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Effect of curing temperature on the mechanical characteristics of cement-treated soils: a review

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Abstract: Nowadays, the treatment of soft soil with cement is gaining popularity to meet the demands of construction development. Various factors, including soil type, cement content and type, water-cement ratio, curing conditions, and others, influence the effectiveness of this method in enhancing soil mechanical properties. The impact of curing temperature on mechanical properties is significant, and the curing temperature in cement-treated soil typically increases due to the heat generated from cement hydration. This heat is retained in the soil for an extended period, particularly in deep mixing columns. This review summarizes the existing papers conducted regarding the effect of curing temperature on cement-soil mechanical properties, focusing on strength and stiffness. The present paper also includes strength prediction models that consider the influence of curing temperature. In addition, the Thermogravimetry analysis (TGA) used to determine the chemically bound water content in cement-treated soil and the X-ray diffraction (XRD) test to explain the chemical mechanism in cement-treated soil are also mentioned.

Keywords: strength, maturity, modulus of elasticity, cement-treated soil, prediction model for strength.

1. Introduction

Cement-treated soils are integral to construction, significantly enhancing the load-bearing capacity, durability, and stability of soils used in foundations, road bases, embankments, and other civil engineering applications. This treatment not only improves the soil's strength, enabling it to support heavier loads and resist deformation but also increases its durability, making it more resistant to weathering and erosion [1–5]. Additionally, cement-treated soils exhibit reduced permeability [6], which prevents water infiltration and mitigates internal erosion and foundation problems. By stabilizing problematic soils such as expansive clays, and loose sands, cement treatment renders them more suitable for construction, often resulting in cost savings by reducing the need for imported high-quality fill material. The effectiveness of cement-treated soils, however, is influenced by various factors, including soil type, the proportion of cement mixed, and water content during mixing and curing, which affect the hydration process of the cement [1],[2]. Moreover, curing time impacts the final strength, with longer curing times generally resulting in improved strength and durability. The thoroughness and method of mixing cement with soil, the level of compaction achieved, and environmental conditions such as temperature and humidity during curing are also critical in determining the mechanical characteristics of cement-treated soils. Proper control of these factors is essential to achieve the desired outcomes in soil stabilization and performance, making this topic a critical area of research in geotechnical engineering. As in the field of concrete, curing temperature is a crucial factor in receiving interest in studying both in the laboratory and onsite in cement-improvement work. This review focuses on two essential properties of cement-treated soils: strength and stiffness, considering the influence of curing temperature.

It is known that the strength and stiffness improvement of cement-treated soil mainly come from products of the hydration process. During the hydration process, cement reacts with water to produce calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$) which binds the soil particles together, forming a solid matrix. This process occurs rapidly during the early stages of curing, and results in faster development of the strength of cement-treated soils. Besides, several studies [1,2,7,8] have shown that the calcium hydroxide generated from hydration encounters mineral constituents including aluminate and silicate clay minerals in the soil, producing a pozzolanic reaction. This subsequent reaction produces more C-S-H and C-A-H (Calcium aluminate hydrate) products which increases enhancement in strength, especially at the long-term stage. Moreover, these hydration and pozzolanic reactions are accelerated at high curing temperatures, increasing the strength of the cement-mixed soil. Previous studies [1],[8]-[10] indicated that the strength of cement-treated soil specimens is significantly improved when treated at higher temperatures, particularly at an early age. Therefore, comprehending how temperature affects the strength development mechanism can enhance the accuracy of strength predictions for cement-treated soils [7].

Typically, heat from outdoor heaters can be applied to improve the strength of cement-treated soils, but this method is less common due to cost and practicality. The actual increase in curing temperature is due to heat generated during the cement hydration, accumulating and maintaining in the large soil bulk known as internal temperature rise. Numerous studies have investigated the temperature rise in situ and found that the temperature in cement-treated soil can increase up to 40-50°C (The peak of temperature rise depends on the cement content, cement type, and other physical properties of soils) and be maintained for a period of one to six months [2],[7]-[11]. Therefore, the strength and stiffness of the cement-treated soil are greatly improved when compared to soil treated at lower temperatures measured at the time of mixing.

This article aims to review recent studies on the influence of temperature on the mechanical properties of cement-treated soil involving strength, and stiffness. The proposed prediction models of strength are also considered. Furthermore, to explain the mechanical behavior of cement-mixed soil under the effect of curing temperature, laboratory experiment tests are also considered including thermogravimetric analysis (TGA) and X-ray Diffraction (XRD) analysis. The purpose of the present review is to synthesize the latest research on the above-mentioned topics, including the results achieved and limitations identified in each study, particularly regarding the improvement in strength and stiffness of cement-mixed soil at higher curing temperatures. It will also suggest potential future research work in the field of cement-treated soils.

2. Soils typically treated

Soft soils are very diverse, depending on where they are distributed worldwide, so each type of soil's properties is also different. Therefore, for a specific soil type used for cement treatment, each necessary physical and mechanical criteria is studied through experiments.

Natural soils treated with cement can be divided into groups, for example, Clay, Clay Soil, Sandy Soil (granular), Silty Soil, Gravel Soil, Loess Soil, Organic Soil, etc. Additionally, the amount of sludge dredged each year is also a very large volume, consuming a large area for storage. Meanwhile, this type of sludge can be reused as a useful source of filling materials and helps sustainable development, increasing the source of on-site filling materials, and ensuring the supply of materials for construction projects, thereby reducing construction costs, and contributing to environmental protection. Regarding dredged sludge, the use of binders such as cement or cement combined with active mineral additives (fly ash or blast furnace slag) mixed with sludge to improve adhesion, and strength and increase waterproofing ability to replace materials in leveling and construction embankments is essential [12].

In general, mixing soil with cement enhances its physical and mechanical properties. In some cases, depending on the soil's specific properties, lime can be an appropriate alternative to cement. For instance, in expansive soils with high plasticity, lime treatment can improve compressive strength more effectively than cement treatment, especially in long-term ages through pozzolanic reactions [13]. However, soil with high organic content can interfere with pozzolanic reactions, as organic matter can coat soil particles and inhibit the chemical bonding necessary for strength gain.

3. The experiment works

3.1. Specimen preparation, unconfined compression test (UC), and triaxial compression test (TC)

In general, the specimens used to determine compressive strength are cylindrical specimens with a diameter of 50mm and a height of 100mm. The molding procedure for treated soil specimens can be seen in detail in the previous study [1] based on the Standard (JIS) R 5201 [23]. The loading procedure is performed for the unconfined compression strength test according to the JIS A 1216:2009 [24],[25]. The procedure of preparing and compressive testing molded specimens of cement soils can be found in other standards such as ASTM D1632 for making soil-cement specimens and ASTM D1633 for test method of compressive strength [26],[27] or EN 13286-41 for the test method for the determination of the compressive strength of hydraulically bound mixtures [28], etc. Depending on the applicable standard, variations may exist in the casting process, sample size, and loading procedures.

In the laboratory, the triaxial compression test is also used to determine the shear strength [7]. This test allows realistic behavior of construction soil such as soil permeability through controlling drainage conditions (drainage, poor drainage, no drainage). The procedure of the consolidated-undrained triaxial compression test is described in JGS 0522-2020 [29], ASTM D4767-11 [30] or the standard described in [7], etc. The stiffness (or modulus of elasticity) of the soil can be determined from the results of the compression test using the stress-strain curve.

3.2. Thermogravimetry analysis (TGA) and X-ray diffraction (XRD)

Thermal gravimetric analysis is based on the principle that compounds including products produced during cement hydration, pozzolanic reactions, etc. are decomposed under extremely high temperatures. At each range of high temperatures, certain compounds will be decomposed, from which, based on the mass loss, the composition of the substances in the treated soil can be determined. In cement-treated soil, the chemically bound water of products from hydration and pozzolanic reactions is a key index to evaluate the degree of these reactions. This helps to explain the mechanism of how strength develops. Similar to concrete, through the TGA method, chemically bound water content in cement-treated soil can be determined. The preparation of the TGA sample and the procedure for TGA are described in detail in the previous study [1].

XRD is a powerful analytical technique that allows us to detect the presence of minerals and determine their composition in materials in general and cement-treated soils in particular. The change in the proportion of mineral components in cement-mixed soil determined by XRD helps clarify the chemical mechanism to explain the change in mechanical enhancement properties of cement-mixed soil. The preparation of the XRD sample and the procedure for the XRD test are described in previous studies [31],[32].

3.3. Field and laboratory temperature investigations

3.3.1. Measuring of temperature in the Laboratory

In the laboratory, a set of three specimens is often prepared to study the temperature rise in cement-treated soils. Adiabatic and semi-adiabatic methods are common techniques used to measure temperature changes in cement-treated soils [7],[33].

With the adiabatic method, the equipment used is resistant to heat loss, while the semi-adiabatic method [7] allows heat loss during curing. This heat loss can be calculated based on the heat transfer properties of the material and is used to determine the actual temperature rise in the specimens. In fact, the equipment used for the adiabatic method is often difficult to manufacture or has a high cost, which is why the semi-diabatic method is often used. The temperature change in the specimens according to the semi-adiabatic method lasts for about 3-4 days until the specimen temperature is stable and equal to the room control temperature. During the experiment, it is also necessary to investigate the room temperature to evaluate the influence on the measurement results.

3.3.2. Measuring of temperature in the Field

To our knowledge, a recent study of measurement of the temperature revolution in cement-treated soils in situ has been performed by Bache et al [7]. In this study, the authors conducted on-site temperature measurements at a construction project utilizing Lime/Cement-columns for the development of multi-story apartment buildings located along the Glomma River in Fredrikstad, Norway. The temperature rise is observed in the treated clay column in the field using lime/cement with a weight ratio of 80kg/m^3 at different depths of columns. The temperature was measured to rise to a peak between 27°C and 44°C and became a steady state equal as in the treated and untreated soil after 30 to 40 days. Enami et al. [11] measured temperatures of approximately 40℃ for cement-treated soils for 30 days. Omura et al. [10] found an increase in temperature to 50℃ in the core of deep mixing columns and it maintained for approximately six months, whereas the highest temperature in the backfilling constructed in tropical countries was reported nearly 38℃ [8].

3.3.3. Prediction of temperature

As mentioned above, the increase in temperature in the treated soil is due to the heat generated during the cement hydration process. The heat generated depends on the cement content and type, the rate of hydration, and other factors such as mineral components of the soil participating in subsequent reactions as known pozzolanic reactions. Many studies seek to build models to predict the temperature increase during the curing process of soil treated with cement, thereby evaluating the ability to improve soil properties such as strength, stiffness, … In the field of concrete, research on thermal modeling has been studied a lot [34]-[36], then included in regulations in standards [37]-[39] and is being widely used. On the contrary, in the field of soil treatment, although receiving similar attention, this issue has not been fully approached and more valuable research is needed in the future.

A popular method today is to use powerful simulation software such as COMSOL, ANSYS, ABAQUS, etc. Nevertheless, the complexity of simulating uncommon properties of materials (the diversity of soil) and the interactions between them is also a challenge when applying these types of software. Fig. 2 describes the revolution of temperature in cement-treated soil using COMSOL software [7].

Several more specialized programs for geochemistry and cement fields such as GEMS (CEMGEMS), CEMHYD3D, HYMOSTRUC, etc. that developed and provided for free/or commercial, and the data is updated regularly. In addition to the ability to model thermodynamics and calculate phase diagrams, they allow for modeling the temperature rise in materials during cement hydration. However, with the complex characteristics of soil composition and limited data, it is not easy to accurately model chemical reactions in cement-mixed soil.

Another simpler approach that researchers can refer to, using the original model proposed by Parrot and Killoh [40] which was built to estimate the degree of cement hydration based on determining the degree of each main clinker. The heat released during the cement hydration process can be calculated from the total heat generated from the hydration of the four main clinkers in the cement when knowing the clinker component ratio and the heat released from 1g of each clinker. Identifying the total heat generated from cement hydration and the heat capacities of materials in the mixture can predict the temperature rise in the soil-cement mixture. In fact, the modified Parrot and Killoh's model (parameters of the original model were modified by using updated data in hydration) is used in CEMGEMS which is a free online tool developed by GEMS.

Table 1. Properties of various cement-treated soils from the literature

Soil	Plastic limit, (%)	Liquid limit, (%)	Plasticity index, (%)	Clay content, (%)	Water content, w (%)	Cement content, (%)	Year/ Reference
Kaolin clay	32.7	81.6	48.9	79.5	122.4	16	2023 [14]
Kibushi clay	27.4	44.7	17.3	17.3	67.1	10	2023 [14]
DL silt	n	n	n	6.5	44.8	8	2023 [14]
Sensitive marine clay	15.91	44.57	28.42	n	56.6	12	2023 [15]
Klett clay	n	n	4–8	30	30–35	7	2022 [7]
Fredrikstad clay	n	n	5–15	35	34–42	7	2022 [7]
Dredged Silt	26.9	58.8	n	35.1	88-132	10, 13, 15, 20	2022 [16]
Toyoura Silica Sand	n	n	n	n	100	8, 15	2020 [1]
Singapore UMC	25-36	85-92	n	50	180	11.8	2014 [8]
Singapore marine clay	36	85	n		135-185	10÷20	2011 [17]
Home Rule kaolin	33	64	31	88	45	1, 5, 10, 20	1967 [3],[18]
Rotoclay kaolin	30	58	28	40	115	10, 20	2010 [3],[19]
Singapore marine clay	35	87	52	68	120	5, 10, 20, 30, 40, 50, 60	2009 [3],[20]
Bangkok clay	43	103	60	69	86, 106, 136, 166	10	2004 [3],[21]
Ariake clay	60	125	65	55	106	10, 20	2003 [3],[22]

n - No data available

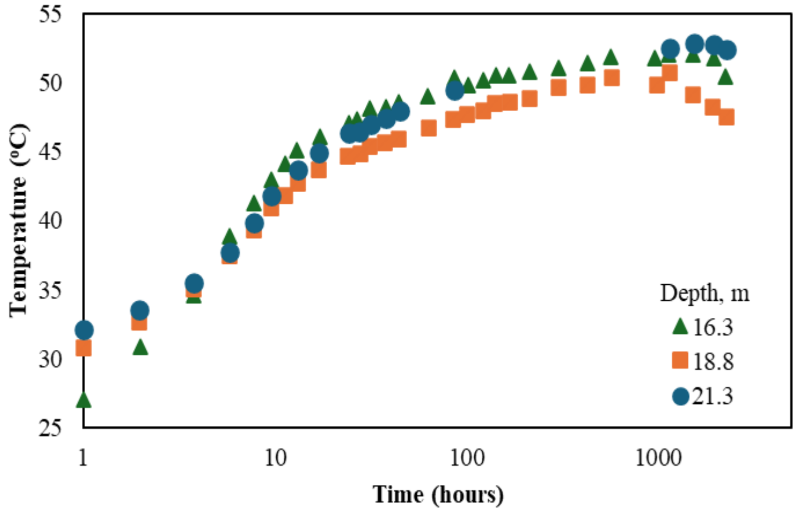


Figure 1. Temperature rise in cement-treated soil measured in situ (modified from previous study [10])

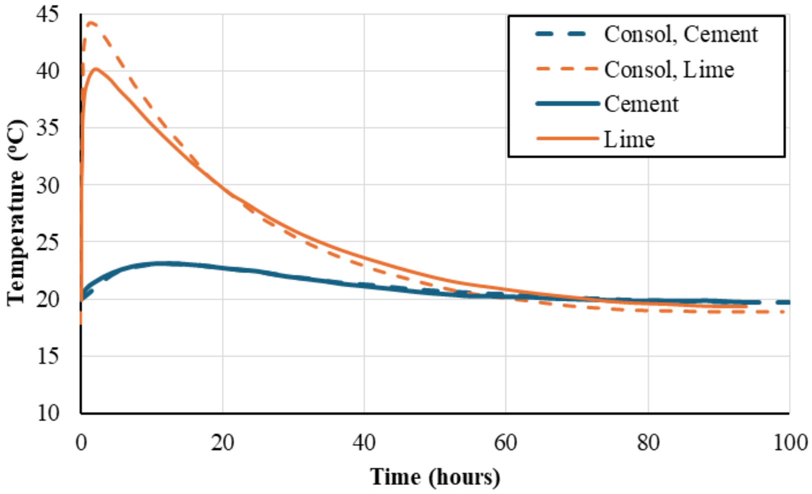


Figure 2. Numerical model (COMSOL) with results from experiment test under semi-adiabatic condition (modified from previous study [7])

4. Mechanical properties of cement-treated soils under high curing temperatures

4.1. The effect of curing temperature on strength development

The increased temperature in cement-treated soil due to heat generated from hydration results in significant strength improvement, especially in the early stages. Ho's study was performed on Toyoura sandy soil with very low pozzolanic properties treated with 15% cement content [1]. The authors used different types of cement: HPC (high early-strength Portland cement), OPC (ordinary Portland cement), and MPC (moderate heat Portland cement), and the molded specimens were cured at room control temperature (20°C) and high temperature (40°C) for each specimen type. In general, the results showed that the compressive strength of the same specimen type at high temperatures is higher than that of specimens at room temperature during the curing period. Nevertheless, in the early stages of less than 7 days, the gap is very large and converges in later stages of curing. At 7 days of curing age, the specimens using OPC increased by more than 30%, of which the MPC specimens increased by 100% while with HPC the trend was lower, and the strength increased insignificantly at the late stage of curing. To explain this phenomenon, the authors believe that when HPC itself is mixed with water, the hydration process at an early age of curing occurs quickly compared to other cement types due to the higher amount of clinker Alite (C_3S) in the HPC composition. At high temperatures, the hydration rate of HPC is promoted, leading to a cross-over phenomenon [41].

Before Ho, in a study by Saitoh et al. in 1980 [2], two types of Yokohama and Osaka clay were treated with cement and cured at five different temperatures of a range from 10÷50°C within 28 days. The results indicated that the strength of the same specimen type at high temperatures is greater than at low curing temperatures. This influence of curing temperature is more dominant on the short-term strength but diminishes with longer curing periods.

In 2009, Kido et al. [2] conducted laboratory experiments on peat soil excavated from Hokkaido, Japan, which has a high water content of 550%, and high organic matter. To treat soil, the authors used both blast furnace slag cement and cement-based special binder with three various cement contents of 20, 30, and 40%, respectively. After casting, molded specimens were cured at five different temperatures: -20, -5, 0, 5, and 20°C. At minus curing temperatures, the strength development of the specimens treated with the above two types of cement is almost not much different at 28 days of curing (Fig. 4a and b). Conversely, at positive curing temperatures, the compressive strength is considerably enhanced, especially at the higher curing temperature. The special cement-based binder shows high applicability for the treatment of this peat soil due to the strength being improved by more than two times compared to specimens treated with blast furnace slag cement.

Most recently, as far as the authors know, the study by Bache et al. on Norwegian clays [5] surveyed the strength of the field specimens (at 28 days) taken from several installed column locations at measured temperatures of 8, 41, and 75°C. It was found that the shear strength of specimens treated at high temperatures (Fig. 5a) was significantly improved by nearly two times at 40°C and more than four times at 75°C compared to specimens at 8°C [7].

Generally, with cement-treated clays, the strength is higher when treated at high temperatures at both early and late ages of curing and is explained by the following: (a) at high curing temperature, the high strength is caused by not only a higher degree of hydration but also a great extent of the pozzolanic reactions. (b) the ultimate strength increases due to the presence of more products from the pozzolanic reactions [8]. This is demonstrated in many previous studies [42]-[45]. However, soil with high organic content treated by cement and cured at high temperatures may have negative effects on strength. One explanation for this is that the acids arising from organic matter in soil react with $Ca(OH)_2$ produced from the hydration of cement. A high curing temperature favors the neutralization reaction between acids and $Ca(OH)_2$ more than the pozzolanic reaction [8].

4.2. Strength and Maturity relationship

Maturity is a concept used in the concrete industry to describe the simultaneous effects of curing temperature and curing time on strength development. Similarly, this concept is accepted in the treatment of soil and employed to combine the influences of time and temperature on mechanical enhancement [1],[2],[46]. Regarding cement-treated soils, several definitions of maturity have been proposed, of which there are four notable proposals [2] as follows:

$$M_1 = \sum (T - T_0) \times \Delta t \tag{1a}$$

a general definition for cement-concrete,

$$M_2 = 2.1^{(T-T_0)/10} \times \Delta t \tag{1b}$$

proposed by Nakama et al. (2004),

$$M_3 = \left\{20 + 0.5 \times (T - 20)\right\}^2 \times \sqrt{\Delta t} \tag{1c}$$

proposed by Ahnberg and Holm (1984), and

$$M_4 = 2 \times \exp\left(\frac{T - T_0}{10}\right) \times \Delta t \tag{1d}$$

proposed by Babasaki et al. (1996).

Where: M_i – maturity of cement-treated soil; T – average temperature during the curing period of Δt; T_0 - datum temperature (-10 °C); Δt - time interval (days).

The relationship between strength and the logarithm of maturity is described differently, indicating that environmental temperatures significantly impact short-term strength but have a minimal effect on long-term strength. Bache [7] appeared to agree with the M_3 definition in their study, while in the study by Ho [1] the M_1 model is applied, which is understandable as Ho used Toyoura sand that has almost zero pozzolanic activity, so the maturity, in this case, is similar to the general definition for cement concrete.

The important meaning when using the maturity concept in cement-mixed soils pointed out by Kitazume and Nishimura (2009) [2] in their research is the ability to predict the strength of the cement-soil mixture according to age (Fig. 6a and b). In this research, two graphs were constructed: (Fig. 6a) Relationship between compressive strength and temperature according to age; (Fig. 6b) Relationship between compressive strength and maturity. Graph (6a) shows that the strength of specimens with the same cement type at 14 days of curing age greater than at 7 days of age for various temperatures. This implies that the data points are distributed into two separate lines depending on the curing age. Meanwhile, when presented in graph (6b), the strength data points are distributed along unique lines, each line represents a different binder content. This helps predict the strength of 28-day-cement-mixed soil cured at normal temperature (20°C) through the early strength test of specimens cured at high temperatures. The authors indicated that according to equation M_4, 4.8 days at 20°C corresponds to 28 days at 40°C concerning maturity. However, estimating long-term strength at very low temperatures (7℃) is challenging to the experimental results they obtained due to the concaved shape of the strength and maturity relationships [2].

Therefore, depending on soil type, maturity can be described as consistent with one of the four concepts mentioned above, and a new maturity concept can even be introduced if it better reflects the strength depending on time and temperature.

4.3. Prediction model for strength development

It is believed that the strength development can be accurately predicted by knowing the temperature development in cement-mixed soil. However, to the authors' knowledge, no widely accepted strength prediction model considers the influence of curing temperature in the soil treatment field.

A proper model proposed to predict the strength of cement-mixed soil in the laboratory as well as in the field needs to assess factors affecting the strength under each specific condition. The main factors affecting strength enhancement behavior in the laboratory must be considered: soil type, cement content and cement type, water content, organic composition, fine particle content, curing temperature, mixing method, etc. In onsite, in addition to the above factors, other factors also need to be considered such as environment, mixing process, machine, etc [2]. Models for predicting the strength of cement-treated soil at room temperature are proposed and reported in several literature [21],[23],[47]-[49]. Nevertheless, building a strength development model of cement-treated soil that considers the influence of temperature is always a challenge for researchers.

In 2004, Chitambira proposed a model for the predicting strength development of granular soils treated with cement at various temperatures based on Arrhenius' law [47]. Arrhenius' law is a famous theory for estimating the effect of temperature change on the rate of chemical reactions. It is widely applied in the field of cement concrete [40], [50], [51]. The strength equation by Chitambira can be expressed as follows:

$$\ln\left[q_u(t,T_r)\right] = \alpha.\left\{1-\exp\left[-\beta.(\ln t)\right]\right\} = \alpha.\left(1-t^{-\beta}\right) \tag{2a}$$

$$\begin{aligned} q_u(t,T) = q_u(t_e,T_r) &= \exp\left(\alpha.\left\{1-\exp\left[-\beta.(\ln t_e)\right]\right\}\right) \\ &= \exp\left(\alpha.\left\{1-\exp\left[-\beta.(\ln t + a_T)\right]\right\}\right) \end{aligned} \tag{2b}$$

$$a_T = \ln\left(\frac{t_e}{t}\right) = \frac{E_a}{R}\left[\frac{1}{T_r}-\frac{1}{T}\right] \tag{3}$$

Where: E_a - apparent activation energy (J/mol); R – universal gas constant (~8.3144 J/mol K); T - curing temperature (K); t and t_e – time required to produce the same amount of reaction product at T and T_r, respectively (days); $q_u(t_e,T_r)$, $q_u(t,T)$ - unconfined compressive strengths (UCS) at curing age t_e and t under the reference temperature T_r and curing temperature T, respectively; α and β – empirical curve-fitting parameters [49],[51]; a_T - is a temperature-based shift factor, which can be determined graphically following the graph-shifting technique proposed by Chitambira [47]. Similar procedures have been employed in ASTM C1074-98 for estimating concrete strength using the maturity methods.

Based on Chitambira's model, Zhang et al. [8] developed and proposed a model proper for the cement-treated Singapore marine clay. The authors added to Chitambira's equation temperature-induced strength improvement factor. This factor is determined by the ratio of the ultimate strength at a given curing temperature to the ultimate strength at the reference temperature $\eta'_T = q_{u,ult}(T)/q_{u,ult}(T_r)$. The coefficient η'_T affects strength at all ages of curing, despite the ratio being between ultimate strengths. This is due to pozzolanic reactions occurring almost concurrently with cement hydration, except during the initial curing stage when the $Ca(OH)_2$ produced from hydration is inadequate and the ultimate curing stage when the cement is completely hydrated. Consequently, the modified Chitambira equation is expressed as follows:

$$q_u(t,T) = \eta'_T.q_u(t_e,T_r) = \eta'_T.\exp\left(\alpha.\left\{1-\exp\left[-\beta.(\ln t + a'_T)\right]\right\}\right) \tag{4}$$

where a'_T and η'_T calculated by using the least squares method. It should be noted that the modified shift factor a'_T determined using this method may differ in magnitude from the shift factor a_T in Chitambira's equation, which is obtained through the graph-shifting technique with a'_T = 0 and η'_T = 1.0 at the reference temperature T_r.

The authors note that this model can be utilized for any new soil type or any new binder type, but pilot testing must first be conducted to establish the model parameters [8].

The most recent study by Hara et al. [14] to the authors' knowledge, proposed a method to estimate the strength of cement-treated soil at a reference temperature (typically, 20°C) for any given material age. However, as noted by the authors in the study, a limitation of the proposed method is that it was applied only to materials aged up to 112 days, and the obtained result was based on three types of fine-grained soils. In this method, specimens are cured at two high temperatures. The curing time selected at each curing temperature must be shorter and longer than the curing time to estimate the strength when converted to the equivalent age. As in the concrete field, equivalent age refers to the age of cement-treated soil cured at a reference temperature that would result in the same degree of hydration and strength development as cement-treated soil cured at different temperatures. The equivalent age is calculated based on Arrhenius's equation, which accounts for the temperature-dependent nature of the hydration reaction. In their study, thermogravimetric analysis is used to evaluate the progress of the hydration reaction based on the concept that hydrates, produced by cement hydration and pozzolanic reactions, dehydrate and decompose at extremely high temperatures (up to 440 °C). To estimate the strength of cement-treated soil by equivalent age, the activity energy (E_a) and represent constants (A, B) must be determined via the least-squares technique using the equation:

$$q_u = A\log(a_e) + B \tag{5}$$

Additionally, an approach widely used in concrete fields to estimate the strength is employing the maturity concept that can also be used for cement-treated soils. This method is presented above in several studies [1],[2],[7].

4.4. Stiffness/Elastic Modulus

The elastic modulus of cement-treated soil (E_{50}), also known as the secant modulus of elasticity, can be determined by using a strength test via a graph of the stress-strain curve. Normally, the elastic modulus has a linear relationship with the strength of the soil [2]. Therefore, the strength of cement-treated soil increases under higher curing temperatures which means that the elastic modulus also increases. Bache demonstrated the shear strength of cement-treated Norwegian clays increased more than four times at 75°C, and about two times at 41°C compared with those at 8°C. Similarly, the elastic modulus of cement-treated Norwegian clays was higher ten times and three times at 75°C and 41°C, respectively than that at 8°C [7]. The explanation is that under high curing both cement hydration and pozzolanic reaction were promoted thereby products such as C-S-H and C-A-H from these reactions produced much more leads resulting in increased strength and stiffness. This phenomenon was also found in various studies reported in [2].

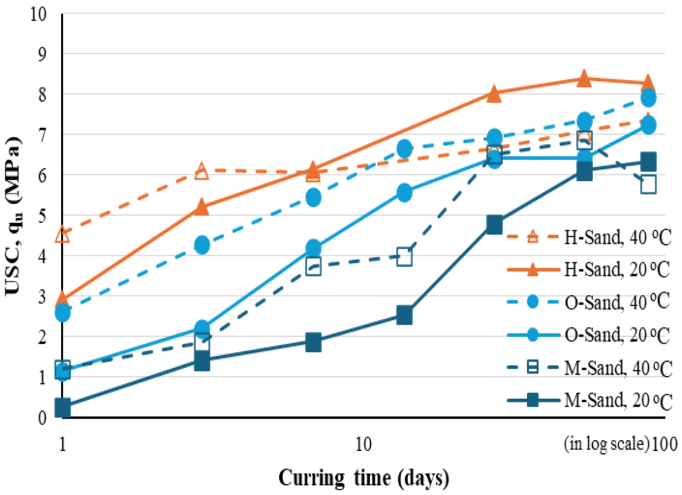
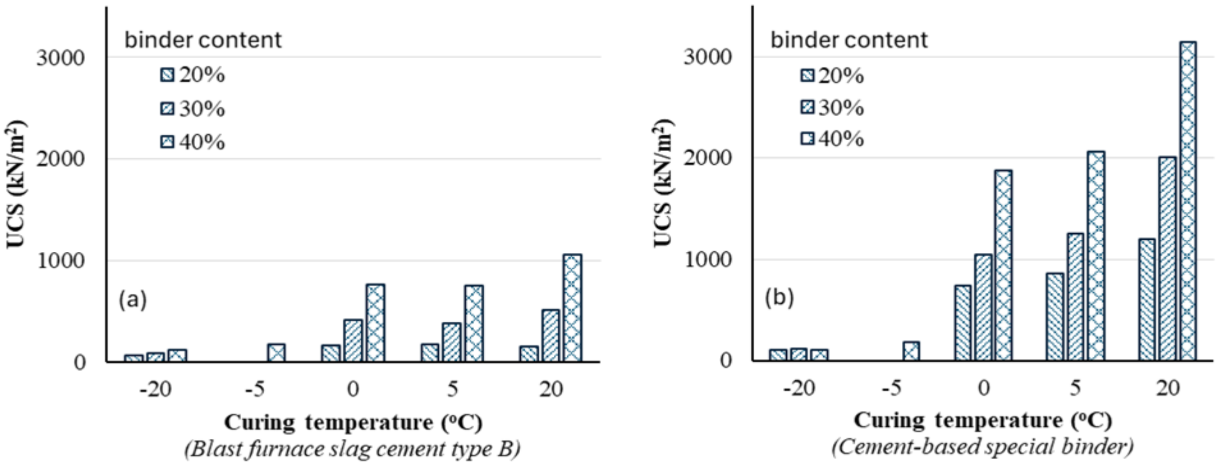


Figure 3. Development of compressive strength of sand treated with a cement ratio of 15% (modified from the previous study [1])



(Blast furnace slag cement type B)

(Cement-based special binder)

Figure 4. Relationship of compressive strengths of cement-treated peat soil and temperatures (modified from previous study [2])

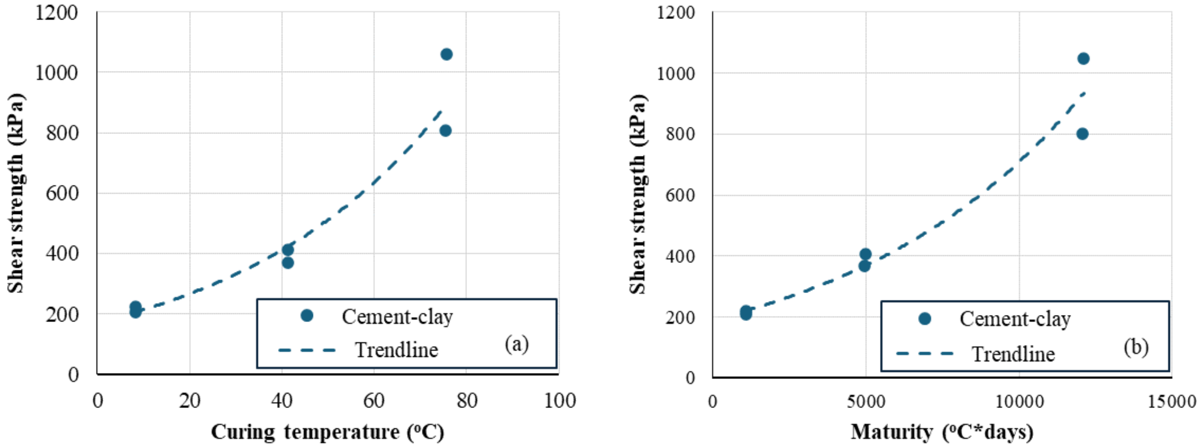


Figure 5. Relationship of shear strength of Cement-treated Norwegian clay against curing temperature/maturity (modified from the previous study [7])

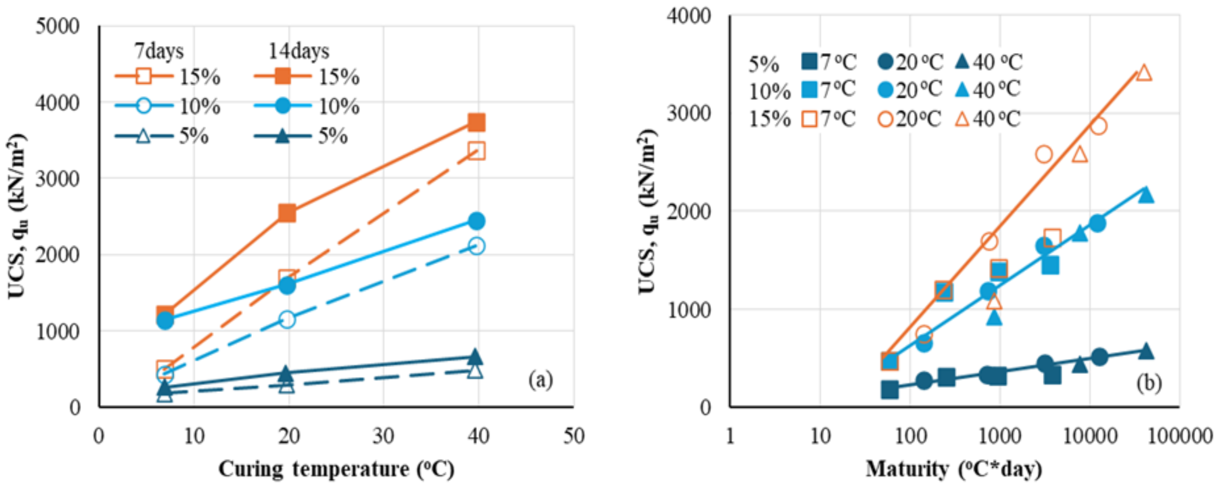


Figure 6. Relationship of compressive strengths, q_u, and temperature/maturity (modified from previous study [2])

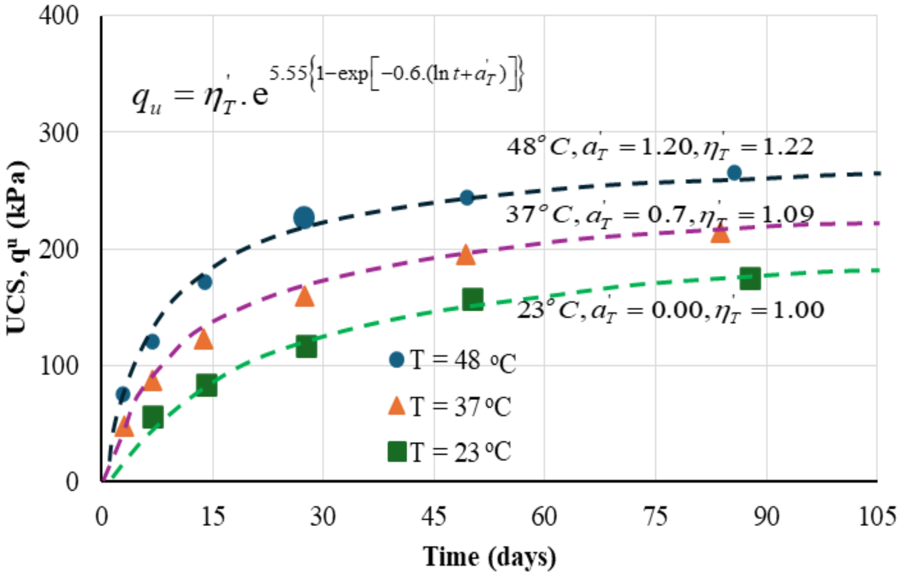


Figure 7. Comparing the developments of strength by Zhang's model and experimental results (modified from previous study [8])

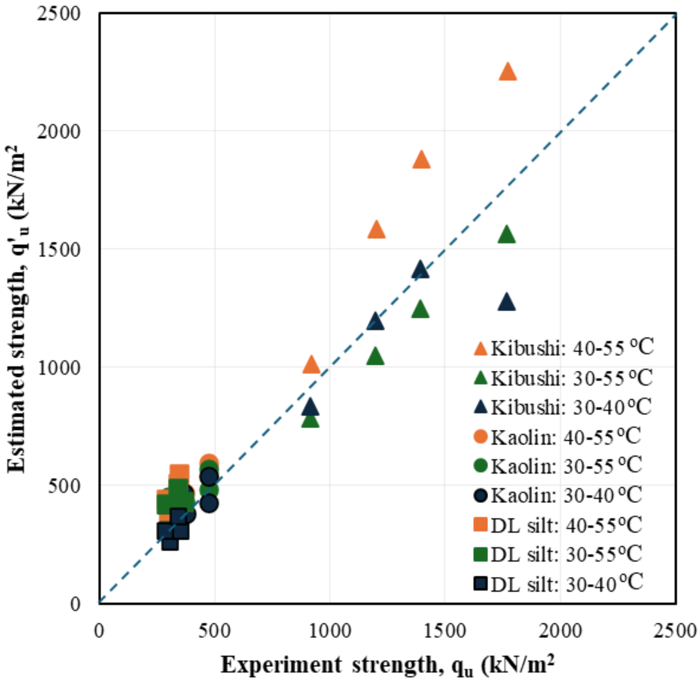


Figure 8. Verification accuracy of estimated strength (for cement treatment of three types of fine-grained soils) determined by using the method proposed by Hara et al. [14]

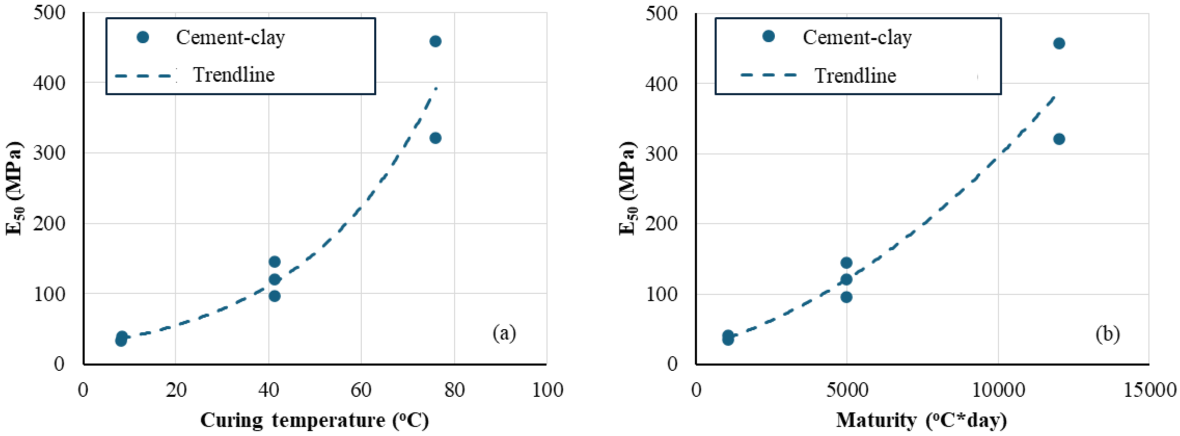


Figure 9. Relationship of modulus of elasticity of Cement-treated Norwegian clay against curing temperature/maturity (modified from previous study [7])

5. Chemical analysis of cement-treated soil at different temperatures

5.1. Thermogravimetry analysis to determine chemically bound water content

The formulas for determining chemically bound water by Ho [1] is expressed as follows:

$$W_{CB} = [L \ - L_C \times (C/100) - L_S \times (S/100)] \times (100/C) \quad (6)$$

Where: W_{CB} is chemically bound water content (% by weight); C, and S are the ratios of cement and soil in the sample (% by weight), respectively; L is mass loss of the sample in the range of 100÷1000°C (% by weight), L_C is the mass loss of the unhydrated cement in range of 100÷1000°C (% by weight), and L_S is the mass loss of soil in range of 100÷1000°C (% by weight). According to equation (6), the mass loss of the sample in the temperature range of 100÷1000°C after deducting the mass loss of unhydrated cement and untreated soil is the dehydration of the reaction products produced from hydration and pozzolan reactions. Nevertheless, other researchers believe that the temperature range where decomposition and dehydration occur is from 110 up to approximately 440°C [14,52]. Therefore, it is necessary to consider an appropriate temperature range to accurately describe the decomposition nature of chemical compound products to increase the reliability of the results.

At high curing temperatures, both hydration and pozzolanic reactions accelerated leading to increased chemically bound water faster, especially at an early stage of curing. This explanation for high strength improvement at the early stage. Ho [1] measured W_{CB} for cement-treated sand using different types of cement under different curing temperatures. Authors indicated that W_{CB} measured under 40°C is always higher than those at 20°C at the early stage of curing up to 14 days. Similar to Ho's research results, Hara et al. demonstrated that an index of the process of hydration reaction (the mass reduction ratio from 110 to 440°C) increased with an increase in curing time for all samples with various soil types under different curing temperatures [14]. In both studies, authors found it applicable to represent the strength development according to W_{CB} [1] or an index of hydration progress [14]. If in Ho's study, the relationship between them is linear with R-square = 0.71, in Hara's study it is described in a curve with R-square = 0.83. Thus, the strength development of cement-treated soils can be predicted through an index related to the chemically bound water calculated based on the TGA test results. It should be noted that the experiment procedure and data analysis need to ensure reliability to avoid errors easily encountered [53].

5.2. X-ray Diffraction

The mechanisms of cement treatment to improve soil properties include the occupation of large pores and the binding of the soil particles by the hydration products of the cement component to form a denser and/or cemented soil structure [2,6]. The main hydration products such as C-(A) S-H gels, Ettringite, and Portlandite that affect the mechanical enhancement of cement-treated soils can be investigated using XRD patterns. Through XRD, main minerals can be identified qualitatively or quantitatively. Regarding qualitative analysis, based on the change in height of the mineral peak to evaluate the change in its composition ratio in the sample (Fig. 12). Quantitative analysis allows accurate assessment of changes in mineral composition ratios, thereby explaining the chemical mechanism occurring during curing time. In fact, studies often combine XRD analysis with one or several other experiments such as TGA, MIP (void volume analysis), or SEM (microstructure analysis) to explain the chemical mechanism more accurately.

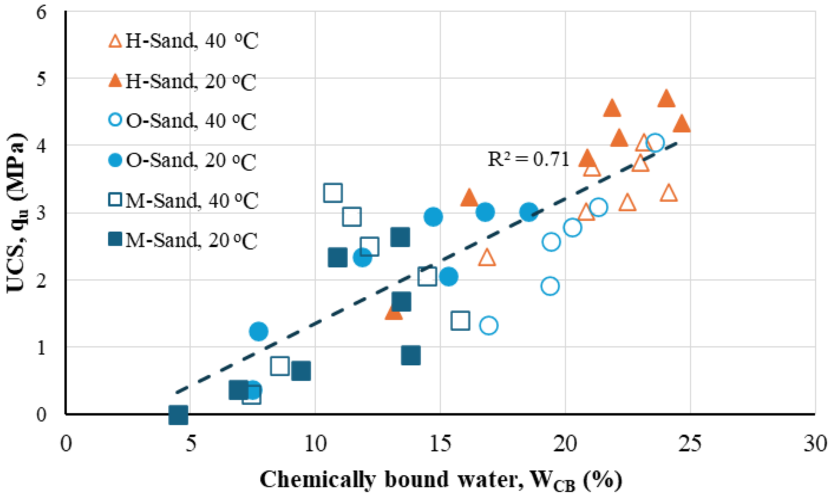


Figure 10. Relationship between the compressive strength, q_u and W_{CB} for Toyoura sand treatment using 8% cement (modified from previous study [1])

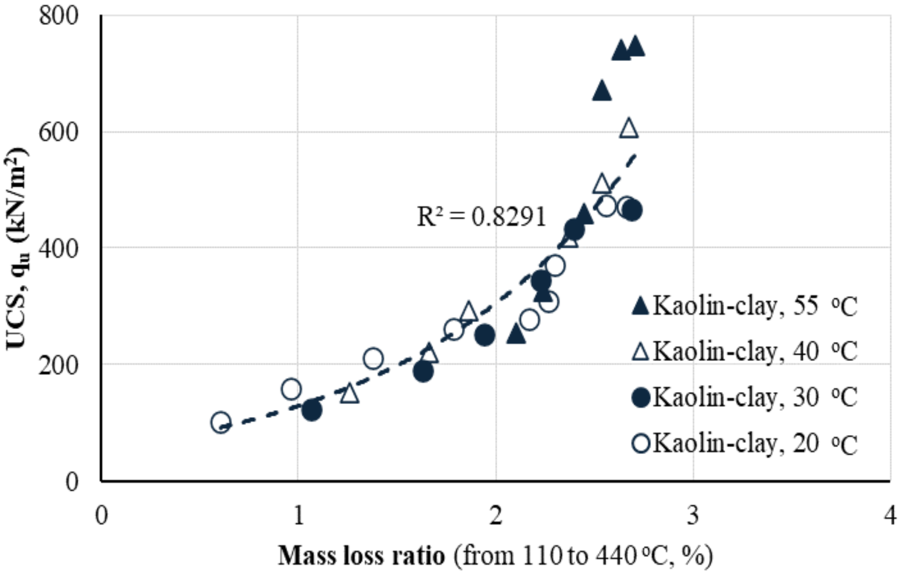


Figure 11. Relationship between compressive strength, q_u, and mass reduction ratio (in %) (modified from previous study [14])

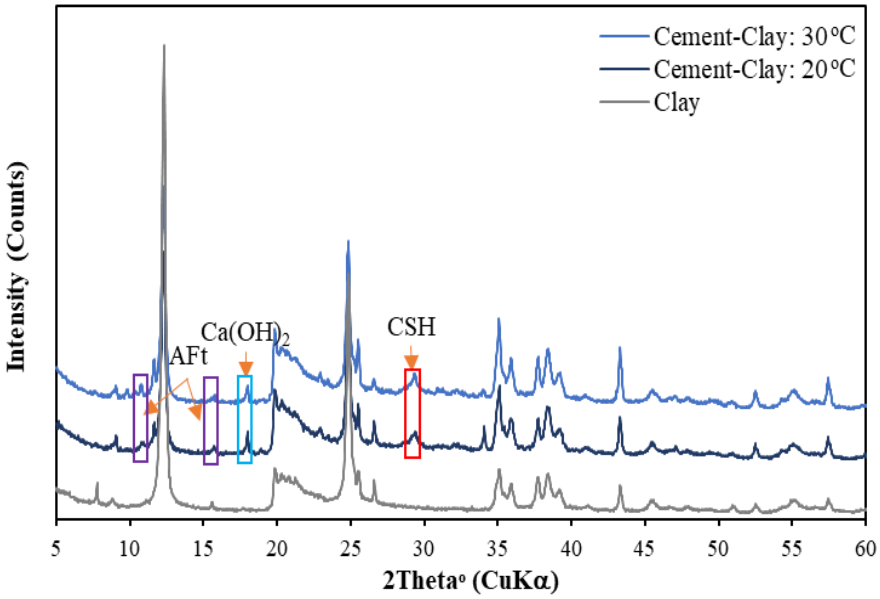


Figure 12. XRD pattern for qualitative analysis of main phases in cement-treated clay excavated from Kanto region, Japan at 28 days of curing

6. Conclusion

According to the review on the effect of curing temperature on the mechanical properties of cement-treated soils, some conclusions can be drawn as follows:

- The strength development and stiffness of cement-treated soil significantly improved under higher curing temperatures, especially at an early stage of curing. Secant modulus of elasticity related to strength by linear relationship.

- The temperature evolution in soil resulting from cement hydration can be predicted for all cement ratios.

- Models for predicting the strength of cement-mixed soils that consider the influence of temperature have been proposed in many studies. Among them, the thermodynamic model based on Arrhenius's theory receives more interest because it describes the nature of the chemical reactions inside cement-mixed soil at environmental temperature change.

- Maturity is applied in cement-treated soil to predict the strength gained over time by considering the temperature history. A relationship between maturity and strength will be specific to a particular binder and its proportion.

- Through the TGA test, the chemically bound water - an index that describes the degree of chemical reactions in cement-treated soil involving hydration and pozzolanic reactions - can be determined. Establishing a model to predict the strength development of cement-treated soil based on chemically bound water is entirely feasible. A range of temperatures chosen to determine the chemical-bound water index should be considered based on the curing conditions.

- Using the XRD test to identify the main phases of cement hydration products, such as C-S-H, ettringite, and calcium hydroxide, is crucial for understanding changes in the mechanical characteristics of cement-treated soil.

Limitations and future work:

- The effect of temperature on other mechanical properties such as tensile strength is not mentioned in the present study.

- The negative influence of temperature on the physical and mechanical properties of cement-mixed soil has not been discussed in depth in the present study.

- Other experimental tests including MIP, and SEM for discussing the microstructure change in cement-treated soil under high curing temperatures are also not mentioned in the present study.

- Other binder like lime when mixed with soil also generates heat to increase internal temperature in soil and additives such as blast furnace slag, fly ash... widely used in practice are also not mentioned in the present study.

- Strength is a key parameter in cement-soil treatments. Accurate prediction of the strength of cement-treated soil can significantly enhance efficiency by reducing testing costs and shortening the project implementation period. Based on the prediction models discussed in this study, developing a new model or enhancing an existing one to predict strength for various soil types, while considering the influence of curing temperature, holds substantial importance in further research work.

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