of the clayey soil-cement stabilization technique.

## 2. Materials and testing methods

### 2.1 Materials

Two materials were used in this experimental work: clayey soil and cement. The soil was obtained from a depth of 1.5 m from the ground surface. The soil samples were oven-dried for 2 days at 60 C° and passed through a 4 mm sieve before use in various tests. The soil specific gravity was 2.68, the liquid limit was 35% and the plasticity index was 16%. All the chemical and physical properties tests were carried out following the ASTM standards and test procedures adopted by Aldaood et al. (2014a). The sample is categorized as CL following the Unified Soil Classification System (USCS). The X-ray diffraction test results presented that the main clay mineral was kaolinite and the non-clay minerals were quartz and calcite. Table 1 presents some properties of the clay soil used in the experimental program.

The stabilizing agent used for this study was ordinary Portland cement. The specific gravity is 3.13 and the specific surface is 3790 ($cm^2$/gm). The main composition of cement is (CaO is 63.1%, $SiO_2$ is 19.4% and $Al_2O_3$ is 5.4%). The loss on the ignition of the cement is 2.33%.

### 2.2 Sample preparation

An oven-dried soil was mixed with a pre-determined quantity of ordinary Portland cement (2%, 4% and 6% of dry soil weight) in dry condition. The soil specimens were prepared at the optimum moisture content of natural soil (i.e. 11%). The formation of lumps was avoided when the water was added to the soil-cement mixture. The soil-cement mixture kept in the plastic bags then left for 10 minutes

**Table 1.** Chemical and physical properties of the natural soil.

| Properties | | Value |
|---|---|---|
| Liquid Limit (%) | | 35 |
| Plastic Limit (%) | | 19 |
| Plasticity Index (%) | | 16 |
| Total Soluble Salts (%) | | 3 |
| Specific Gravity | | 2.68 |
| pH | | 8.2 |
| Electrical Conductivity (mS/cm) | | 0.42 |
| Gravel (%) | | 7 |
| Sand (%) | | 18 |
| Silt (%) | | 56 |
| Clay (%) | | 19 |
| Wave Velocity (m/sec) | | 540 |
| Gas Permeability ($m^2$) | | 2.20E-13 |
| Unified Soil Classification System (USCS) | | CL |
| Standard Compaction | Optimum Moisture Content (OMC) | 11% |
| | Max. Dry Unit Weight ($kN/m^3$) | 17.5 |

for homogeneity (Khattab & Aljobouri, 2012). After that, the soil specimens were statically compacted in a specific rigid mold related to the type of the test. A standard Proctor compaction test (ASTM, 2003) was adopted in the preparation of soil-cement specimens to obtain the maximum dry density of natural soil. All treated and untreated specimens were compacted statically to dry density of (17.5 kN/m$^3$), which is the maximum dry density of natural soil. After compaction, the treated soil specimens were wrapped in cling film and coated with paraffin wax to prevent moisture loss, then specimens were left at room temperature of 20 C$^\circ$ for different periods of 3, 10, 30, 60 and 90 days to be cured.

### 2.3 Testing methods

The pore size distribution and microstructural characteristics of the natural soil and cement-treated soil specimen were measured using a scanning electron microscope (SEM) and porosity tests. These tests were conducted on the natural and cement-treated soil specimens, following the test procedures suggested by Aldaood et al. (2014b)

To conduct the UCS, a cylindrical (50 mm diameter × 100 mm height) soil specimens were statically compacted at the optimum moisture content and maximum dry unit weight obtained from the standard compaction curve of natural soil. The rate of compaction was (1 mm/min) to obtain a uniform unit weight of the soil sample. The UCS has been determined according to the ASTM D-2166 and D-1633 (ASTM 2000). procedures for untreated and cement-treated soil samples, respectively. Before testing, the wave velocity of the soil specimens was determined using A PUNDIT device with a frequency of 82 kHz.

The commonly used alternative procedure for the determination of tensile strength is the Brazilian tensile test, which is generally referred to as the (ITS) (Das et al., 1995). The soil specimens were prepared in a metal mold with dimensions of (50 mm high and 25 mm diameter). The soil specimens were compacted statically, at the same rate as for preparing the UCS specimens. After the preparation of the natural soil specimens, they were extracted from the stacking mold and tested. While the cement-treated specimens are encapsulated as in the UCS test and exposed to the same curing time before tested. The ITS test was performed according to the method approved by the ASTM (2011), by applying compressive strength along the diameter of the model and with the rate of the unconfined compressive resistance test (1.27 mm/min) until the specimens fail. The (ITS) is calculated using Equation 1

$$S_t = \frac{2P_{\max}}{\pi t d} \quad (1)$$

where $S_t$ is the indirect tensile strength and $P_{max.}$ ; is the maximum applied load on the sample; t is the average height of the sample with d as diameter.

For For pH and electrical conductivity test (EC), a portion of failed (tested) samples in the UCS test was used to determine the pH and EC values, following the tests procedures suggested by (Eades & Grim, 1966; Aldaood et al. 2014a).

For gas permeability, the test procedure suggested by Aldaood et al. (2016) was adopted to measure the gas permeability of cylindrical soil specimens of 50 mm diameter and 50 mm height. The soil specimens were statically compacted inside a cylindrical metal mold so that it reached the maximum dry unit weight of natural soil. The gas permeability specimens were exposed to different curing times as the specimens for UCS and ITS tests. The coefficient of gas permeability was estimated using the modified Darcy's equation as follows:

$$K_A = \frac{Q}{A} \times \frac{2\mu L P_{atm}}{\left(P_i^2 - P_{atm}^2\right)} \quad (2)$$

where: Q is the volume flow rate (m$^3$/sec), L is the thickness of the sample (m), μ is the viscosity (1.76*10$^{-5}$ Pa.s for nitrogen gas at 20 °C), $P_{atm}$ is the atmospheric pressure (Pa) and $P_i$ is the injection pressure (Pa), A is the cross-sectional area of the sample (m$^2$).

It worth noting that, the measurements of permeability were conducted in an air-conditioned room having a constant temperature of 20 °C. Each permeability test involved four measurements of apparent permeability at various injection pressures.

The soil–water retention curve (SWRC) of natural and cement-treated soil specimens was determined by using the vapor equilibrium technique, osmotic membrane, and tensiometric plates. The vapor equilibrium technique was used to evaluate the SWRC in suction pressure more than 1500 kPa. The osmotic membrane determined the SWRC in the suction pressure range of 100 kPa and 1500 kPa. The evaluation of the SWRC continued in low suction pressure ranging between 10-20 kPa by using tensiometric plates. The required time to reach the balance condition (in the determination of the SWRC) varied between 20-35 days, depending on the desired technique. More details about these techniques can be found in Aldaood et al. (2015). It worth noting that, all the previous SWRC determination techniques were carried at room temperature of (20 °C).

## 3. Results and discussion

### 3.1 Assessment of pH and Electrical Conductivity (EC)

The pH values of cement-treated soil specimens before and after curing were determined. Cement addition increases the pH value from (8.2) for natural soil to 12.5 for 6% cement-treated soil specimens, which promotes cation exchange (due to increasing calcium $Ca^{++}$ ions). In the literature (Al-Mukhtar et al., 2014; Eades & Grim, 1966; Feng et al., 2001), it was agreed that the pH value of 12.5 represent the necessary value to get a favorable environment for producing the cementing materials, and thus, the development of acceptable mechanical performance. Table 2 shows the changes in pH and EC values of cement-treated soil specimens after various curing times. It is observed that

**Table 2.** Variation of pH and electrical conductivity values of soil specimens with cement content and curing times.

| Curing Time (day) | pH value | | | EC (mS/cm) | | |
|---|---|---|---|---|---|---|
| | 2% Cement | 4% Cement | 6% Cement | 2% Cement | 4% Cement | 6% Cement |
| **3** | 12.2 | 12.3 | 12.4 | 2.5 | 3 | 3.7 |
| **10** | 12.1 | 12.2 | 12.3 | 2.18 | 2.63 | 3.44 |
| **30** | 11.85 | 12.0 | 12.1 | 1.9 | 2.21 | 3 |
| **60** | 11.5 | 11.8 | 11.9 | 1.66 | 2 | 2.76 |
| **90** | 11.2 | 11.65 | 11.7 | 1.43 | 1.8 | 2.57 |

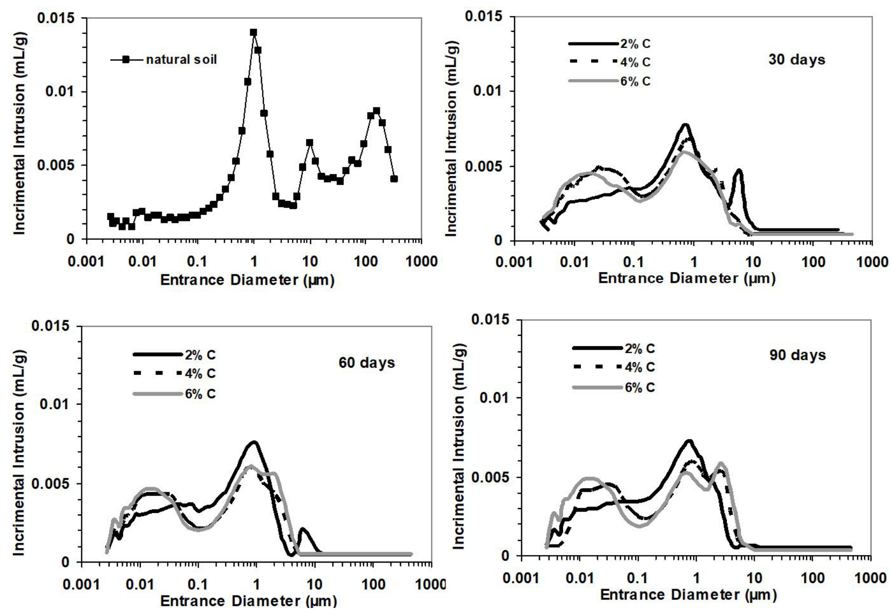


**Figure 1.** PSD of natural and cement-treated soil specimens with different cement content and curing times.

the pH values of soil specimens decreased slightly as the curing time increased. More reduction in pH occurs for low cement content and high curing time and the value reached 11.2. At this level of pH value, the pozzolanic products such as (CSH and CAH) will continue. (Al-Mukhtar et al., 2014) reported that, as calcium cation is existed and the pH is high enough (more than 10.5), the pozzolanic reaction continues. Moreover, Chen & Wang (2006) documented that, when pH value (≤ 9) low level of hardening will produce or even no hardening. The reduction in pH values of soil specimens related to the reduced amount of $Ca^{++}$ and $(OH)^{-}$ ions due to the development of the pozzolanic reactions.

The electrical conductivity values (EC) of soil specimens followed the same trend as pH values. Cement addition causes an increasing in EC values from (0.42 mS/cm) for natural soil to (3.9 mS/cm) for 6% cement-treated soil specimens. This increasing related to the existing high calcium ions in adding cement (CaO is 63.1%). As the curing time increases, the EC value of soil specimens continues to down, but slightly. The reduction in EC values related to the consumption of calcium ions during the pozzolanic reactions. Finally, obtaining pH and EC values corroborate the next-obtained results of unconfined compressive and indirect tensile strengths, where significant cementing materials (such as CSH and CAH) were formed.

### 3.2 Microstructural characterization

Microstructural analyses were carried out to investigate the variations in the microstructure of the cured specimens and for natural soil as a comparison. These analyses helped in understanding the increase in strength of cemented soil specimens at a microscopic level. The analysis focused on the formation of cementing materials named calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH); which normally presented in lime and cement stabilized soils (Aldaood et al., 2014a; Mengue et al., 2017). Figure 1 presents the pore size distribution (PSD) of natural and cement-treated soil specimens. The natural soil specimens exhibited a tri-modal PSD with a large number of macrospores centered at (1–200 μm) and with a less pronounced peak centered at (0.01 μm). The PSD curve of natural soil supported the SEM results, where the texture of the natural soil specimens exhibited a fairly open type of microstructure, as illustrated in Figure 2. Besides, many coarse grains (sand grains) relatively well calibrate and assembled with fine grains (clay grains) in a dispersed arrangement, resulting to form many voids in different dimensions.

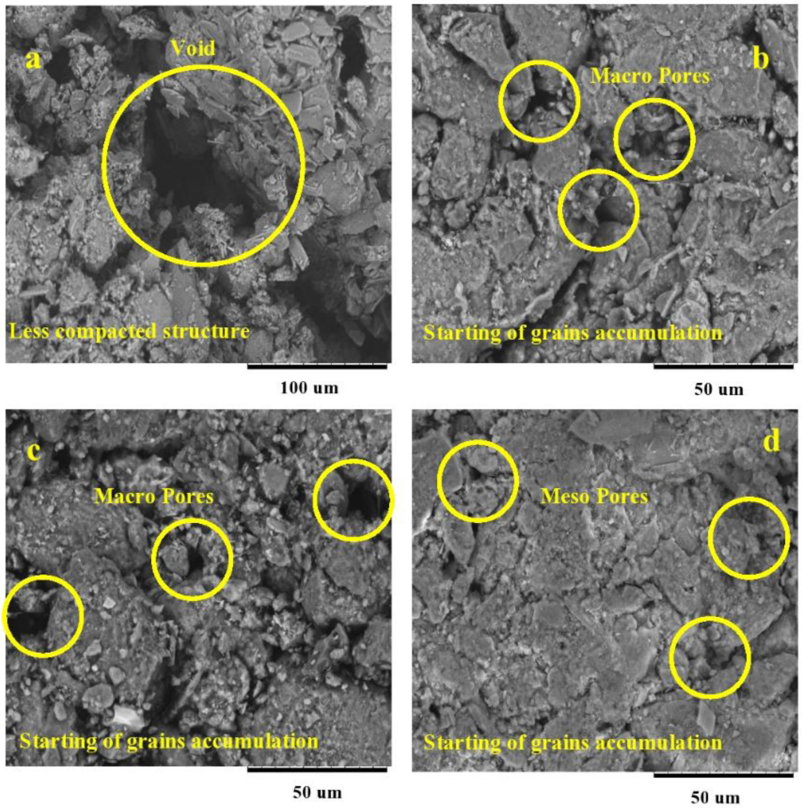


**Figure 2.** SEM images (a) natural soil (b, c, d) 30 days cured specimens treated with 2, 4 and 6% cement content, respectively.

Cement addition enhanced the PSD of soil specimens by decreasing the amount of macropores (> 10 μm) and increasing the micropores (≤ 0.01 μm), see Figure 1. The changes in the PSD of cemented soil specimens related to that, the pores (especially macrospores) covered and filled by the hydrated cement. During cement addition and with the presence of water, the clay and cement particles grow together to large clusters. Then cement gel is stable in macropores and micropores due to the attractive forces, leading to enhance PSD of cemented soil specimens (Horpibulsuk et al., 2009, 2010). Further, as the curing times increase the hydration products grow and cause more reduction in the macropores. An investigation of the structure of the cemented soil specimens allowed to reflect the changes in the structure of specimens from open structure to denser one with fewer voids formation (Figure 2). Further, as the cement content increase, the soil structure became tighter than the structure of natural soil and the cluster of grains become more effective (Mengue et al., 2017). It is noting that the cement addition was more affected on the PSD of soil specimens than curing times, as presented in Figure 1.

### 3.3 Unconfined Compressive Strength characteristics (UCS)

The results of USC for cement-treated soil specimens were illustrated in Figure 3. This figure also presents the effect of curing time on the UCS. The results suggest that

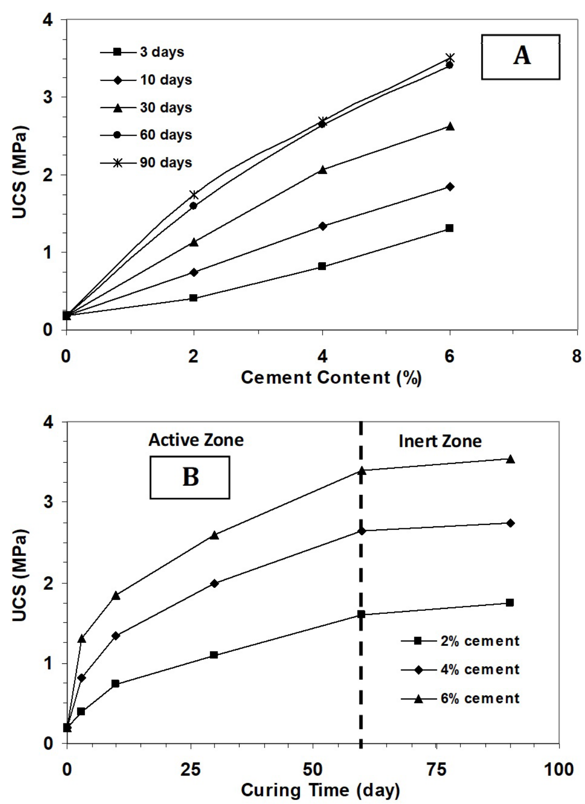


**Figure 3.** UCS of soil specimens with (A) cement content and (B) curing times.

the cement content has a significant effect on the strength characteristics of soil specimens and the UCS of soil specimens increase with cement content. The increase in the UCS was approximately linearly with the increase in the cement content. This finding is consistent with the findings of previous studies by (Chenari et al. (2018) and Pakbaz & Alipour (2012). The increase in USC with increasing cement content was attributed to the pozzolanic reactions between soil and cement mixtures. The pozzolanic reactions resulting in the formation of cementing compounds named calcium silicate hydrate (CSH) and calcium aluminate hydrates (CAH). These cementing compounds enhanced the inter-cluster bonding strength and filled the pore space between soil particles (see Figure 1). As a result, the strength values (i.e. UCS and ITS) of the soil specimens increased with an increase in cement content (Sharma et al., 2018). Moreover, as the cement content increases, the contact points among cement and soil particles increases and, upon hardening, gives a suitable amount of bonding at these points. Further, during cement addition, the flat and smooth particles of soil disintegrate into rough and crumbled portions and this behavior improves the cohesion value among the particles, which then increases the strength values. It worth noting that, the development of white cementing compounds (CSH and CAH) on the surfaces of soil particles aids as an indicator of the pozzolanic reactions, as illustrated in Figure 4. Similar results have been noticed for various types of soil (Lemaire et al., 2013; Sharma et al., 2018).

The role of curing time on the strength improvement of the cement-treated soil specimens was illustrated in Figure 3B. It is observed that as the curing times increased, the UCS increased. At specific cement content, the UCS increased significantly until a curing time of 60 days. After 60 days of curing, the UCS increases gently as shown in Figure 3B. The UCS increase can be classified into two zones. As the curing times increase up to 60 days, the UCS increased and this zone is referred to as the active zone. After this zone, the UCS improvement slows down while still gradually increasing and this zone is designated as the inert zone. This behavior may be due to that kaolinite is exhausted by the pozzolanic reactions, which lead to reducing the action of pozzolanic reaction with increasing curing time. Besides, the continuous reduction in water content during curing times could affect the pozzolanic reactions. Great attention has been given to calculating the residual water content (RWC) of the soil samples, as shown in Figure 5. RWC means the water content of soil samples after the end of specific curing time. The RWC decreased with the increasing of curing time and cement percentages. Most reduction in water content occurs during the first times of curing until 60 days, after that the reduction in water content continued slightly. The reduction in the RWC could be due to the hydration process of cement and to completion of the pozzolanic reactions. It worth noting that, all the UCS curves (for all cement content) follow the same pattern with curing times.

The stress-strain of UCS test results is presented in Figure 6. Results showed that the failure strain decreases considerably as the cement content and curing time increases. While the slope of the stress-strain curves (before and after the maximum stress value), increases with increasing both cement content and curing times. This means that the utilization of cement addition increased the UCS, reduced the strain at failure, and changed the soil behavior from ductile to brittle behavior. The influence of curing times on the stress-strain curves was more pronounced for higher cement content. Many researchers reported that the natural soil specimen exhibited ductile behavior; while the stabilized soil specimen posed brittle behavior (Horpibulsuk et al., 2012; Mousavi & Leong Sing, 2015). It worth noting that, all the stress-strain curves were similar, except the difference in the maximum stress values.

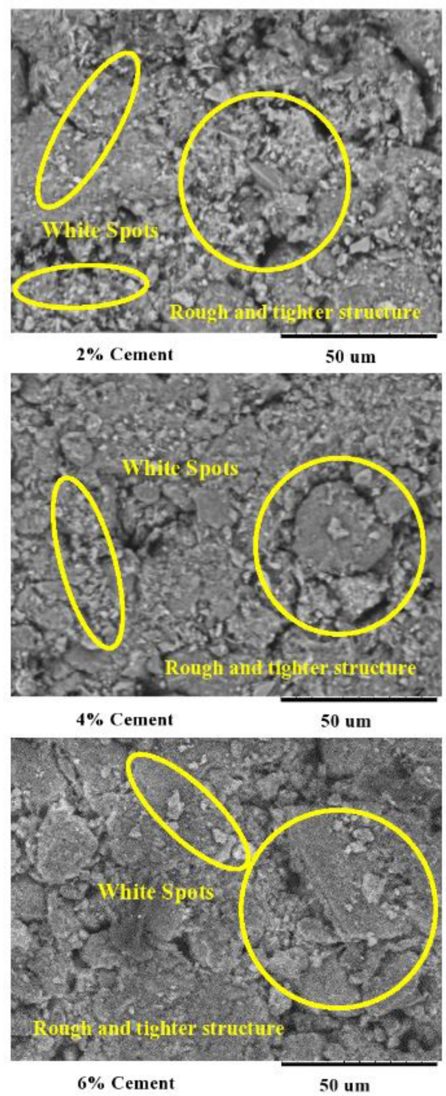


**Figure 4.** SEM images of cement-treated soil specimens cured for 90 days showing the roughness of the soil structure.

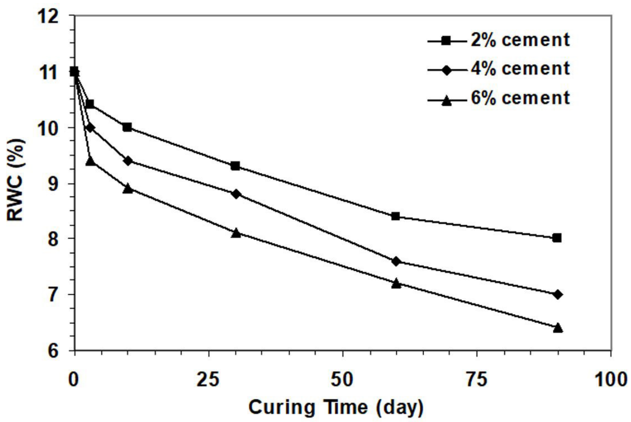


**Figure 5.** RWC of cement-treated soil specimens cured for different curing times.

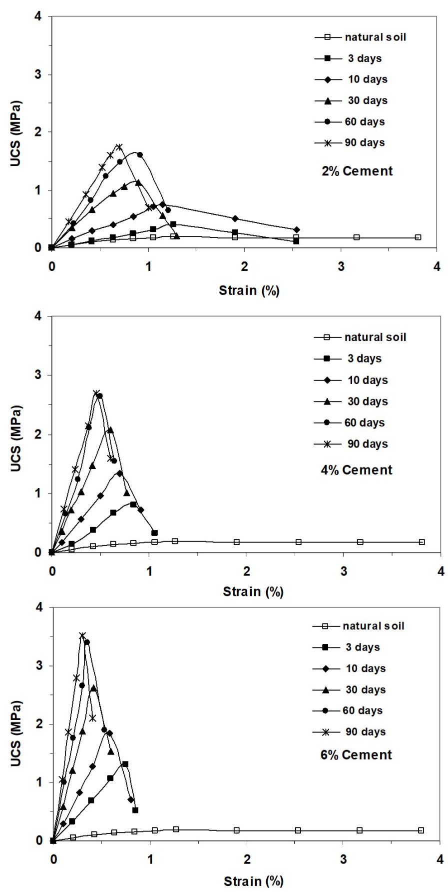


**Figure 6.** Stress-strain curves of cement-treated soil specimens cured for different curing times.

## 3.4 Indirect Tensile Strength characteristics (ITS)

The ITS test results of cement-treated soil specimens were shown in Figure 7. The data show a significant increase in the ITS of treated soils in comparison to the natural soil. It is also shown that the tensile strength increases linearly with the increase of both cement content and the curing times. The linear increase in ITS with a high slope at 3 days of curing was attributed to the short-term reactions and

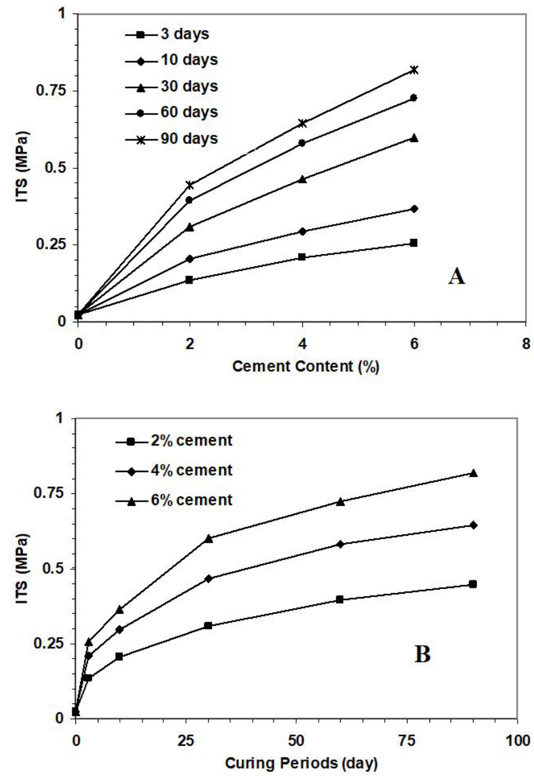


**Figure 7.** ITS of soil specimens with (A) cement content and (B) curing times.

cement hydration. Further, this behavior largely depended on the cement content. As the curing times increase the ITS was likely to be more reliant upon the pozzolanic reactions. Also, Figure 7B implies that ITS improvement for all cement contents starts to moderate beyond 60 days of curing. This is consistent with the steady of the pozzolanic reaction at high curing times (more than 60 days). The most obvious explanation for this significant increase in the ITS is that this strength is indirectly calculated and is based on the compression pressure ($P_{max.}$) used in Equation 1. Thus, the same reasons considered to explain the increase in UCS can be used to illustrate the significant increase in ITS values.

## 3.5 Wave velocity results

A wave velocity test was performed on natural and cement-treated soil specimens, and the results were presented in Table 3. The results show that the wave velocity increases with increasing both cement content and curing times and followed the same trend as UCS. In general, the increase in wave velocity from the value of natural specimens to the 3 days of curing was more pronounced than the increase from 3 days to 10 days of curing. Sequentially, this value was more than other intervals of curing times (i.e. the interval between 10 to 30 days, etc.). As the curing times increase, the reactions between the soil particles and cement increased and result to increase the stiffness of the soil specimens. As a result, the wave velocity propagation increased with increasing

**Table 3.** Variation of wave velocity values of soil specimens with cement content and curing times.

| Curing Time (day) | Wave Velocity (m/sec) | | |
|---|---|---|---|
| | 2% Cement | 4% Cement | 6% Cement |
| **3** | 890 | 965 | 1115 |
| **10** | 1045 | 1200 | 1385 |
| **30** | 1350 | 1625 | 1880 |
| **60** | 1550 | 1780 | 2060 |
| **90** | 1620 | 1850 | 2170 |

both cement content and curing times. Mandal et al. (2016) documented similar test results. Besides, Yesiller et al. (2000) reported that the wave velocity of cement-treated soil specimens was higher than the wave velocity of the natural specimens.

Further, the cementing compounds and the unreacted cement help to filling the voids among soil particles, resulting to create other paths with short traveling times. This behavior increases the wave velocity values of soil specimens.

### 3.6 Gas permeability results

Gas permeability is the capacity of soil to allow air to flow in the existence of a pressure gradient. In this research, gas permeability is used as a pointer of the structural changes of soil specimens. The use of gas permeability rather than water permeability avoids the interaction of water with the soil-cement mixtures. The variations of coefficient of gas permeability (Ka) values with both cement content and curing times were illustrated in Figure 8. In general, the Ka of soil specimens decreased with increasing both cement content and curing times. The values of Ka decreased from ($2.2 \times 10^{-13}$ $m^2$) of natural soil to ($8.9 \times 10^{-14}$, $7.6 \times 10^{-14}$ and $6.8 \times 10^{-14}$ $m^2$) of soil specimens treated with 2, 4 and 6% cement content respectively, and cured for 3 days. While the values of soil specimens cured for 90 days were ($4.9 \times 10^{-15}$, $2.4 \times 10^{-15}$, and $8.4 \times 10^{-16}$ $m^2$) of soil specimens treated with 2, 4, and 6% cement content respectively. It is well known that the voids and pores (macropores and micropores) of soil specimens play a major role in the gas permeability values (Aldaood et al., 2016; Wang et al., 2017). As discussed previously in section (3.2), the PSD of soil specimens mainly affected by cement content and curing times. Before cement addition (i.e. natural soil), the pores available for gas flow are larger (see Figures 1 and 2), resulting in larger values of Ka. Again, the Ka is a function of two parameters: the porosity and the interconnectivity between the pores (Aldaood et al., 2016). When the cement was added and the soil specimens cured for different times, both porosity and the interconnectivity between the pores decreased due to the formation of cementing compounds during the pozzolanic reactions. As a result, the Ka decreased with both cement content and curing times. Further, it is observed that the decrease in Ka values from the value

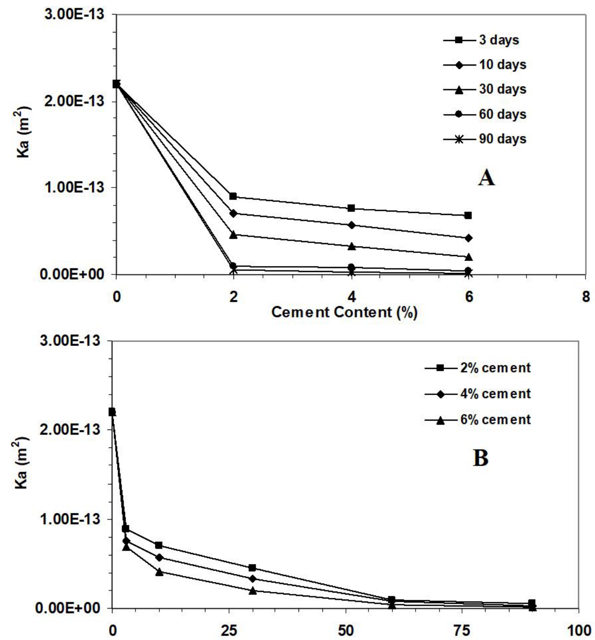


**Figure 8.** Gas permeability of soil specimens with (A) cement content and (B) curing times.

of natural specimens to the 60 days of curing was more pronounced than the decrease from 60 days to 90 days of curing. This behavior is attributed to the formation of most cementing compounds (as discussed previously) and these compounds will bound the soil grains and hinder the gas flow in soil specimens. Therefore, the Ka values of soil specimens decreased. Another reason to decrease the Ka values (especially at short curing times) of soil specimens was the unreacted cement particles which act as a filler and fill the voids among soil particles, leading to enclosed the voids and decreasing the gas permeability.

### 3.7 Soil-water retention behavior

The soil-water retention curves (SWRC) referring to both cement content and curing times were plotted together to comment on the general shape of the SWRCs and whether these curves affected by the cement content and curing times. Figure 9 presents the influence of the cement content and curing times on the SWRCs in terms of suction pressure and volumetric water content. In general, the cement addition and curing times have an insignificant influence on the shape of the SWRC, and all curves having an S-shape curve. For all cement contents, the SWRCs of soil specimens cured for 90 days were lie above the other curves (see Figure 9). This behavior was attributed to high capillary and absorptive forces resulting from finer soil structure (Aldaood, 2020). Moreover, the influence of curing times on the SWRCs was larger at low suction pressure than at high suction pressure. Another interesting observation from Figure 9 is that there was a continuous reduction in the volumetric water content of soil specimens with increasing suction pressure. This reduction was found to be dependent

**Table 4.** Variation of volumetric water content values of soil specimens with cement content and curing times.

| Curing Time (day) | θ at 10 kPa (%) | | | θ at 1500 kPa (%) | | |
|---|---|---|---|---|---|---|
| | **2% Cement** | **4% Cement** | **6% Cement** | **2% Cement** | **4% Cement** | **6% Cement** |
| **30** | 35.7 | 39.0 | 46.5 | 25.3 | 27.2 | 29.6 |
| **60** | 42.4 | 45.3 | 51.0 | 29.1 | 31.5 | 35.2 |
| **90** | 54.2 | 59.2 | 66.0 | 33.8 | 35.7 | 40.2 |

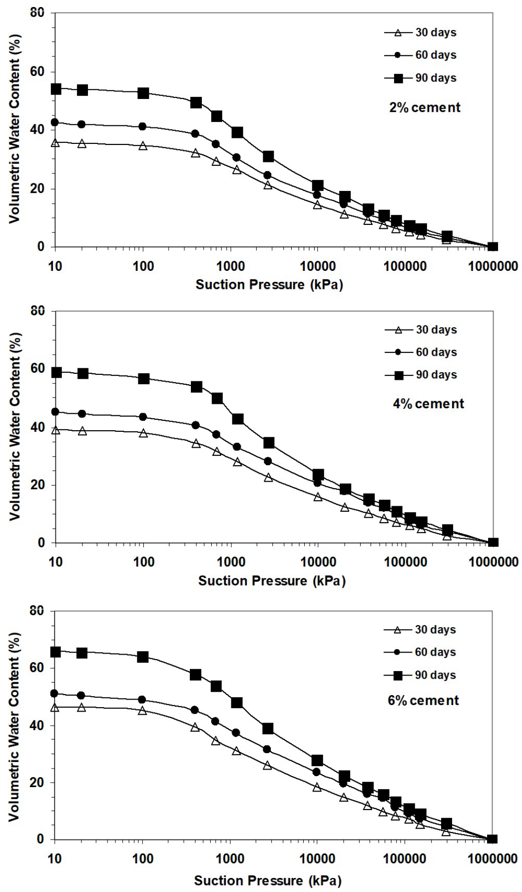


**Figure 9.** SWRCs of soil specimens with various cement content and curing times.

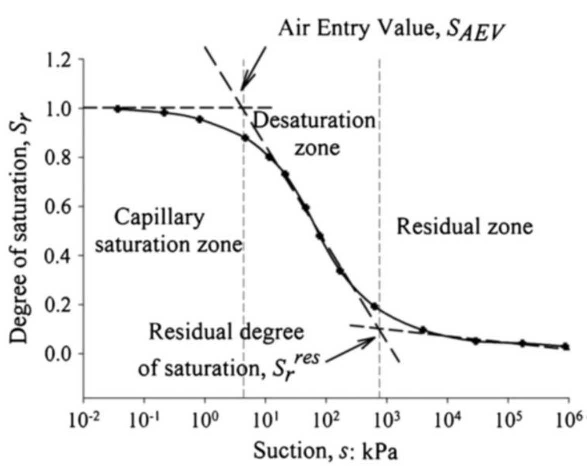


**Figure 10.** Typical SWCC showing the saturation, desaturation and residual zones (Vanapalli et al., 1999).

on both cement content and curing times as presented in Table 4. The differences between the volumetric water content values of soil specimens were obvious at suction pressure lower than 1500 kPa. While at suction pressure larger than 1500 kPa the differences in values were slight particularly for soil specimens cured at 60 and 90 days. This behavior is attributed to the more pozzolanic reactions in the soil specimens. Certainly, increasing curing time promotes the pozzolanic reaction within the soil mixture and resulting to the development of cementing materials (i.e. CSH and CAH), so that they help to the change in the PSD of soil specimens as discussed previously. Moreover, cement addition can help to enhance the microstructure properties of soil specimens, thus make the PSD more uniform and improving the water-holding performance of treated soil specimens (Jiang et al., 2019).

The key parameters of SWRC were established using the method suggested by Vanapalli et al. (1999), as illustrated in Figure 10. The main zones (states) of the SWRC are saturated and residual zones. The saturation volumetric water content **(**$\theta_a$**)** and the air entry value AEV **(**$\Psi_a$**)** represented the saturation state. While the residual volumetric water content **(**$\theta_r$**)** and the corresponding residual suction pressure **(**$\Psi_r$**)** represented the residual state. As the suction pressures of soil specimens increased from 10 kPa to the AEV the volumetric water content of the soil specimens was approximately constant. Beyond the AEV, there was a continuous reduction in the volumetric water content of the soil specimens with increasing suction pressure. Further, the slope of the SWRCs of soil specimens cured for 90 days in part between the AEV and the residual water content was larger than the slope of other parts. This means that the soil structure was uniform and compact then resulting in better water holding capacity (Aldaood et al., 2014). Table 5 presents the saturation and residual state values of soil specimens with all cement contents and curing times. It is observed that both **(**$\theta_a$**)** and **(**$\theta_r$**)** increased with increasing cement content and curing times. The increase in **(**$\theta_a$**)** was greater than the increase in **(**$\theta_r$**)**. The AEV showed insignificant changes with cement addition and curing times. Further, no obvious relationship was observed for the residual suction pressure with cement content and curing times. The difference in saturated and residual states values with cement content and curing times reveals the mineralogical and microstructural variations in soil specimens as discussed in section 3.2.

**Table 5.** Saturation and residual states values of soil specimens with cement content and curing times.

| Curing Time (day) | Cement Content (%) | Saturation State | | Residual State | |
|---|---|---|---|---|---|
| | | Air-Entry Value, $\Psi_a$ (kPa) | $\theta_a$ (%) corresponding to $\Psi_a$ | Residual Suction, $\Psi_r$ (kPa) | $\theta_r$ (%) corresponding to $\Psi_r$ |
| 30 | 2 | 200 | 35.7 | 30000 | 8 |
| | 4 | 240 | 39.0 | 12000 | 11 |
| | 6 | 255 | 46.5 | 20000 | 13 |
| 60 | 2 | 205 | 42.4 | 17000 | 10 |
| | 4 | 245 | 45.3 | 13000 | 13 |
| | 6 | 255 | 51.0 | 18000 | 15 |
| 90 | 2 | 210 | 54.2 | 16000 | 12 |
| | 4 | 260 | 59.2 | 28000 | 14 |
| | 6 | 270 | 66.0 | 14000 | 21 |

## 4. Conclusions

The following conclusions can be driven from this study:

- Increasing both cement content and curing times increased the strengths properties and wave velocity values of soil specimens. On the other hand, the gas permeability, pH, electrical conductivity values, and the failure strain were decreased with increasing curing times;
- The strength improvement of cement-treated soil specimens with curing times is divided into two zones: active and inert zones. Inactive zone the soil structure became compactness rather than the structure of natural soil and the cluster of grains become more effective. In the inert zone, there were insignificant changes in soil structure, thus there was a slight increase in strength value;
- Cement addition and curing times considerably modified the microstructural behavior of soil specimens. Cement content enhanced the volume and the morphology of pores (particularly the macropores), suggesting more cementing compounds formed and its action was more than the curing times;
- Interesting agreements between the microstructural, mechanical, and unsaturated hydraulic properties were obtained. Whereas the states of pores over time mainly affect the strength, gas permeability, and soil-water retention behavior;
- The AEV of soil specimens did not affect considerably with cement content and curing times. While the water holding capacity of soil specimens increased with these parameters. The most influences of cement content and curing times were on the part of SWRC with suction pressure smaller than 1500 kPa.

## Declaration of interest

The authors declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

## Author's contributions

Ibrahim M. Alkiki: investigation, methodology, validation. Mohammed D. Abdulnafaa: data curation, writing - original draft preparation. Abdulrahman Aldaood: writing - reviewing and editing.

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