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ORIGINAL PAPER

Geotechnical characterization of a clay–cement mix

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Abstract Soft clay deposits are highly plastic, normally consolidated fine grained soils characterized by their low inherent shear strength. The mixing of soft clays with cement as a chemical stabilizer has become a well-known stabilization technique. The resulting strength of the clay–cement mix is controlled by different factors, but mainly the water to cement ratio, the cement content, and the curing conditions. It is crucial to develop a clear understanding of the changes in engineering behavior of the clay–cement mix that result from changes in controlling factors. A phase diagram was established to define the initial conditions of the mass–volume relationships of air, cement, clay, and water of a typical clay–cement mix. This phase diagram was then used to determine the total dry density, void ratio, and specific gravity of the clay–cement mix as a function of the cement content and water to cement ratio. The main objective of this work was to develop generalized trends for the geotechnical properties of clay–cement mixes. These trends were evaluated based on unconfined compressive strength as well as consistency tests carried out on soft clay samples before and after mixing with cement and at different curing times. A reduction in the plasticity index (PI) of 16 % and an increase in the unconfined shear strength of more than 200 kPa were obtained from the addition of 15 % cement. The reduction in the PI of the clay–cement mix was found to be an efficient tool to represent the improvement in the strength of the clay after mixing with cement.

Keywords Soft clay · Clay–cement mix · Curing time · Unconfined compressive strength · Volume–mass relationships · Soil stabilization

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Introduction

The main engineering challenges presented by construction on soft clay deposits are low shear strength (typically <25 kPa) and bearing capacity. Foundation design on soft clay has been a continuous source of concern for engineers since the beginning of geotechnical engineering (Chen and Morris 2000). These design concerns include the factor of safety against shear failure and overall stability. The key characteristics of the performance of natural clays include time/rate dependency, strength/stiffness anisotropy, and structure/destructuralization (Grimstad et al. 2010). The engineering behavior of soft soils is controlled by the parent material's source, depositional processes, erosion, re-deposition, consolidation, and fluctuations in groundwater levels (Gue and Tan 2000). The physical and mechanical properties of soft clays usually vary significantly due to the variations in sedimentary processes associated with different environmental conditions (Ho and Chan 2011).

Cement stabilization of soft clay soils has become an efficient ground improvement technique, and it has been attempted with much success over the last few years. Chemical stabilization of soft soils has been extensively applied in both shallow and deep applications to improve inherent soil properties such as shear strength and compressibility indices (Bergado et al. 1996; Chen and Wang 2006). Mass stabilization with cement has been successfully used to treat soft clays, saving time in comparison with other ground improvement techniques, such as preloading (AASHTO and FHWA 2003). Cement stabilized soils were found to be a reliable engineering alternative to satisfy the entire requirements of sustainable infrastructure. The increased bearing capacity of chemically stabilized subgrades can result in a significant reduction of the required base course layer thickness of highways (Austroads 1998).

Field applications of cement stabilization of soils have recently become more feasible due to the development of commercial stabilization systems that are able to stabilize soft soils up to a depth of about 5.0 m. Stabilizing the upper 3.0–5.0 m of soil materials by mixing the soil with a stabilizing agent (mass mixing) is an optimum foundation improvement technique for highway construction. Cement stabilization of soft clays is commonly accomplished through the addition of dry or wet cement to the volume of the soil. Stabilization of the soft clays occurs when both the cement and water react to form cementitious calcium silicate and aluminate hydrates while binding the soil particles together (Ho and Chan 2011). The work described in the present paper was intended to aid geotechnical engineers in finding a quick estimation of engineering properties of a clay–cement mix. Generalized volume–mass relationships were established in order to understand the engineering behavior of clay–cement mixes. The improvement in soft clay strength was also measured for different cement contents and at different curing times.

Background

The increased strength of a clay–cement mix results from the physicochemical reactions between soil and cement, such as the interaction between the substances founded on the soil and the products of the hydration of cement (Chen and Wang 2006). The development of higher strength and stiffness is achieved by: (1) reducing void space, (2) bonding particles and aggregates together, (3) maintaining flocculent structures, and (4) preventing soil swelling (Oh 2007). The most commonly used cement type is Portland cement. Portland cement is composed primarily of calcium aluminates and calcium silicates that hydrate after mixing with water, creating the cementing compounds calcium silicate hydrate and calcium aluminate hydrate. The hardening process of the clay–cement mix occurs immediately after mixing water with the cement. The hardening agent provides the hydrated calcium silicates, hydrated calcium aluminates, and calcium hydroxide, thereby forming hardened cement structures (Saitoh et al. 1985).

The two major chemical reactions which govern the behavior of clay–cement mixes are the primary hydration reaction between cement and water and the secondary pozzolanic reactions between the lime released by the cement and clay minerals (Bergado et al. 1996). The hydration reaction causes the formation of primary cementitious products, leading to the initial gain in strength of the clay–cement mix. However, the secondary pozzolanic reaction occurs when a sufficient concentration of hydroxide ions (OH^{-}) is achieved in the pore water (Xiao and Lee 2008). Pozzolanic reactions occur between the silica and alumina found in the clay and the calcium ions of the cement, which forms cementitious products, including calcium aluminate hydrates, calcium silicate hydrates, and calcium aluminum silicate hydrates (Solanki and Zaman 2012). The resulting cementitious material and the calcium hydroxide are the main components that stabilize both granular and fine-grained soils.

The improvement of cement-stabilized soil depends predominantly on the chemical components of the cementing agent and soil properties (Kawasaki et al. 1981). Generally, coarse-grained soils have been shown to gain a larger increase in undrained shear strength than fine-grained soils do when mixed with the same cement content (Taki and Yang 1991). The hardening properties of cement-stabilized clay mixtures are influenced by a number of factors, such as the mixing mechanism, compaction, moisture content, and temperature, as presented in Fig. 1 (Kezdi 1979). The mixing criteria for the cement and clay control the hardening characteristics of cement-stabilized clay mixtures, and include the mixing speed, temperature, and compaction specification. The main factors that govern the strength development of cement-stabilized soils are the cement content, water to cement ratio, and the curing duration of the cemented soil. Clay–cement mixes generally have a lower dry density than that of untreated clay at the same degree of compaction. However, the optimum moisture content of stabilized clay increases with increasing cement content (Sherwood 1993). The hydration process takes place immediately after the cement comes into contact with water. Therefore, it is important to compact the clay–cement mix as soon as the cement comes into contact with water. Any delay in compaction may result in additional compaction effort.

The moisture content is important for hydration and compaction processes of clay–cement mixes. Pozzolanic reactions are highly affected by any changes in temperature. Lower temperatures may influence the pozzolanic reactions between binders and soils and result in lower shear strength. Therefore, in cold regions, it may be practical to limit the mixing of binder and soil to warm seasons, however the curing process of the stabilized soil can take

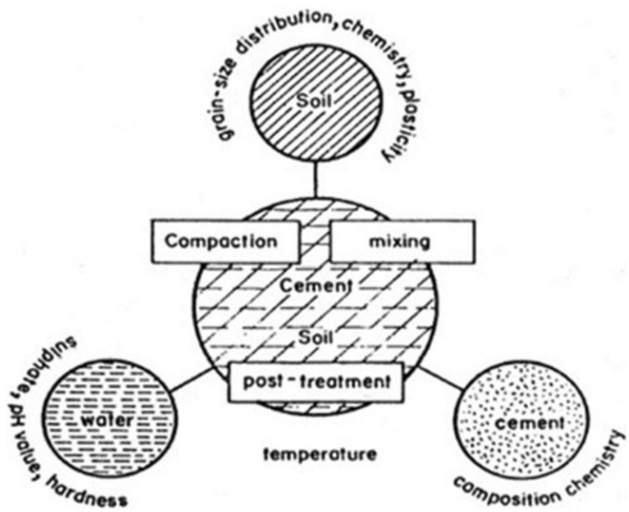

Fig. 1 Factors affecting the properties of cement-stabilized soils (after Kezdi 1979)

place throughout the year (Maher et al. 2004). Al-Tabbaa and Evans (1998) reported that cement stabilized soils may not withstand freeze–thaw cycles in the field. Therefore, it is important to insulate the stabilized soils against frost action. Cement-stabilized clays are also influenced by frequent dry–wet cycles, so adequate field protection is typically necessary (Maher et al. 2004).

The compressive strength of a clay–cement mix generally increases with increasing cement content up to a certain percentage, after which the rate of increase in strength decreases (Uddin et al. 1997). The required cement content depends mainly on the desired properties of the cement-stabilized soil and soil type, and typically varies from 5 to 15 % of the weight of the soil (Jaritngam and Swasdi 2006). An undrained shear strength parameter (c_u) of cement-stabilized soils was obtained for cement-stabilized soil samples where the mass of dry cement to soil volume ranged from 200 to 450 kg/m^3, according to Federal Highway Administration report no. FHWA-SA-98-086 (FHWA 1998). The undrained shear strength of the cement-stabilized soils typically ranged from 10 to 50 times the undrained shear strength of the natural soils. The upper and lower limits of the strength increase were obtained for higher cement contents and/or cohesionless soils, as well as for lower cement contents and/or cohesive soils, respectively.

The water to cement ratio is considered a significant factor governing the engineering behavior and strength of cement-stabilized clays (Miura et al. 2001). The unconfined compressive strength of clay–cement mixes decreases considerably as the initial water content of natural soil increases. The water to cement ratio generally influences the effect of the cementing agent, which controls the strength of the clay–cement mix. A higher initial water content requires more cement to achieve any significant effect during the stabilization of the clay. As a general trend, the unconfined compressive strength decreases significantly with increasing water to cement ratio of a clay–cement mix (Miura et al. 2001; Hassan 2009).

The compressive strengths of cement-stabilized clays have been found to increase significantly with increasing curing time (Kawasaki et al. 1981; Uddin et al. 1997). The increase in the compressive strength of the clay–cement mix is rapid early in the curing period and then slows down over time (Porbaha et al. 2000). White and Gnanendran (2005) illustrated that during the preparation of the cement–soil mix, up to a 40 % decrease in the resulting unconfined compressive strength of the cement-stabilized soil can be expected if any delay occurs between the mixing and compaction processes. Saitoh et al. (1996) reported that the compressive strength ratio ranged from 1.2 to 2.1 during days 7–28. Horpibulsk et al. (2011) showed a generalized equation for the increase in the unconfined compressive strength with the curing time:

$$\frac{q_D}{q_{28}} = 0.039 + 0.283\ln(D), \tag{1}$$

where D is the curing time in days, q_D is the strength at time D, and q_{28} is the strength at 28 days.

Volume–mass relationships

The generalized volume–mass relationships of a clay–cement mix can be used beneficially in ground improvement engineering practices. The moisture content is an important property for hydration and compaction processes of a clay–cement mix. In order to be fully hydrated, cement requires around 20 % of its own weight in water from the surrounding moisture (Sherwood 1993). This amount of moisture will be consumed over time during the hydration of cement. The relationships between the total dry density, void ratio, and specific gravity were established for the initial condition of a clay–cement mix based on the assumption that there is no water loss during the mixing period of the clay–cement slurry. The change in the initial geotechnical properties of the clay–cement mix with time is another essential factor that should be considered for field applications. Figure 2 shows the multi-phase diagram for a generalized case of a saturated clay–cement slurry, including water, clay, and cement. The volumes of these phases are expressed as V_w, V_c, and V_{cm}, respectively. The total void ratio (e_t) is defined as the ratio of the volume of voids, V_v, to the volume of soil solids, V_s, as shown below:

$$e_t = \frac{V_w}{V_c + V_{cm}}. \tag{2}$$

For wet mixing processes, natural water content and the amount of water added to the soil are taken into account in

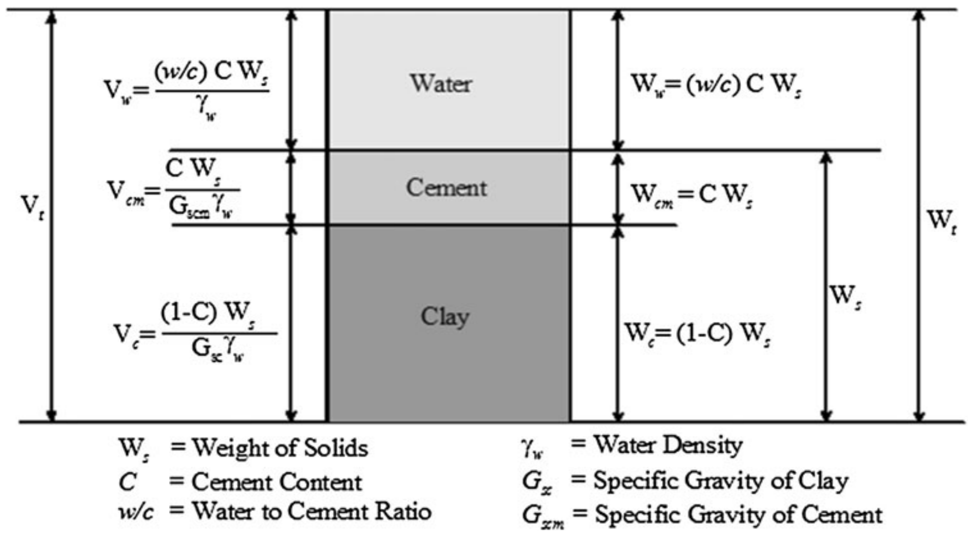

Fig. 2 Volume–mass phase diagram for a clay–cement mix

the numerator of the clay water to cement ratio, which governs the engineering parameters of the clay–cement mix (Miura et al. 2001). Cement content is defined as the mass of cement over the total mass of soil solids (W_s). Equation 2 can be presented in terms of the cement content and the clay water to cement ratio as

$$e_t = C\left[\frac{(w/c)}{\frac{C}{G_{scm}} + \frac{(1-C)}{G_{sc}}}\right], \tag{3}$$

where (w/c) is the clay water to cement ratio, C is the cement content, G_{scm} is the specific gravity of cement, and G_{sc} is the specific gravity of clay.

Using the geotechnical definition of the total dry density, and under the same compaction energy, the dry density of a clay–cement mix can be established as follows:

$$\gamma_d = \gamma_w\left[\frac{1}{(w/c) + \frac{C}{G_{scm}} + \frac{(1-C)}{G_{sc}}}\right], \tag{4}$$

where γ_d is the total dry density and γ_w is the density of water.

The total specific gravity of the clay–cement mix can also be determined as the average value of the combination of the specific gravities of clay and cement, as shown below:

$$G_{sct} = (1-C)G_{sc} + CG_{scm}, \tag{5}$$

where G_{sct} is the total specific gravity of the clay–cement mix.

The selection of the water to cement ratio and cement content has a considerable effect on the resulting density and the void ratio of the clay–cement mix, and therefore influences the design of field applications. A parametric study was conducted to show the effect of soil and cement parameters on the resulting properties of the clay–cement mix. The developed property trends can be useful for the selection of the appropriate mixing criteria and to obtain the optimized design parameters. The predicted relationships for the clay–cement mix were plotted in Fig. 3 in accordance with the developed Eqs. 3 and 4. The trends for a water to cement ratio of 2 were verified against the measured void ratio and dry density of a clay–cement mix.

Using the same water to cement ratio, increasing the cement content of the clay–cement mix resulted in an increased void ratio due to the increase in water volume, which resulted in decreased total dry density. It was noted that the compaction effort should be different at distinct cement contents in order to achieve the same total dry density of the resulting clay–cement mix. Higher compaction efforts should be applied with increasing cement content. In addition, the water to cement ratio was found to govern the resulting dry density of the clay–cement mix,

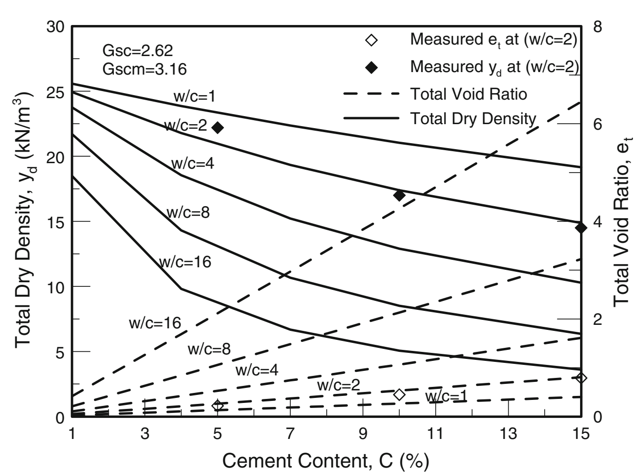

Fig. 3 Total void ratio and dry density versus cement content for a clay–cement mix

which influenced the overall effect of cement on the natural clay.

Selection criteria for the optimum cement content

The liquid limit (W_L), plastic limit (W_p), and plasticity index (PI) are representative geotechnical parameters for clayey soils. The PI and W_L are predominately used in strength correlations and consolidation estimates (Bowles 1996). At higher plasticity indices, soils behave more plastically, making them non-preferable for use in construction. A simple method of predicting the improved performance of clay is to measure the change in its plasticity characteristics using the PI parameter (PI). Typically, a reduction in the range of 12–15 % in PI serves as the criterion for selecting cement content for the purpose of soil stabilization (PCA 2003).

Figure 4 shows the change in PI ($\Delta PI = PI_{clay} - PI_{clay\text{–}cement}$) at a curing time of 28 days with increasing cement content. Three rates were observed for the change in clay plasticity with the addition of cement (Saadeldin and Siddiqua 2013). Initially, the PI showed a minor decrease as the cement content increased to 5 %. As the cement content rose from 5 to 15 %, the PI decreased rapidly. Above 15 %, the rate of decrease of plasticity decreased considerably with rising cement content. The maximum reductions in the PI of about 16 and 19 % were obtained at cement contents of 15 and 20 %, respectively. A comparable trend was observed in previous testing data on cement-stabilized clay presented by Kamruzzaman et al. (2000). The optimum cement content for cement stabilization of the clay was found to be about 15 %, after which the decrease in plasticity was relatively low. It was also noted that the reduction in the PI at a cement content of 15 % fell within the range of 12–15 % reported by PCA (2003).

Normalized strength relationships

Methodology

Unconfined compression tests were conducted on soft clay samples to determine the physical and mechanical properties of soft clay before and after mixing them with cement (Saadeldin et al. 2011). These tests, in accordance with ASTM D2166 (2006), were implemented to measure the undrained shear strength of clay–cement mixes. The soft clay was composed of 4.9 % sand, 16.1 % silt, and 79 % clay. The natural soft clay has a liquid limit of 80 %, a plastic limit of 30 %, and a field water content of 69 %. According to the unified soil classification system (USCS), the soil was classified as highly plastic clay (CH). The geotechnical index properties of the soft clay are summarized in Table 1. Portland cement was used as the chemical stabilizer, and the clay–cement mix was investigated for cement contents of 5, 10, and 15 %, as well as for a total water to cement ratio of about 2 %. The cement slurry was slowly added to the remolded clay and then mixed for a period of 5 min until the mix was visually homogeneous, as recommended by Den Haan (2000). Rafalko (2006) illustrated that there was an increase in the unconfined compressive strength of a cement-stabilized clay as the mixing time was increased from 5 to 10 min, after which the change was insignificant. As a general guideline, the most reliable and repeatable indication of the homogeneity of the clay–cement mix is the visual appearance (EuroSoilStab 2002). However, for comparable tests on a given soil under different stabilizer and dosage conditions, it is necessary to adopt the same mixing time, which can be a period of 5 min, where possible (EuroSoilStab 2002).

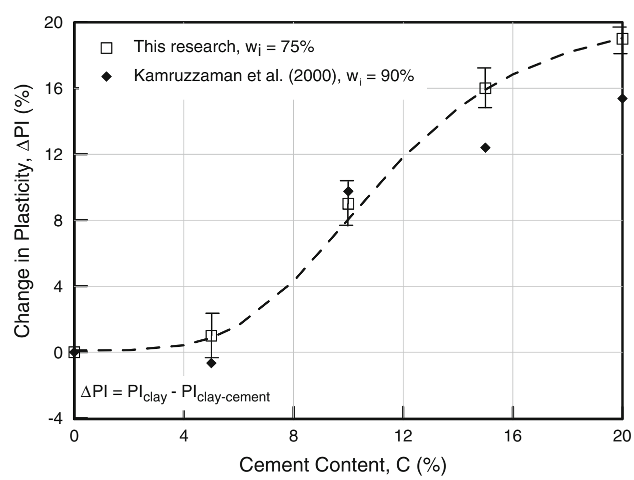

Fig. 4 Change in plasticity of a clay–cement mix at different cement contents

Table 1 Geotechnical index properties of the soft clay

Property	Value
Natural water content (%)	69
Moist unit weight (kN/m^3)	15.8
Void ratio	1.81
Specific gravity	2.62
Liquid limit (%)	80
Plastic limit (%)	30
Sand (%)	4.9
Silt (%)	16.1
Clay (%)	79

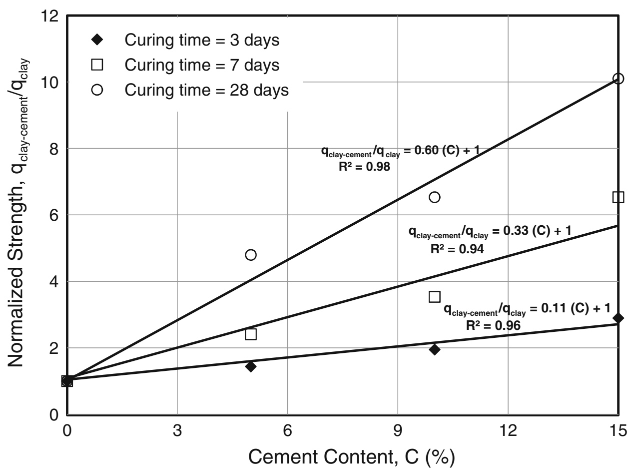

Fig. 5 Unconfined compressive strength of a clay–cement mix at different cement contents

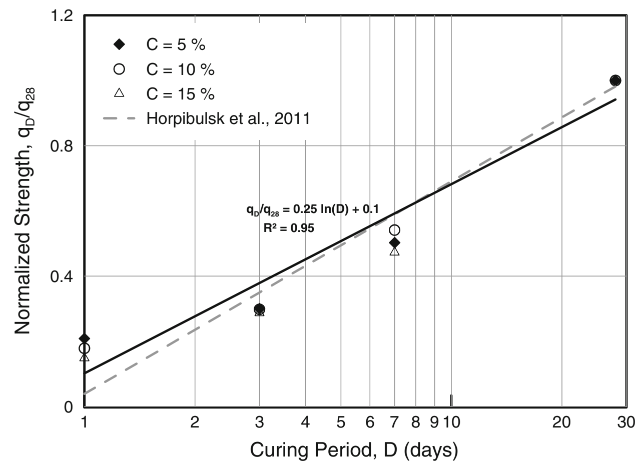

Fig. 6 Unconfined compressive strength of a clay–cement mix at different curing times

Cement content versus normalized unconfined strength

The effect of cement content on the normalized unconfined compressive strength of the cement-clay mix is shown in Fig. 5. As the cement content increased, the unconfined compressive strength increased according to the general relationship defined by Eq. 6 below. Improvement in unconfined compressive strength can be obtained as a ratio of the cement content, and this increasing ratio varied with curing time.

$$\frac{q_{\mathrm{ucement-clay}}}{q_{\mathrm{uclay}}} = 1 + F \times C, \qquad (6)$$

where C is the cement content (%) and F represents an increasing factor due to cementation, which varies with curing time.

For the clay tested, F was found to be 0.6, 0.33, and 0.11 for curing times of 28, 7, and 3 days, respectively. For a cement content of 15 % and a curing time of 28 days, the unconfined compressive strength (q_{u}) increased by about 10 times, from 24 kPa for natural soft clay to 242 kPa for cement-stabilized clay—a result that is in agreement with the findings reported by FHWA (1998).

Curing time versus normalized unconfined strength

The effect of the curing time on the normalized unconfined compressive strength of cement-stabilized soft clay is shown in Fig. 6. For the cement contents tested, the unconfined compressive strength increased with the curing time up to about 28 days, after which the increase in compressive strength was less significant. Esrig (1999) showed that most noticeable gain in the strength of the clay–cement mix occurs within the first 28 days after mixing, and the strength continues to increase at a slower rate thereafter (Jacobson 2002). Xiao and Lee (2008) showed that the increase in clay strength is dependent on different factors, including the cement content, and in some cases the increase in strength can still occur after 28 days. For the cement contents tested, the unconfined compressive strength (q_{u}) ratio at 7–28 days ranged from 1.8 to 2.1, which is in agreement with the ratio (1.2–2.1) reported by Saitoh et al. (1996). A generalized equation was developed for the normalized unconfined compressive strength of clay–cement mixes applicable for different cement ratios, particularly 5, 10, and 15 %, as shown in Eq. 7 below. The results of Eq. 7 were found to be in close agreement with the equation developed by Horpibulsk et al. (2011), as presented in Eq. 1.

$$\frac{q_D}{q_{28}} = 0.1 + 0.25\ln(D), \qquad (7)$$

where D is the curing time in days, q_D, is the strength at time D, and q_{28}, is the strength at 28 days.

Conclusions

Soft clay soils consist of normally consolidated clays and are generally identified by low shear strength. In the scope of the tests carried out on soft clay samples, cement was used as a soil stabilizer in order to improve the mechanical properties of the natural soft clay. This paper was intended to provide a quick estimation of the role of curing time and cement content on the geotechnical properties of a clay–cement mix.

A change in the plasticity of the clay–cement mix was observed as the cement content was increased for a curing time of 28 days. Three rates were obtained for the decrease in PI with increasing cement content. It was found that a reduction of 12–15 % in the PI of the clay–cement mix is a reasonable indication of the optimum cement content to stabilize the tested clay soils.

Experiments suggested that the overall geotechnical index properties of clay–cement mixes were controlled by the water to cement ratio, as well as the cement content. Therefore, a phase diagram was developed to present the geotechnical index properties, such as dry density, specific gravity, and void ratio of a typical clay–cement mix. This phase diagram showed that increasing the cement content of the clay–cement mix resulted in an increased void ratio and decreased total dry density for the same water to cement ratio. Therefore, higher compaction efforts may be needed to achieve the same dry density with increased cement content.

The clay–cement mix had a greater strength than the natural soft clay. The unconfined compressive strengths of clay–cement mixes increased significantly with increasing cement content and followed linear relationships at different curing times. The increase in unconfined compressive strength was presented as a percentage of the cement content, which varied from 11 to 60 % as the curing time increased from 3 to 28 days. The normalized unconfined compressive strength also increased linearly as curing time increased up to 28 days.

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