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Mechanical properties and microstructures of cement-treated soils: a review

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Abstract: The use of cement-treated soil is a crucial and traditional method for stabilizing soft ground and the bases or sub-bases of road pavement. However, due to the variable characteristics of soil worldwide, there is no precise design for the mixture proportion of cement-treated soil.

This review paper aims to summarize the existing research to identify the main factors influencing the mechanical characteristics of cement-treated soil, specifically unconfined compressive strength (UCS), tensile strength, and modulus of elasticity. The compressive strength of cement-treated soil is governed by many key factors such as cement content, cement type, compaction type, curing time, and curing condition. The UCS of cement-treated soil shows improvement with increased cement content and curing period, and various prediction models for UCS development are summarized and reviewed. Additionally, this review covers methods for estimating tensile strength and modulus of elasticity based on UCS. Besides, microstructure investigation is also mentioned to comprehensively provide evidence for the explanation of strength development.

Keywords: cement treated soil, unconfined compressive strength, tensile strength, elastic modulus, microstructure.

1. Introduction

Due to the rapid increase in population, many infrastructures have been built in the areas that face the soft soil problem. Soft soils, characterized by low bearing capacities, are prone to settlement and instability, leading to foundation issues. The diminished shear strength of these soils makes them susceptible to deformation and failure under heavy loads, potentially causing damage to transportation networks and utilities. Moreover, soft soils are also more prone to landslides and may not be able to prevent damage to existing structures during the construction of new structures next to. To improve the properties of soft soils, various methods can be employed including replacement, vertical drain, and using cement-treated soil. Among these approaches, cement-treated soil stands out as a popular method in practice due to its cost-effectiveness, versatility, and ease of implementation. This method involves using a chemical binder to improve the soil properties and has been used in many applications, including embankment, backfilling, subbase, and base of road pavement.

The enhancement of the improvement of soil is expressed via the enhancement of the mechanical properties and numerous mechanical properties of cement-treated soil are crucial for assessing its suitability for various construction applications. In this review, the authors will specifically focus on three key properties: compressive strength, tensile strength, and elastic modulus. These properties of cement-treated soil have been intensively assessed in previous studies [1–5], and they are influenced by various factors, including soil types, cement content and type, curing period, curing condition, and even compaction method [6–9]. For example, a previous study investigated the effect of cement type on the strength evolution of cement-treated soils under different curing temperatures and found that cement type strongly affected the compressive strength of cement-treated soils [10]. That study indicated that at the same curing condition, early-strength Portland cement achieved the greatest compressive strength compared to ordinary Portland cement and moderate-heat Portland cement. Another factor that strongly influences the strength of soil is the curing period. For concrete, the strength of the specimen at long curing age is slightly higher than that at 28 days. However, for the cement-treated soil, it was reported that the compressive strength of specimens at 2 years was two or three times higher than that at 28 days [11–13]. The higher compressive strength in this case was explained by the pozzolanic reaction between cement hydrate products and soil particles. In addition, curing condition also significantly influences the strength development of cement-treated soils. Previous studies indicated that the compressive strength of specimens in saturated and sealed conditions was much lower than that of the specimen under dry curing conditions [10,14,15]. Other studies considered soil type and compaction type and concluded that soil and compaction types greatly impacted strength development. For example, the strength of soil containing high organic matter (humic acid) was significantly smaller than that of the soil without organic matter [6,16,17].

To explain the mechanical properties, different microstructural investigations have been employed, including porosity measurement using mercury intrusion prosimetry (MIP), microstructural changes using scanning electron microscopy (SEM), and mineral changes using x-ray diffraction (XRD) [15,18]. These microstructural investigations were used to detect the formation of different cementitious products from cement hydration as well as pozzolanic reactions. To understand the change in mechanical properties and microstructures of cement-treated soils, which consider different influenced factors; this study aims to review the recent studies on cement-treated soils. In this review paper, various mechanical properties of cement-treated soils such as compressive and tensile strengths, and elastic modulus were evaluated. Different influenced factors were considered and included to examine the change in mechanical properties. Finally, some common microstructural investigations such as MIP, SEM, and XRD were reviewed to explain the mechanical behaviors of cement-treated soils.

2. Cement-treated soils and laboratory investigation

2.1. Cement-treated soils

Cement-treated soils are composite materials, which consist of cement, water, and soil in place. Indeed, cement-treated soil is one type of cement-treated material. Cement-treated soils are used widely in the backfill, subgrade, road base, or subbase layer. Based on the depth of improvement, there are two categories of cement-treated soils, including shallow and deep mixing. The practical applications of cement-treated soils are shown in Table 1. In Vietnam, cement-treated soils are used popularly for soft soil improvement such as cement deep mixing columns. It was reported that the number of cement deep mixing methods (CDM) constructed in Vietnam from 2013 to 2016 was around 10.4 million meters with different applications such as road foundation (59%), slope stability (22%), marine construction (11%), building foundation (5%), and revetment foundation (3%) [19]. It was estimated that from 2016 to 2018, the quantity of CDM in Vietnam was approximately 7.2 million meters [19].

Table 1. Practical applications of cement-treated soils

Name of mixture	Type of soil	Applications
Cement-stabilized soil	Clay soil and clay	Shallow and deep mixing such as subbase, road base, subgrade layer, cement deep mixing column
cement-treated aggregate material	Granular such as sand, gravel mix sand	subbase, road base, and subgrade layer
cemented paste backfill	Tailing	Backfill
controlled low-strength materials	Fine soil, mud, soil and fine aggregate in construction waste	Backfill

2.2. Laboratory experiment

To examine the mechanical characteristics (including compressive and tensile strength, and elastic modulus) of cement-treated soils, extensive laboratory experiments such as unconfined compression, triaxial compression tests, and column tests have been conducted. The most common test used in experiments is the unconfined compression test [10,20–23]. For the unconfined compression test, the cylindrical specimen with a size of 50 ×100 mm is usually used for the test. The loading rate of 1 mm/min is usually applied for the unconfined compression test.

Microstructural and mineral tests such as mercury intrusion porosimetry test (MIP), XRD, and SEM were employed to investigate the changes in microstructures of cement-treated soils to explain the changes in microstructures. The MIP is generally applied to measure the porosity of cement-treated soils [15,18]. MIP test can the pore size ranging from 3 nm to 100 μm, which describes from gel pore to compaction pore caused by chemical reactions (cement hydration and pozzolanic reaction) and compaction. Besides, SEM was used to detect the product formation of cement-treated soil, e.g. ettringite, calcium hydrate silicate, and so on due to reactions of cement and between cement hydrates and soil minerals. Finally, the XRD test was employed to explore changes in mineralogy to explain he mechanical behaviors of cement-treated soils.

3. Some typical mechanical properties of cement-treated soil

3.1. The unconfined compressive strength (UCS)

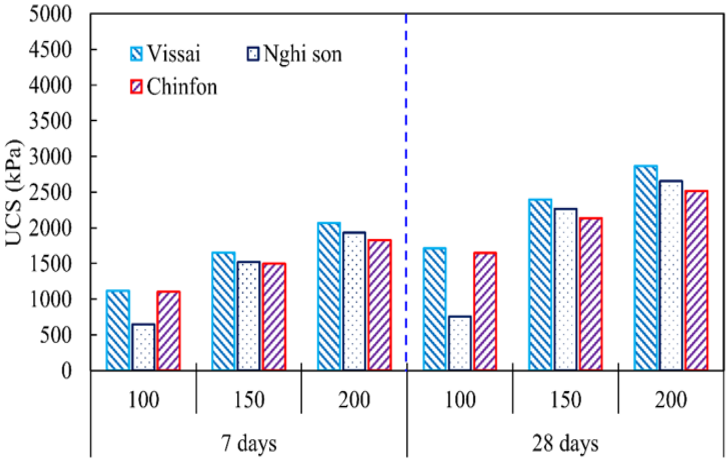
3.1.1. Influence of cement content and type

In general, soft soils with low strength and bearing capacity pose common challenges in many engineering constructions, including backfilling, base and subbase of road foundations, deep excavation, underground construction, and retaining walls [24–26]. Their inadequate strength and high compressibility make them unsuitable to support loads during both construction and the service life of structures. Several soil improvement methods have been suggested and developed to enhance the strength and compressibility of these soft soils, including soil replacement, preloading, mechanical compaction, and chemical stabilization [27–29]. Each of these techniques has its own advantages and disadvantages and is suitable for various soil types and geological conditions. Among the array of soil improvement methods, chemical stabilization stands out as an effective method introduced several decades ago. This method enhances soil properties by incorporating cementitious binders to meet the different purposes and requirements of construction projects.

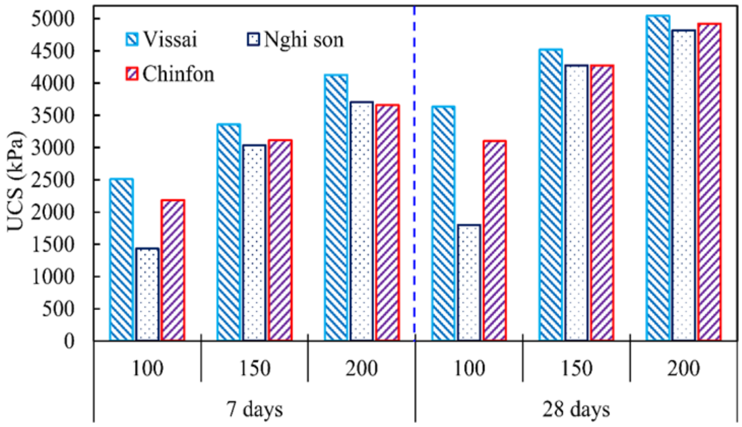
Cement treatment stands out as the most widely adopted technique for enhancing the strength of soft soil to date. However, our understanding of the mechanisms behind strength development is not universally extensive, and the cement industry has experienced limited progress in the design of mixtures for cement-treated soil over the past four decades [30]. By adjusting the cement content or utilizing different types of cement, it becomes possible to modify soils in a manner that yields hardened soil materials meeting the desired strength properties for construction purposes. This flexibility offers a practical approach to tailoring soil characteristics through variations in cement application.

Cement, utilized as an binder for improving strength characteristics, has been investigated extensively. Many of these studies uniformly observed that an increment of cement amount leads to the enhancement in the UCS of soil [18,24,31–34]. However, in practical application, it is essential to determine the optimal amount of cement required to enhance a specific soil before initiating the treatment process. Vu et al. [31] investigated the effect of cement content and type UCS of different soil and concluded that the (UCS) of soils treated with cement exhibited an upward trend as the cement content increased, irrespective of variations in types of cement, curing ages, and soil types. Greater cement content corresponded to increased UCS in the specimens, likely owing to the denser of the microstructures. The increase in cement content resulted in the formation of more cement hydrate products, contributing to denser microstructures in the specimens. Additionally, the rise in cement amount strongly impacted the moisture content of cement-stabilized soils, thereby exerting a substantial effect on UCS [31], seen in Figs. 1 and 2. Cong et al. [24] and Huang et al. [33] also reported that UCS of OPC stabilized clays increased with increasing the OPC content and decreasing the water content/cement content. According to Li et al. [34] the UCS of the specimens raised from 0.285 MPa to 1.577 MPa, an increment of 453.3% when the cement content increased from 0 to 7%.

Likewise, Horpibulsuk et al. [24] measured UCS development of type-I Portland cement-treated silty clay under given water content and categorized it into three distinct zones: active, inert, and deterioration, as depicted in Fig. 3. Regarding active zone (cement content less than 11%), the contact point between cement and grain soil is increased since there is a increase in cement content. The formation of more cementitious compounds is thus grown up, resulting in enhanced UCS. Transitioning into the inert zone (cement content ranging from 11 to 30%), the UCS still gradually increases but the development slows down. Regarding the deterioration zone (cement content: 30%–50%), a lack of an adequate amount of water retards the formation of cementitious compounds. Consequently, as cement content increases, soil strength decreases. Additionally, an excessive amount of cement may promote the development of shrinkage cracks, potentially leading to preferential seepage through the treated clay layer [35]. However, the finding of Horpibulsuk et al. [18] was inconsistent with that discovered by Yao et al. [32] who carried out UCS on Portland cement-stabilized marine clay. Yao et al. [32] showed that for a specific total water content, the inclusion of cement caused a significant increment of the UCS of cement-treated marine clay, as seen in Fig. 4. The differences in findings between the two studies, as suggested by Yao et al. [32], can be ascribed to variations in the water content of wet clay. Horpibulsuk et al. [18] employed a maximum water content of only 26%, whereas the clay's water content in this study exceeded 100%, providing more than sufficient hydration for the cement.

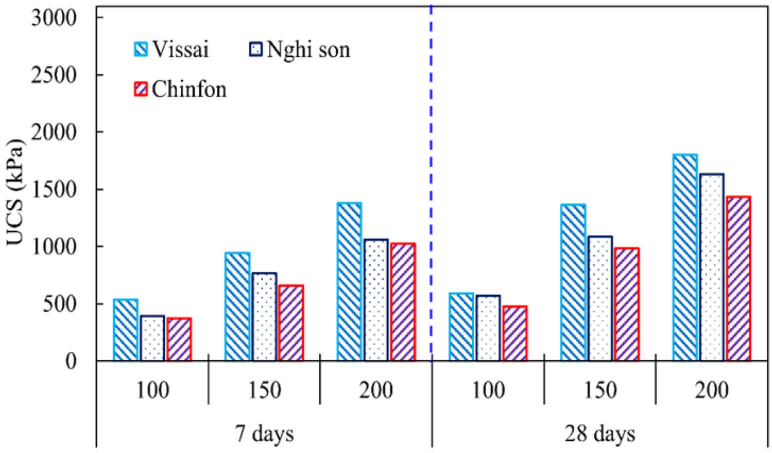


a) UCS of cement-treated yellow clay under sealed condition

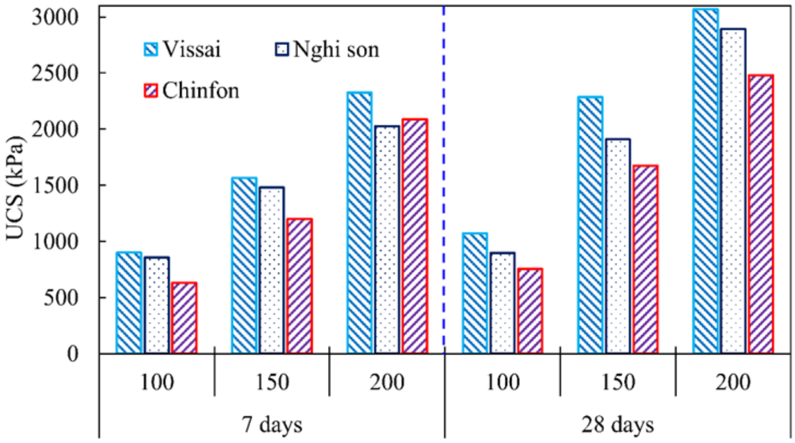


b) UCS of cement-treated yellow clay under drying condition

Fig. 1. Influences of type of cement and cement amount on UCS of cement-treated yellow clay (modified from [31]).



a) UCS of cement-treated black clay under sealed condition



b) UCS of cement-treated black clay under drying condition

Fig. 2. Influences of type of cement and cement amount on UCS of cement-treated black sandy clay(modified from [31]).

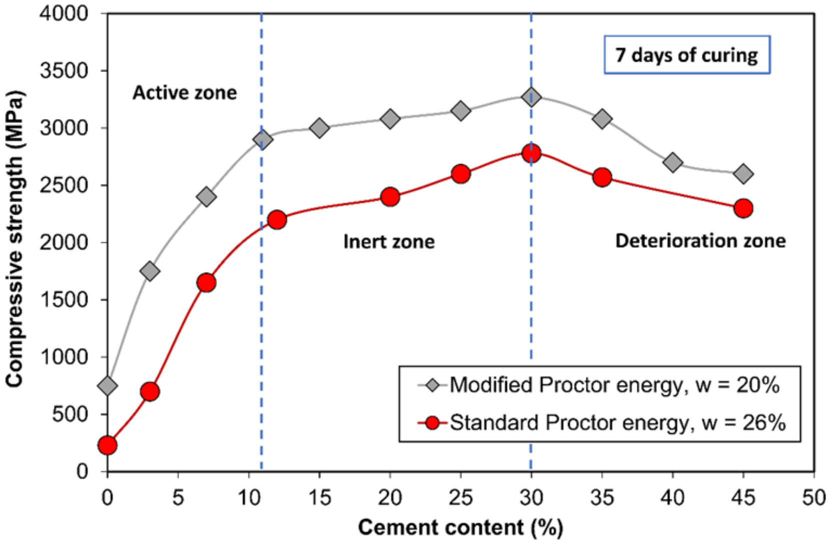


Fig. 3. Relationship between compressive strength and cement content (modified from [18])

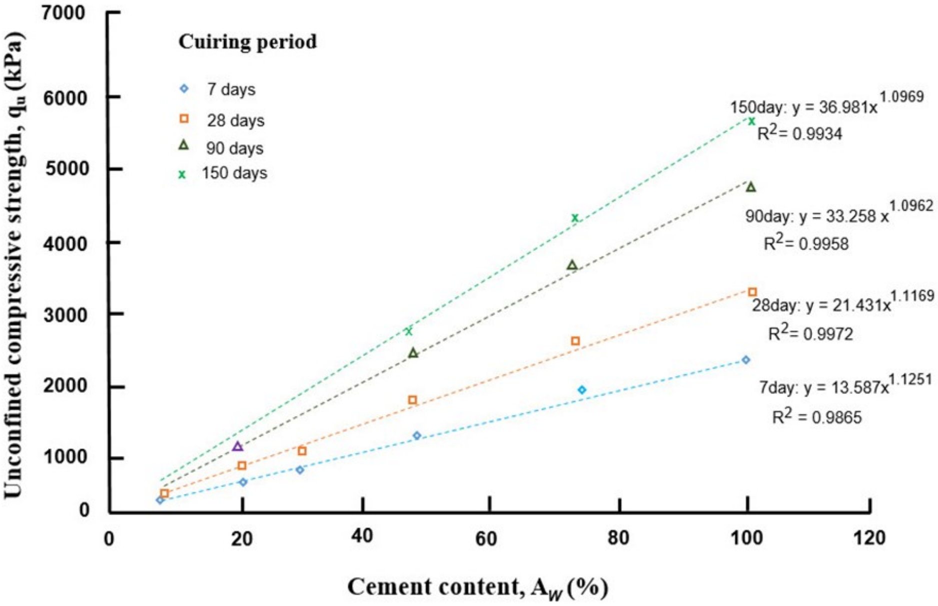


Fig. 4. Effect of cement content on UCS (modified from [32])

Due to its availability and cost-effectiveness, Ordinary Portland cement referred to as Type I cement is the most widely used for soil stabilization [36]. The suitability of Ordinary Portland Cement (OPC) is determined by two key factors, namely its effective mixability with clay and the attainment of sufficient strength and stiffness by the soil matrix after mixing and compaction [35]. However, with sustainable development and reuse of waste materials from industries such as fly ash or blast furnace slag, the addition of them into the cement composition leads to various cement type production. This also results in the differences in observation between researchers. As can be seen in Figs. 1 and 2, the UCS of treated specimens was different among various cement types. As suggested by Vu et al. [31], the reason could be due to difference in fineness and chemical composition of cement, which strongly impact the strength development of cement-treated soils. Bergado et al. [37] reported that Type III cement (early strength cement) results in a greater level of early strength gain of treated soil compared to OPC. The development of higher initial strength is linked to the larger surface area of cement grains and a higher C_3S value. When water is present, cement grain exposes more soil to water, and a higher C_3S amount results in faster hydration. Mahedi et al. [38] illustrated that the high amount of C_3S is responsible for the higher UCS of Type I/II cement at the early stage compared to that of Type V. Meanwhile, due to the higher amount of C_2S and lower loss on ignition of cement Type V compared with cement Type I/II, the long-term UCS gain of cement Type V treated specimens is relatively higher than that with Type I.

3.1.2. Effect of compaction type

In practice, the density of the mixture is significantly influenced by the degree of compaction. When the compaction degree increases, both the density and the UCS tend to increase. This is a key factor in achieving a high UCS for cement-treated soil, as it is obtained through a high degree of compaction. This approach is grounded in the understanding that, while a low density can be offset by an increase of the cement amount, it is generally more cost-effective to attain high strength through thorough compaction. Horpibulsuk et al. [18] demonstrated that at a specific curing time, the UCS curve of soil treated with 10% cement depends greatly on the compaction energy. When compaction energy increases, maximum strength increases and water content correspond to maximum strength decreases. Kenai et al. [39] investigated the different compaction methods, namely dynamic, static, and vibro-static and with various cement amount in the dry state on UCS and concluded that dynamic compaction results in the greatest compressive strength across all levels of cement stabilization, see in Fig. 5. Greater dynamic compaction produced a compressive strength exceeding 10 MPa, in contrast to a maximum of 8 MPa achieved using static compaction. Specifically, at a 12% water content, an increment of cement amount from 2% to 15% resulted in an increase in compressive strength from 4.25 MPa to 8.2 MPa and from 5.9 MPa to 10.5 MPa for static and dynamic compaction, respectively.

In fact, there is a delay time between the mixing and compacting stages of cement-treated soil at the construction site during construction because of climate changes, hitches, or technical breaks for logistic reasons. As a result, the delayed compaction certainly influenced the performance of cement-treated soil. For example, Ali and Mohamed [40] implemented an experiment study on lime-treated expansive clay and they indicated that a significant reduction in UCS happened with a long delay of compaction; and the first 12 h delay of compaction was recognized as the most vital period, which affects the long-term strength development of lime-treated clay. The investigation by Nazari et al. [41] on cement-stabilized subgrade soil indicated that delay of sampling led to a decrease of the compressive strength (approximately 11.31 to 37.25%) in comparison with those without delaying, as depicted in Fig. 6.

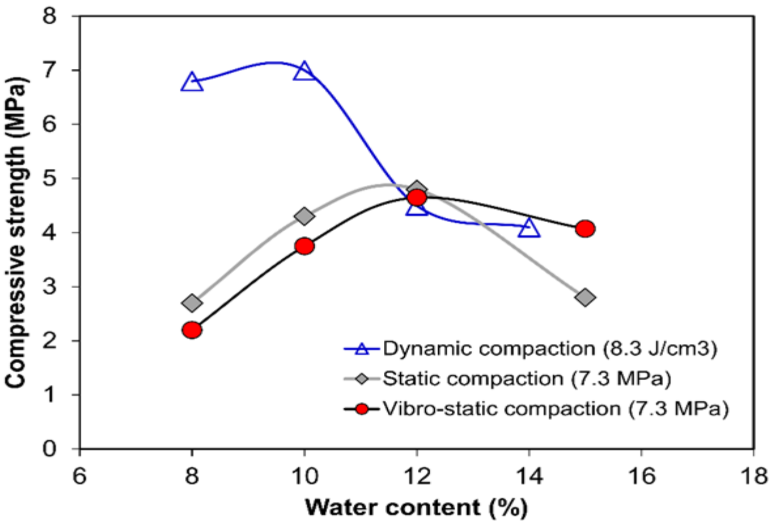


Fig. 5. Influence of compaction method on UCS of cement-treated soil (modified from [39])

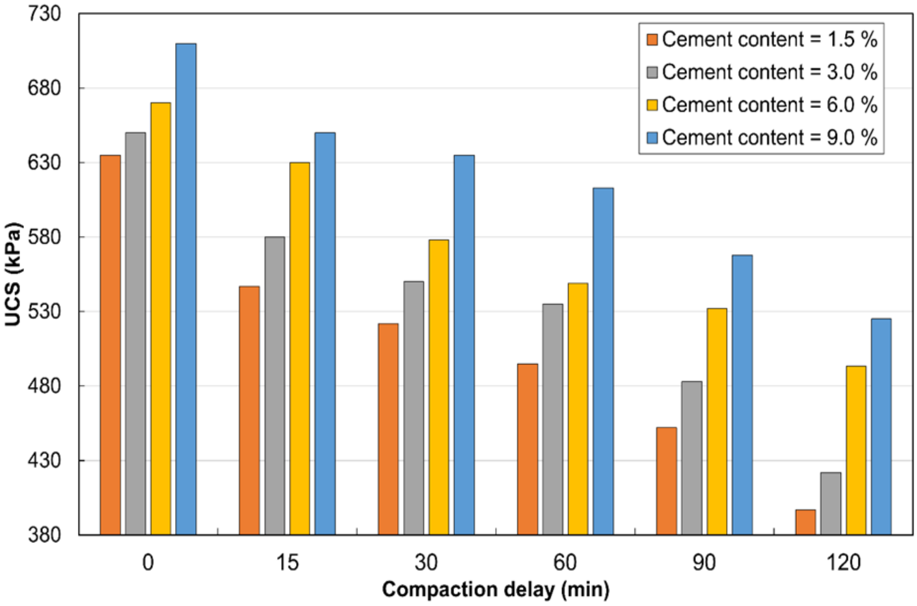


Fig. 6. Effect of delay of compaction on UCS of cement-treated soil (modified from [41])

3.1.3. Effect of curing period

The curing period is also one of the important characteristic influencing the UCS of cement-treated soil. Generally, most of the researchers concluded that the development of UCS increases with the curing period is due to the establishment of cementitious products [24,26,32,33]. At the early curing period, UCS of cement-treated materials experiences rapid growth, reaching a plateau after 28 days. Lim et al. [42] proposed the equation for predicting UCS of cement-treated soil based on the modification of ACI Committee model. This modification gives an accurate prediction of UCS for both short and long-term curing.

$$f_c(t)= f_c(28)\frac{t}{2.5+0.9\times t} \qquad (1)$$

where $f_c(t)$ is the UCS at time t; $f_c(28)$ is the UCS at 28 days; t is the time.

3.1.4. Effect of curing condition

The UCS of cement-treated soil depends not only on the cement hydration and pozzolanic reaction but also on the curing condition. Besides the difference in moisture content of wet clay, the inconsistency in findings between Horpibulsuk et al. [18] and Yao et al. [32] is due to curing conditions. Horpibulsuk et al. [18] demolded samples from the molds, then wrapping them in vinyl bags before placing them in a chamber with a specific humidity. In contrast, specimens in the study of Yao et al. [32] kept in the molds and then were soaked in water for the whole curing period. This indicates that the cement reacts more with available water, facilitating the generation of more cementitious products and providing to the increase in strength. In the tests implemented by Horpibulsuk et al. [18], however, available free water was limited, and an increase in cement amount would decrease the quantity of the free water due to chemical reactions, thus restricting the degree of hydration. As illustrated by Vu et al. [31] (seen Figs. 1 and 2), the UCS of the specimen under the drying condition was much higher than that under the sealed conditions regardless type and content of cement, soil type, and curing period due to calcium carbonate formation. Particularly, the UCS of specimens under drying condition was at least 1.5 times higher than those under sealed condition at 28 days. Under drying condition, carbonation occurred, and $CaCO_3$ was produced from the reaction between Portlandite, C-S-H with CO_2. The $CaCO_3$ from carbonation process could fill in void between soil particle, which produced a denser structure. Meanwhile, Ho et al. [15] reported that carbonation had both positive and negative influence on the strength development of cement-treated sand-clay samples under drying conditions, as shown in Fig. 7. Consequently, its compressive strength remained constant or slightly decreased after 28 days due to carbonation shrinkage. Chaiyaput et al. [43] mentioned that the UCS of soil-cement samples cured under lime-saturated water showed a higher rate of hydration process, resulting in the highest UCS in comparison with those cured under tap water, plastic wrapping, and open ambient at 28 days. In addition, an elevated curing temperature remarkably improved the early UCS gain and long-term performance [44]. The same finding can be found by Ali and Mohamed [40] who revealed that the gain in UCS after 24 h from mixing was generally faster and higher at 40 °C than those measured at 20 °C. According to Jamsawang et al. [45], the UCS of soaked samples was lower than that observed in the unsoaked ones.

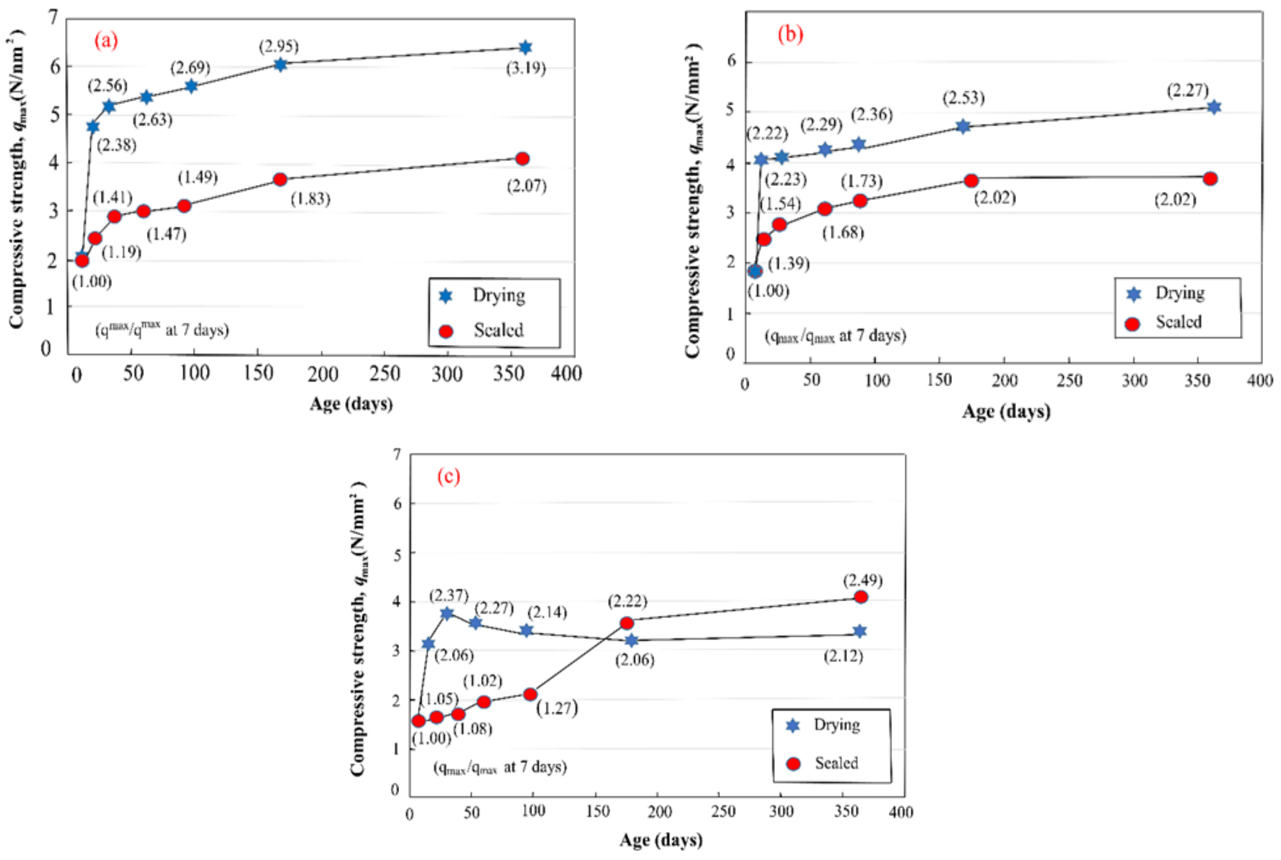


Fig. 7. Strength evolution with time of (a) sand mixture, (b) sand-loam mixture, and (c) sand-clay mixture under sealed and drying conditions (modified from [15])

3.2. Tensile strength

The compressive strength of cement-treated soil has been well-documented, whereas its tensile strength has not received as much attention. However, the tensile strength of cement-treated soil is always considered as a significant material factor in the conceptual design of pavement structures. The reason is due to the tensile stress that occurs at the bottom of the cement-treated soil layer. The tensile strength of cement-treated soils is generally evaluated via direct tensile test, flexural test, and splitting tensile tests. The results obtained from those tests change from each other due to the different stress distributions under different condition of testing.

Williams [46] implied that the aggregate type is not a primary factor that could influence the relation between the UCS and the direct tensile strength of cement-treated soil. For the cement-treated soils, the direct tensile strength (f_{dts}) is typically approximately one-tenth of the UCS (f_{ucs}). Meanwhile, Tran et al. [47] proposed a linear correlation between UCS and direct tensile strength with the relation coefficient of 0.071 based on their experiment, as can be seen in Fig. 8 and the following expression:

$$f_{dts}=0.071 \times f_{ucs} \quad (2)$$

Besides, a correlation between indirect tensile strength (f_{idts}) and UCS is established as Eq. (3), expressing their approximately linear correlation. The experimental coefficient is not affected by the cement type and gradation of the granular material [48], whereas it varies and depends on the test. For example, the experimental coefficient suggested by Liu et al. [49] who conducted on cement-treated Champlain sea clay is 0.071 and 0.046 for the Brazilian tensile strength test and the unconfined penetration test, respectively.

$$f_{idts}=k \times f_{ucs} \quad (3)$$

where k is an experimental coefficient

Simply, the flexural strength of cement-treated soil was also suggested to have a linear relationship with UCS. The experimental parameter was from 0.2 to 0.25 [42]. Anggraini et al. [50] revealed that the coconut fibers could significantly enhance the flexural strength of cement-treated marine soil in the Selangor State of Malaysia. Moreover, Vinolas et al. [51] found the method to enhance the flexural strength of cement-treated soil by adding 10.5% clay, 42.5% fine sand, and 48.5% coarse sand. The material dosage includes 23.5% cement and 76.5% of soil. The authors concluded that the flexural strength of high-performance soil cement was equivalent to that of high-performance concrete with lower content of cement and without the need for materials from mining, such as sand and gravel, or superplasticizers, which are adopted in some high strength concrete mixtures.

Generally, Namikawa and Koseki [52] used analytical simulation to explain the differences in the values of the tensile strength of cement-treated sand obtained from the three types of tests, including direct tension, splitting tension, and bending test. The analysis results indicated that the direct tension test yields reliable values of actual tensile strength that will be mobilized under an ideal condition of uniaxial tension.

3.3. Elastic modulus

In geotechnical studies, the modulus of elasticity at 50% of the UCS (E_{50}) in cement stabilization has frequently been used [31,41,45]. Based on previous research, it is evident that all models estimating the elastic modulus are formulated based on the UCS. A previous study conducted by Vu et al. [31] indicated that elastic modulus of the specimens under the drying condition was around 1.3 to 2.0 times larger than that of the specimens under the sealed condition. Similarly, Jamsawang et al. [45] reported that the

E_{50} of samples under unsoaked conditions was higher than that under soaked conditions. Based on the experiment, the authors also proposed a linear function to predict the E_{50} from the UCS, as shown in Fig. 9. Nevertheless, the reported models were only applicable to the specific mixture components and conditions provided. Other prediction models take into consideration the impact of cement content, gradation, and moisture content to achieve accurate predictions of modulus values [24,42,53]. Cong et al. [24] suggested the estimation of E_{50} depending on the water content, cement content, and curing time. Consequently, these models illustrate the impact of mixture variables not only on the UCS but also on the elastic modulus.

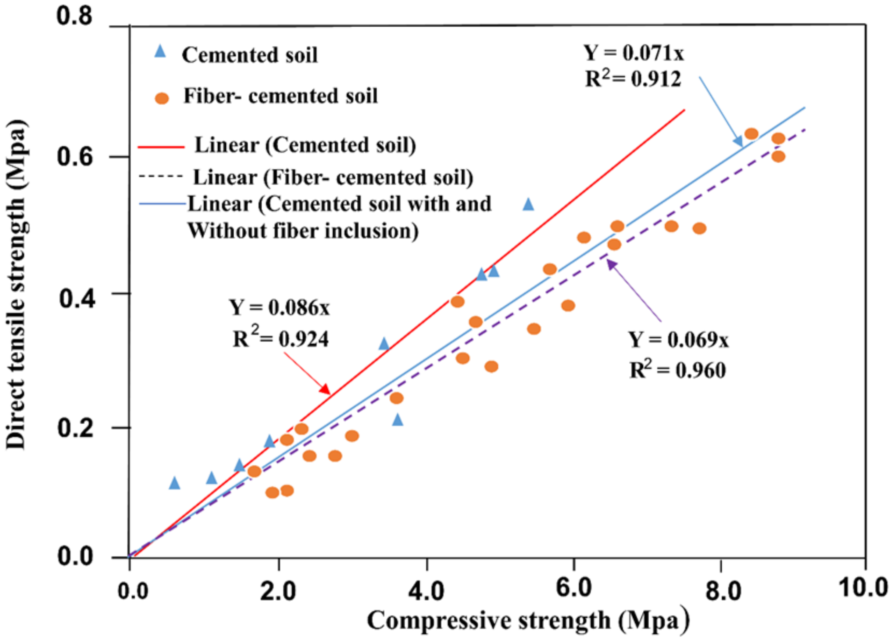


Fig. 8. The correlation between direct tensile strength and UCS (modified from [47])

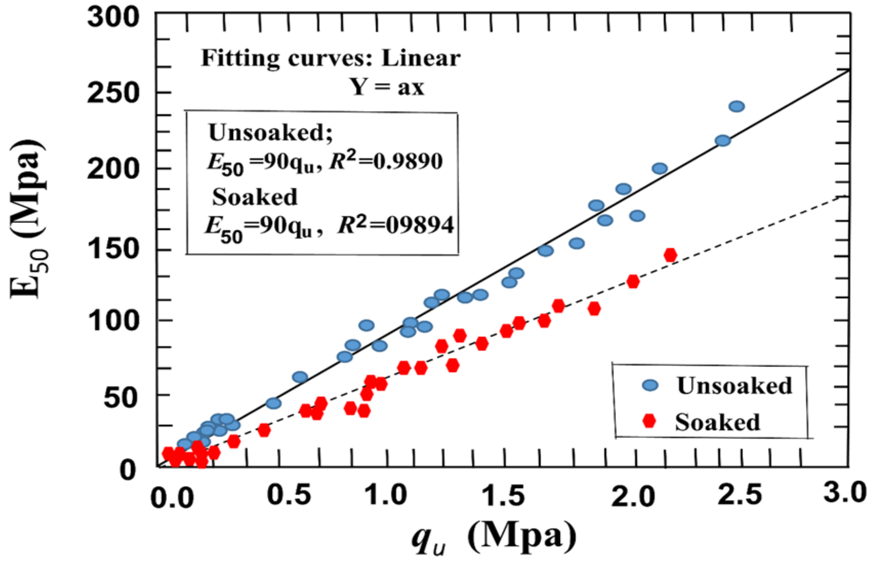


Fig. 9. Relationship between E_{50} and UCS (modified from [45])

4. Microstructures of cement-treated soils

4.1. Porosity of cement-treated soil

To enhance the explanation of the factors influencing strength development, the alteration in porosity of cement-treated soil was analyzed [15,15,18,33]. Horpibulsuk et al. [18] demonstrated that water content not only influences the hydration products but also the pore volume, particularly for pores in the range of 1.0–0.1 µm, which exhibit the highest volume. The densest state, characterized by the lowest total pore volume, is achieved at the optimum water content. Additionally, during the early stage of hydration (within the first 7 days of curing), the volume of pores smaller than 0.1 µm exhibits a significant decrease, while the volume of pores larger than 0.1 µm shows a slight increase. The volume of pores smaller than 0.1 µm is substantially reduced with the addition of cement, resulting in an overall reduction in total pore volume. Both the volumes of the highest pore size interval (1.0–0.1 µm pores) and the total pore volume tend to increase with the addition of cement. This is attributed to the significant reduction in water content with increased cement content, leading to a decrease in the degree of hydration and, consequently, in cementitious products. It is consistent with the observation of Huang et al. [33]. Likewise, Ho et al. [15] revealed that the drying curing condition could remarkably affect the size and volume of the small pores ranging from 0.006 to 10 µm in the matrix of cement-treated soil, seen in Fig. 10. This phenomenon is attributed to the influence of carbonation shrinkage.

4.2. X-ray diffraction patterns and scanning electron microscopy of cement-treated soil

The influence of cement-stabilized soil on the change in mineralogy was also investigated by previous studies [15,34,45]. Through X-ray diffraction patterns, the C–S–H and AFt (ettringite) which are the products from the cement hydration could be identified. Hence, these product formations made the denser microstructure and enhanced the strength of cement-treated soil, as depicted in Fig. 11. Even, Ho et al. [15] semi-quantitative calculated amount of portlandite and calcite based on the hypothesis that quartz is not changed in contact with cement with the curing time. Hence, the peaks of portlandite and calcite could be normalized with respect of the quartz peaks. Although this technical could not provide accuracy in determining the number of peaks, it can be used to calculate the intensity ratio for comparison in some cases. To be comprehensive, scanning electron microscopy combined with energy dispersive spectroscopy was employed to evaluate the microstructure of cement-treated soil [18,24,33,34]. This method can effectively facilitate the identification of the crystalline structure of hydrated products of the sample as well as the alteration in the microstructure, as shown in Fig. 12.

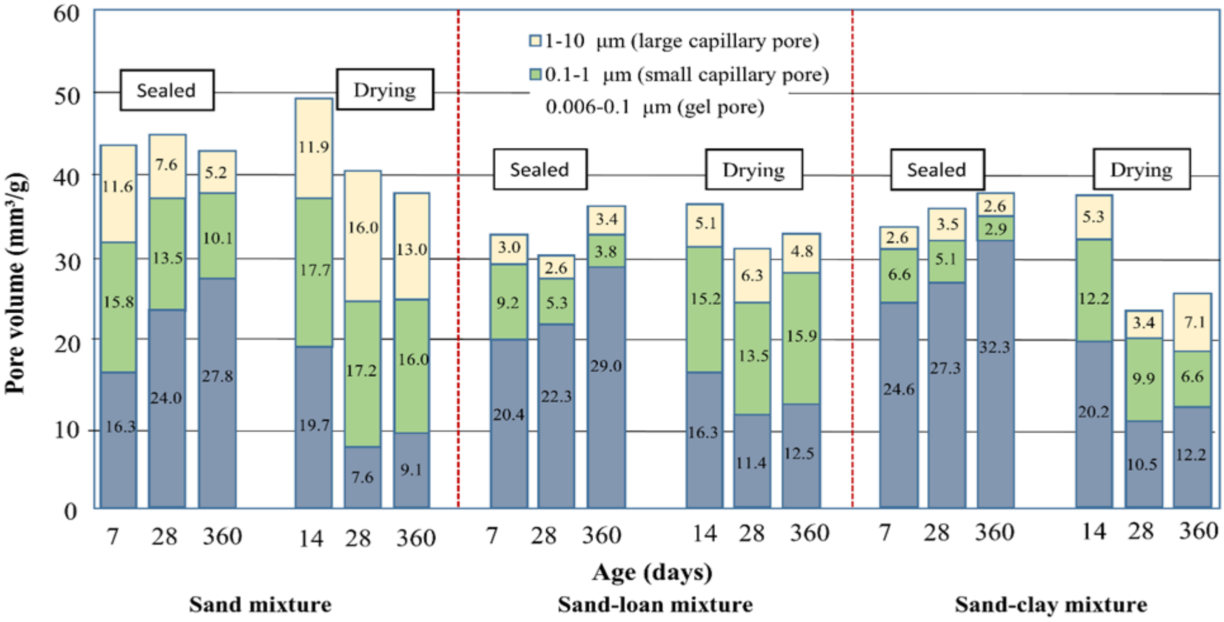
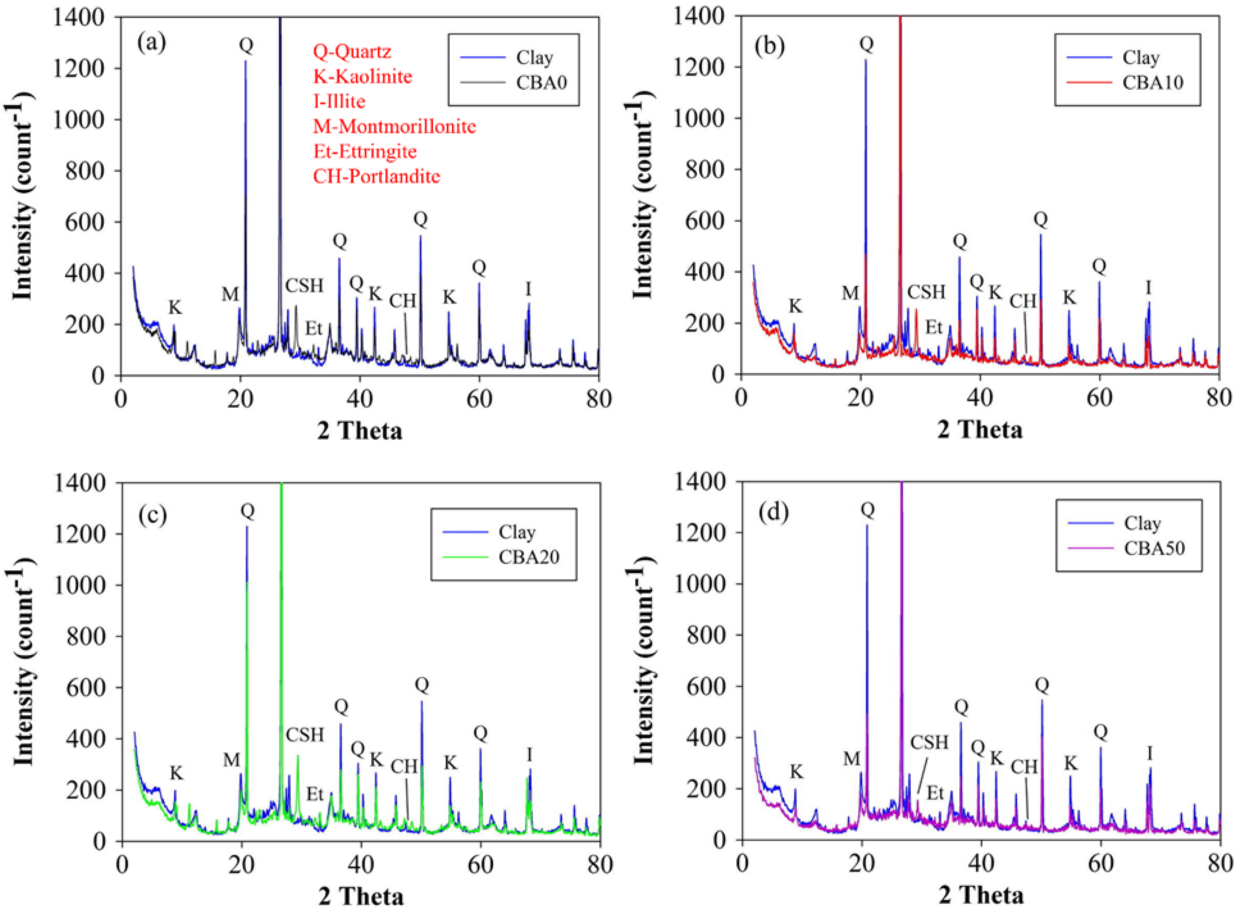


Fig. 10. Percentage of pore volume (modified from [15])



Note: In term "CBA0", the word CBA indicates cement- bagasse ash, and "0" means the amount of BA replacement for cement.

Fig. 11. X-ray diffraction results (modified from [45])

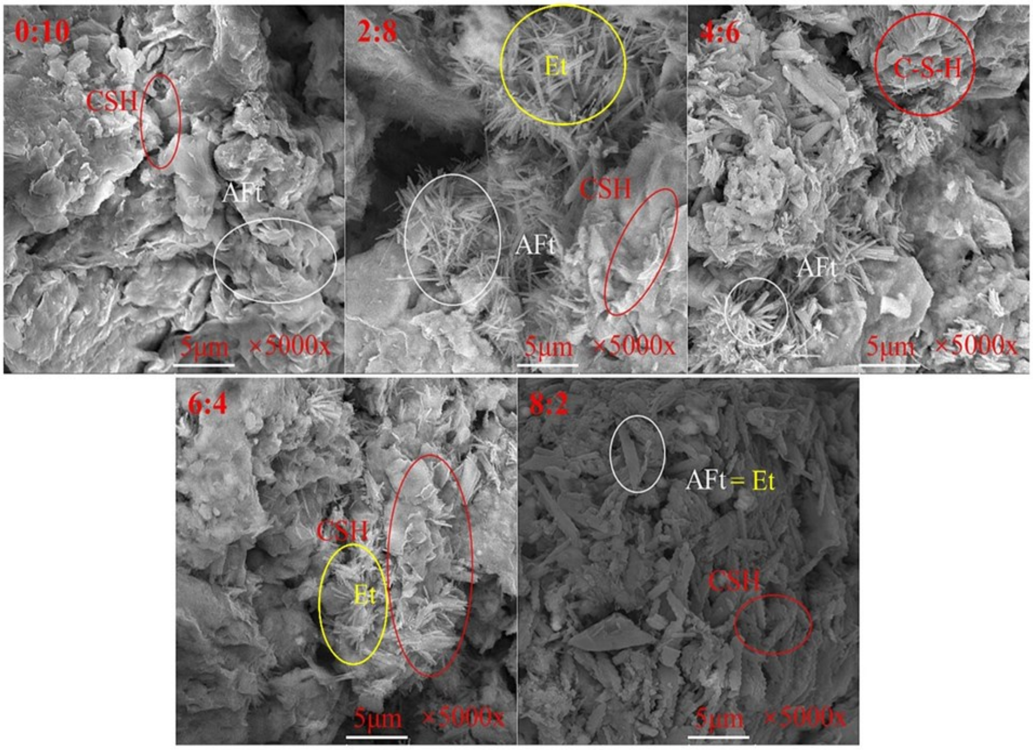


Fig. 12. Microstructure diagram of cement-treated soil (modified from [33])

5. Conclusion

A comprehensive review on the mechanical characteristics and microstructure of cement-treated soil was explored in this study. According to the review on mechanical properties and microstructure of cement treated soil from previous studies, some conclusions can be drawn as follows:

- The compressive strength of cement-treated soil depends on various factors such as cement content, cement type, compaction type, curing period, and curing conditions. Normally, the UCS has a relationship with cement content and curing period. Meanwhile, the UCS of cement-treated soil could be affected by the compaction delay and carbonation shrinkage due to drying curing conditions.

- The tensile strength and modulus of elasticity of cement-treated soil are usually related to its UCS. The model for predicting tensile strength and modulus of elasticity of cement treated soil is linear regression with its UCS.

- The microstructure of cement-treated soil is significantly modified due to hydrated products since cement is used to stabilize. This can be absolutely proven through the microstructural test.

Limitations and future work:

- Other factors influencing the compressive strength of cement-treated soil should be investigated such as soil type, water-to-cement ratio, organic or sulfate content in soil, etc. Hence, the prediction model for UCS of cement-treated soil should pay attention to these factors instead of curing time only.

- The effect of other factors on tensile strength and modulus of elasticity is not obvious. The prediction models for these characteristics should be established based on not only UCS, but also moisture content, cement content, or organic content.

- The influence of other additives for example lime, and supplementary cementitious materials should be mentioned in another work. Finally, the change in physic-mechanical properties of soil before and after treatment should be clarified in future.

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