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Comprehensive analysis of cement-stabilised dredged marine soil: Evaluating physical, microstructural, and mechanical characteristics

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Abstract:

This study evaluates the index, microstructural, and mechanical behaviour of cement-stabilised soft soil. The marine soil dredged from Hangzhou is taken for the study. Different percentages of ordinary Portland cement (OPC) by dry mass were added to the soils during reconstitution, i.e., 5, 10, 15, and 20%. The reconstituted samples were analysed in the laboratory to determine basic properties such as moisture content, void ratio, density, specific gravity, consistency limits, and particle size distribution. The microstructures of the reconstituted samples were also evaluated through scanning electron microscopy. Results inferred a significant impact on the physical properties of the soil. An increase in cement content increases the consistency limits. Additionally, the specific gravity, plasticity index, and density of the treated soil initially decreased but increased upon further addition of cement content. The microstructure of the soil transformed from a dispersed to a flocculated structure, with larger and denser particles. The change in microstructure was also evident in the particle size distribution, with an increase in cement content leading to larger size particles. Finally, the unconfined compression test conducted on the reconstituted soil indicates a substantial enhancement in strength with higher cement content and prolonged curing periods.

Keywords: **cement, mechanical properties, microstructure, self-pozzolanic, soft soils, soil stabilisation.**

Classification number: **2.3**

1. Introduction

Soil is the product of various physical and chemical phenomena of nature, varying from place to place and over time due to factors influencing its formation. A significant factor in soil formation is water, whether flowing, stagnant, frozen, or sub-surface. Consequently, weak soils are often prevalent along riverbanks and coastlines. Nevertheless, construction on such flatlands with weak soil has been commonplace since ancient times. Many major cities worldwide have been established on riverbanks, lacustrine deposits, or coastal areas. Consequently, weak soil with poor mechanical properties poses a challenge for engineers in constructing infrastructure in these urban areas due to excessive deformation and failure in the foundation and substructure. To address these challenges, various methods of ground improvement have been employed to either compact or chemically modify soft soil to enhance its index and engineering characteristics. Common chemical stabilisers used for this purpose include cement, lime, fly ash, silica fumes, rice husk ash, eggshells, among others [1-5]. Following technological advancements, chemical stabilisation using cement has become the predominant ground improvement technique. However, many studies have pointed out sustainability issues using cement as the chemical stabiliser [6-7]. This method is preferred over other chemical stabilisation techniques such as lime and fly ash. Lime treatment may lead to an increase in site pH, while many fly ash products contain heavy metals. Moreover, for soft soil with high compressibility and low permeability, cement treatment is favoured over traditional techniques like dynamic compaction, which can cause detrimental vibrations in urban areas.

Numerous studies have been conducted to quantify the strength of cement-treated clays and have reported significant strength improvements compared to untreated clays [8-12]. Similarly, research has explored the mechanical behaviour of cement-treated clays, resulting in various constitutive models. However, limited attention has been given to the physical changes and behaviour of cement-treated clays [9, 13-16]. Therefore, this research aims to experimentally investigate soft soil to determine changes in physical, microstructural, and mechanical behaviours resulting from chemical reactions between soil and cement.

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The improvement in soil properties is primarily attributed to chemical reactions with cement. Portland cement, comprising tricalcium silicates (C_3S), dicalcium silicates (C_2S), tricalcium aluminate (C_3A), and tetracalcium alumino-ferrite (C_4AF), is the most commonly used cement in soil improvement. Major reactions between soil and cement include dehydration, ion exchange, and pozzolanic reaction [17, 18]. The primary hydration reactions and pozzolanic reactions processes are outlined below [18, 19]:

Primary cementitious product

$$2C_3S + 6H^+ \rightarrow C_3S_2H_3(\text{hydrated gel}) + 3Ca(OH)_2 \quad (1)$$

$$2C_2S + 4H^+ \rightarrow C_3S_2H_3 + Ca(OH)_2 \quad (2)$$

Secondary cementitious product

$$Ca(OH)_2 + SiO_2 \rightarrow C - S - H \quad (3)$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow C - A - H \quad (4)$$

The hydrated lime releases calcium ions (Ca^{2+}), causing a rise in pH, which is crucial for pozzolanic reaction. These calcium ions then react with the soil silica and soil alumina to form cement hydrates; hydrated calcium silicates (C-S-H) and hydrated calcium aluminates (C-A-H), respectively [20]. This reaction formed soil-cement structures, which play a vital role in strength development. The term "structure" was coined by R.J. Mitchell (1970) [21] and defined by J.B. Burland (1990) [22] as the amalgamation of bonding and fabric. The fabric component deals with the arrangement of soil particles, while bonding defines the forces between soil fabric. Under load, the degradation of cementation mainly occurs due to the loss of bonding structures [23, 24] while the fabric component remains stable and unaffected by loading. The process of soil-cement hardening was first proposed by S. Saitoh, et al. (1985) [25], as shown in schematic diagrams (Fig. 1), which illustrates the change in the soil-cement structures during the hardening process. Specifically, Fig. 1A shows that initially the clusters of clay particles are surrounded by a cement slurry. Then, the primary hydration reaction occurs in the cement slurry so that hardened cement is formed around the cluster of clay particles (Fig. 1B).

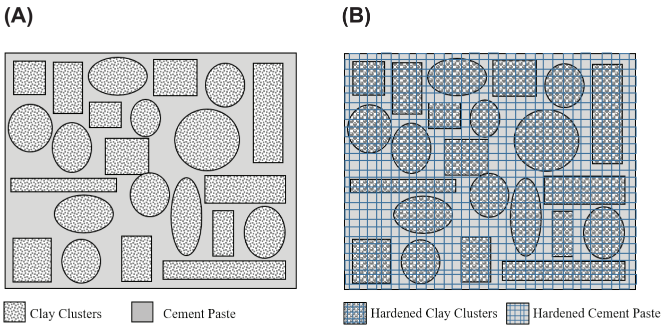

Fig. 1. Schematic illustrations of improved soil: immediately after mixing (A), after hardening (B).

The microstructure of treated soils is primarily influenced by the type of admixture used for stabilisation. For example, the absence of primary hydration reaction in lime-treated soil may result in a distinct microstructure compared to cement-treated soil. Several studies have investigated microstructure using techniques such as X-Ray Diffraction (XRD) and scanning electron microscope (SEM) [26-30]. Research on Singapore clay noted that untreated clay exhibits an open microstructure, while cemented clay shows a flocculated microstructure where clay-cement clusters are separated by large intercluster voids [28]. Similarly, a study on very expansive Handan clay treated with 12% cement content observed structural changes from a dispersed to a flocculated and finally agglomerated structure over the long term [31]. The effect of cement on microstructure is significant, with higher cement content leading to a more flocculated nature of soil fabrics [17].

The major factors controlling physical changes in cement-stabilised soil are the amount of cement and the curing period [18, 26, 30]. However, few studies have focused on evaluating the physical properties of cemented soil. One comprehensive laboratory investigation on cement-treated Bangkok clay reported negligible changes in liquid limit (LL) due to treatment [11]. However, plastic limit (PL) gradually increased with the amount of cement and curing period, leading to a significant decrease in the plasticity index (PI) of treated soil. Similarly, the specific gravity of treated soil decreased with increasing cement content and curing period. The predominant parameter for the decrease in specific gravity (G_s) and PL is the curing period, allowing time for reactions between cement and clay constituents. Another study on treated soil cured without confinement showed a higher LL than cured under pressure, attributed to entrapped water within soil particles that did not affect particle interaction [29]. This increase in LL is attributed to entrapped water within the soil particles, which does not affect the interaction between particles. Moreover, the study on Bangkok clay revealed that the unit weight of the treated specimen increases with the increase in the cement and curing period.

2. Materials and methods

2.1. Materials

Soil: Dredged soil collected from the coastal region of Hangzhou, China, underwent examination for its physical characteristics and chemical composition, as detailed in Table 1. This marine soil has an LL of 52.33%, a PI of

16.29%, and 4.41% organic matter. According to the Unified Soil Classification System (USCS), it falls into the category of high-plasticity silt. The primary chemical components of this soil consist of SiO_2 and Al_2O_3. Additionally, a gradation analysis revealed that over 99% of the soil is fine-grained, with clay-sized particles (<2 µm) constituting only 16%, as depicted in Fig. 2.

Table 1. Physical properties and chemical composition of soils.

Physical Properties		Chemical composition	
Liquid limit (LL)	52.33%	SiO_2	58.69%
Plastic limit (PL)	36.04%	Al_2O_3	19.63%
Plasticity index (PI)	16.29%	Fe_2O_3	8.24%
Specific gravity (G_s)	2.76	Na_2O	4.42%
Clay (%), size range <2 µm	15.84%	MgO	3.69%
Silt (%), size range 2-75 µm	84.14%	K_2O	2.74%
Sand (%), size range 75-200 µm	0.02%	CaO	2.39%
Organic content	4.41%	MnO	0.15%
Soil classification	MH		
Depth of sampling	-		
Location	Hangzhou, China		

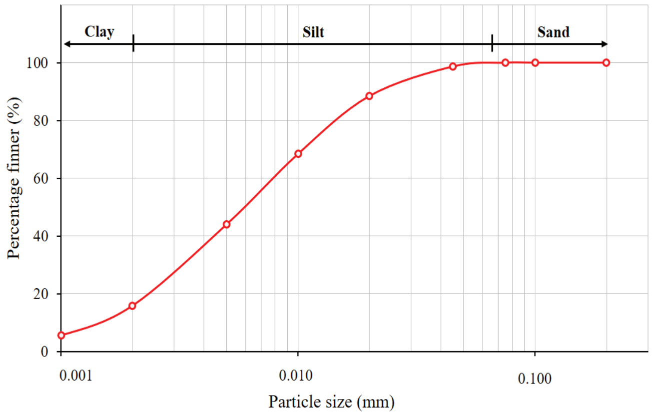

Fig. 2. Particle size distribution of dredged marine soil.

Cement: Regular Portland cement was employed for chemical stabilisation in this study. The composition of ordinary Portland cement (OPC) was determined using X-ray fluorescence spectrometry (XRF) and comprises: CaO 57.25%, SiO_2 23.54%, Al_2O_3 6.6%, Fe_2O_3 3.25%, SO_3 2.74%, Na_2O 0.15%, and K_2O 0.71%, along with a loss on ignition of 3.13%. Reconstituted samples with varying cement content were prepared to assess the effect of cement.

2.2. Sample preparation

The soil was dried at room temperature, and after seven days, negligible moisture loss was observed, thus considered as dry soil. The air-dried soil was pulverised using a wooden hammer, sieved through a 425 µm [No 40] sieve, and stored in an airtight plastic bag to prevent further moisture exchange. Before sample preparation, distilled water was de-aired using a vacuum pump with a capacity of 100 kPa.

The soil was then mixed with predetermined amounts of cement and water. The water content used for reconstitution was taken as 100% of dry soil mass [32, 33]. The water content is selected based on the natural water content of soil found in different places like, Singapore, Hong Kong, Bangkok, and Japan, which varies from 80 to 120% and the commonly used water content in deep cement mixing and grouting also varies from 90 to 110% [34]. The samples were prepared following methods from the literature [5, 30, 35]. As presented in the Fig. 3, the soil-cement-water mixture was mixed for 10 minutes, considering the significance of mixing time [36]. The mixture was then poured into a mold with a diameter of 39.1 mm and a height of 80 mm. These samples were cured under free drainage conditions at a constant temperature of 25°C for different periods of up to 56 days. Cement-treated soil samples were prepared as presented in Table 2 to evaluate the effect of cement on the physical, microstructural, and mechanical behaviour of reconstituted soil through various laboratory investigations (Figs. 3I-3IV).

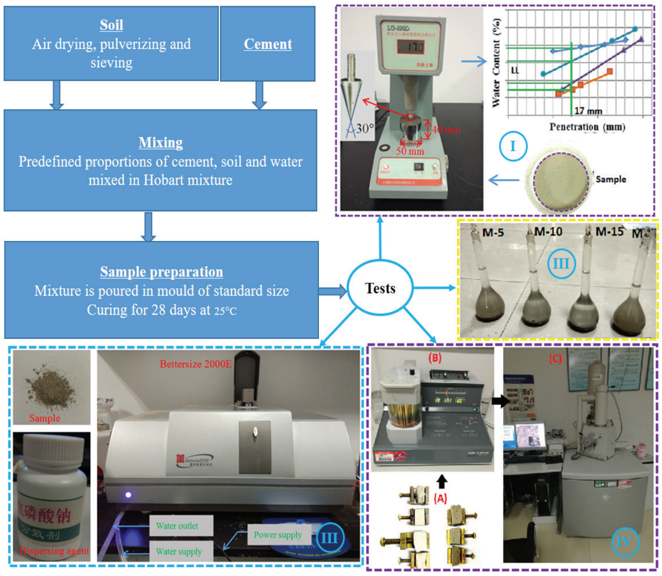

Fig. 3. Sample preparation flow chart and laboratory equipment. (I) Specific gravity, **(II)** Liquid limit and plastic limit, **(III)** Particle size distribution analysis using Bettersize 2000E, and **(IV)** with **(A)** SEM samples, **(B)** BAL-TEC/SCD 050 sputter coater and **(C)** FEI Quanta 200 ESEM/VPSEM scanning electron microscope.

Table 2. Characterisation of cement-treated samples.

Soil	Cement content (%)	Water content (%)	Curing days	Curing temperature	Sample code
Marine Soil	5	100	28	25°C	M-5
	10	100	28	25°C	M-10
	15	100	28	25°C	M-15
	20	100	7, 14, 28, 56	25°C	M-20

3. Results and discussion

The changes in physical properties due to cement were thoroughly studied, considering various physical quantities. Furthermore, microstructural behaviour was examined through SEM, and mechanical behaviour was assessed using uniaxial compressive strength (UCS). Dredged marine soil reconstituted with 5, 10, 15, and 20% cement content was utilised to evaluate behaviours. The results from the laboratory investigation are discussed as follows.

3.1. Effect of cement on the specific gravity of stabilised soils

The variation in specific gravity (G_s) of the cement-treated soil is presented in Fig. 4F. For dredged marine soil, the G_s value decreased from 2.76 to 2.69 when the cement content increased to 20% in the untreated soil. The rate of decrease is small at lower cement content but increases with the increase in cement content (up to 15%) and remains constant afterwards. A study on cement-treated Bangkok clay concluded that an increase in cement content significantly reduced the specific gravity [11]. The decrease in the rate of reduction of G_s at higher cement content resembles the behaviour observed in this study. This reduction may be attributed to the agglomeration of fine particles forming clusters with entrapped air [37]. Therefore, it can be inferred that an initial increase in cement content significantly reduces the G_s of treated clay, but after a certain cement content, G_s increases with further cement content.

3.2. Effect of cement on index properties of stabilised soils

The variations in the LL of the treated samples are presented in Fig. 4A. The result shows that the increase in cement content significantly increases the LL. Similar observations have been noted in lime-treated Louiseville clay [38] and cement-treated Singapore clay at lower cement content [17]. In Singapore clay, the LL slightly increased for cement content higher than 10%. This increase in LL may be due to the entrapped water in the cluster formed by aggregation and cementation of particles. On the other hand, H. Brandl (1981) [37] reported a divergent trend depending on the plasticity of untreated soil. He concluded that with more plastic soils, the LL decreases with an increase in cement content because of the formation of the clay clusters. Moreover, the trend is the opposite for low plastic soils, the presence of entrapped water in soil clusters plays the dominant role.

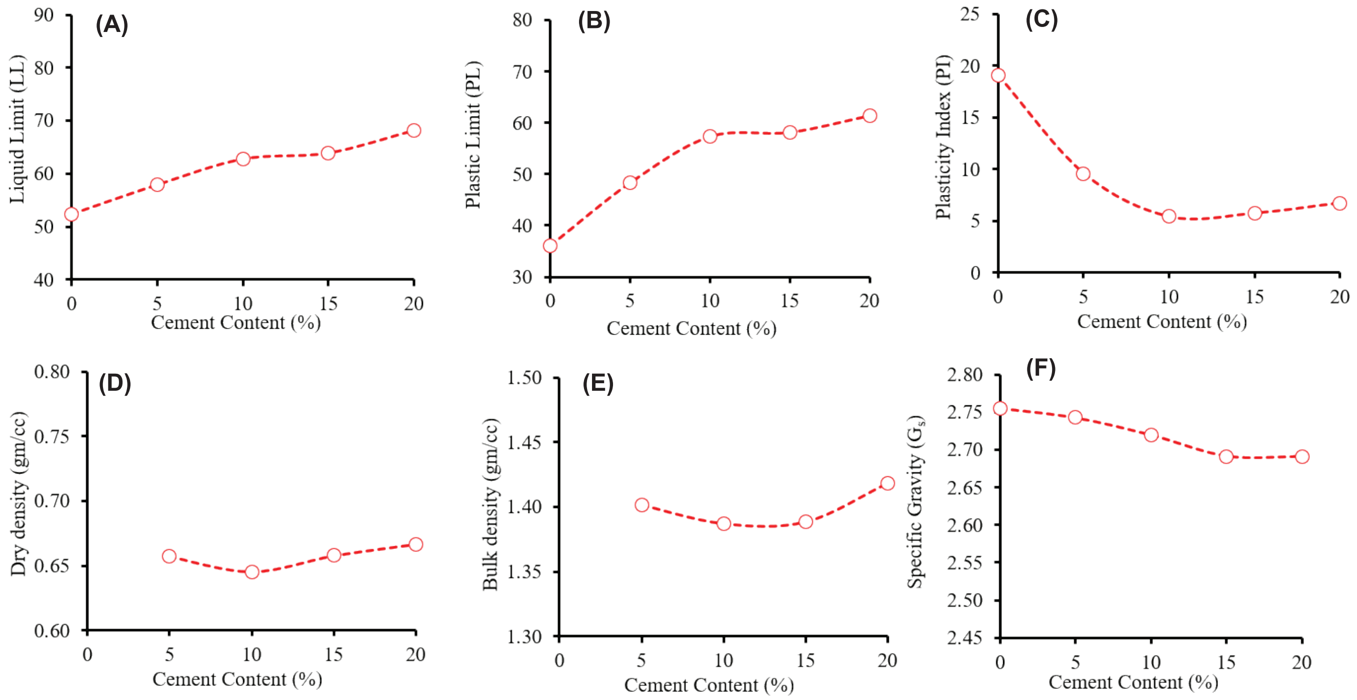

Fig. 4. Variation of physical properties of cement-treated soils.

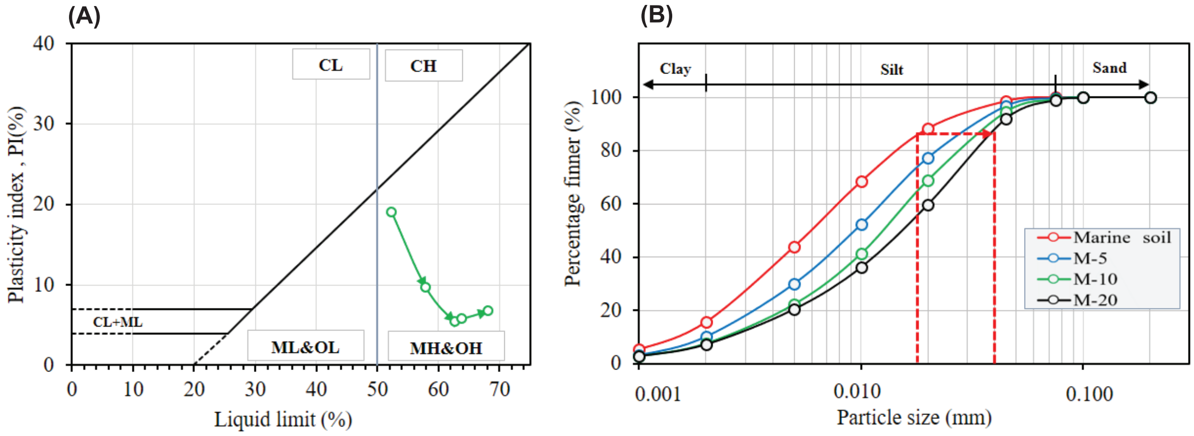

Fig. 5. Phase transformation of the cement-treated soils: plasticity chart (A), particle size distribution (B).

From Fig. 4B, it is evident that the PL of the cement-treated soils was higher than untreated soils. PL increases gradually until the 10% cement content, with an increment of 21.32%. However, further increases in cement content do not significantly affect the PL. A similar trend for PL was reported in cement-treated Bangkok clay [8]. The results show that both the LL and PL of the cement-treated soils increase with the increase in cement content. However, the increment rate of PL is higher than LL for lower cement content, resulting in a sudden decrease in PI (Fig. 4C). In contrast, PI for all ranges of cement content used in this study was found to be lower than untreated soil, although PI increases beyond a certain cement content (i.e. 10%).

The summary of Atterberg's limits is plotted on the plasticity chart based on the USCS (Fig. 5A). The chart infers that the soil lies in the high plasticity silt or organic soil category, with or without cement modification. The soil exhibits more silty behaviour after treatment with 15% cement content. The soil regains plasticity characteristics upon further increase in cement content but remains on the lower side compared to untreated soil.

3.3. Effect of cement on sample density of stabilised soils

The density for each specimen was calculated and plotted in Figs. 4D and 4E. The results show that the minimum density was found at 10% cement content, and the treated soil is denser on both sides of the cement content. A similar trend is observed in the dry density, with a minimum density at 10% cement content. According to a study treating soft, lean clay with cement up to 10%, the density rises with cement content [39]. The difference in the trend is primarily due to the presence of organic matter in the soil used in this study, unlike the inorganic soil used in previous research. However, the variation in density is found to be small and insignificant.

3.4. Effect of cement on the particle size distribution of the stabilised soils

The results of particle size distributions of treated and untreated dredged marine soil are presented in Fig. 5. Fig. 5B shows that the particle size distribution curve significantly shifts to the right side (coarser side) for the cement-treated marine soil. When the soil is treated with 5% cement content, the effective size (D10) increases to 1.967 from 1.454 µm. Furthermore, D10 increases to 2.45 µm after increasing the cement content to 10%. This trend is even more pronounced for the mean particle size (D50) of cemented soil, which increases from 5.914 to 15.56 µm when treated with 20% cement content. This increase in particle size is the result of aggregation of soil particles. A similar trend has been observed in cement-treated Singapore marine clay [17]. The increased pH value causes dissolved bivalent calcium ions (Ca^{2+}) to replace the monovalent ions (Na^+, K^+) of the minerals. The presence of Ca^{2+} on the surface of clay particles brings them together, resulting in increased particle size [40, 41].

3.5. Microstructural behaviour of cement stabilised soil using scanning electron microscope

The SEM analysis of the soil reveals how the soil structure has transformed from a dispersed to a flocculated fabric after being treated with cement, as shown in Fig. 6. The examination of untreated soil Fig. 6A indicates the presence of fine, flaky particles with many small-sized voids distributed throughout the section. Additionally, the particles formed small clusters in a more or less homogeneous manner. However, the soil treated with 10% cement content (Fig. 6B) exhibited a transformed structure characterized by open configurations and a few needle-like microstructures, along with some indications of reticulation. Reticulation was prevalent when cement content increased from 10 to 20%. The size of the particle significantly increases with

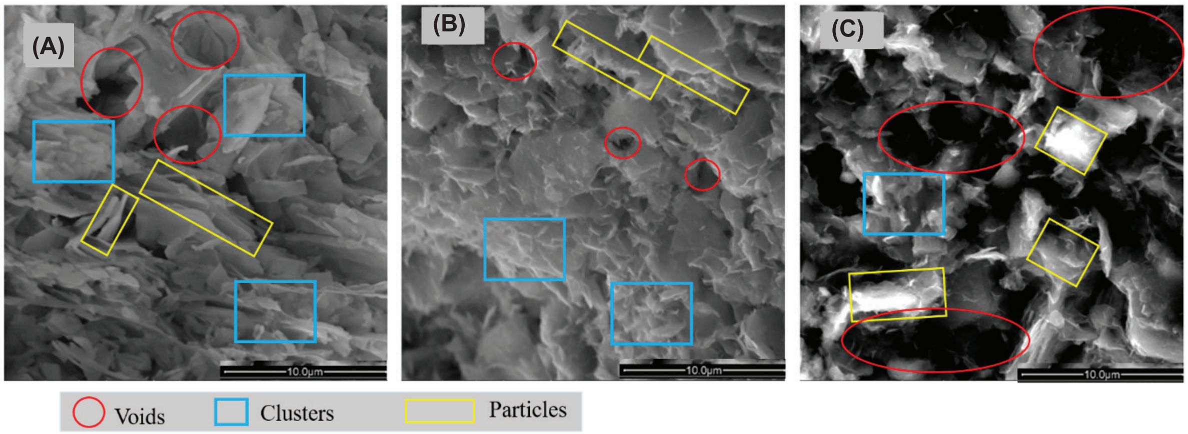

Fig. 6. SEM image of cement-treated soils. (A) Untreated, **(B)** M-10, **(C)** M-20.

dense structure, increased pore size, and decreased number of pores. Furthermore, some precipitated crystals were found individually or as clusters creating the cementation bonds between the soil particles. These aggregated and precipitated crystals create an open-type structure in both soils. These observations have been corroborated in similar studies, wherein the degree of reticulation increases as the amount of cement increases in dredged materials from flood spill channels, Singapore marine clay, and Ballina clay [42-44]. This aggregation and cementation of the soil structures significantly improved the compressive strength [35, 45, 46], yield strength, and compression characteristics of the soil [11, 47]. Furthermore, the microstructure of solidified soils has been defined by five different parameters: particle circularity, particle direction fractal dimension, particle size fractal dimension, pore area ratio, and particle equivalent diameter, and found that these parameters are well-correlated with the strength of soils [48].

3.6. Effect of cement content and curing time on the strength of the stabilised soil

The findings from compression tests conducted on marine soil [11] were further extended with different curing periods along with the strength development pattern corresponding to various cement contents, which are illustrated in Fig. 7A. The outcomes reveal that the sample treated with 5% cement content exhibits lower strength. Notably, a distinctive peak in the stress-strain curve is observed when the cement content is increased to 10%, resulting in an approximately fourfold increase in strength (q_u=86.94 kPa). Likewise, as the cement content further doubles to 20%, the UCS values are increased by more than 3 folds (290.4 kPa). These results signify the enhancement in the strength of marine soil with increasing cement content and curing period, aligning with the findings of previous researchers [49-51].

Moreover, as depicted in Fig. 7A, the increase in cement content leads to a reduction in failure strain (εf). Specifically,

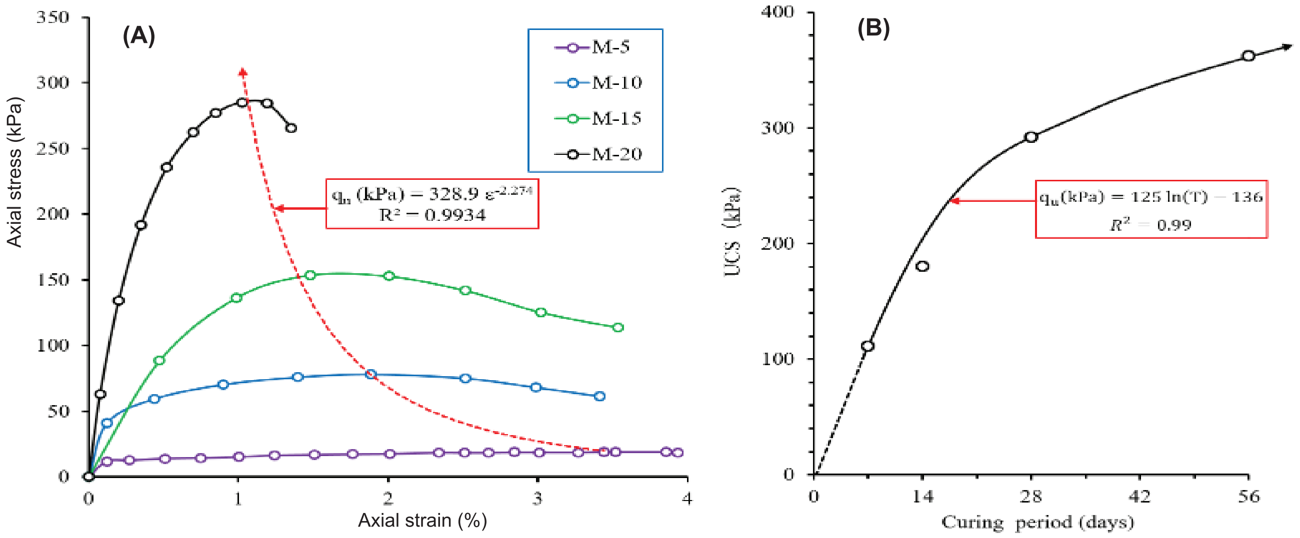

Fig. 7. Variation of unconfined compressive strength with cement content (A), curing period (B).

εf decreases to 1.65, 1.45, and 1.08% at cement contents of 10, 15, and 20%, respectively, compared to the higher value (3.84%) observed at 5% cement content. This trend indicates that an increase in cement content results in higher brittleness in the treated soil.

Additionally, the soil treated with a cement content of 20% was cured for different durations (7, 14, 28, and 56 days) to assess the impact of the curing period on soil strength. Fig. 7B illustrates a substantial increase in soil strength with prolonged curing periods. The mobilised peak strength of the soil was recorded as 111.31 kPa after 7 days of curing, which increases to 180.56 kPa at 14 days and further increases to 362.09 kPa after 56 days of curing. The improved strength of stabilised soil is attributed to the increased particle size, change in the soil microstructure and cementation between the particles. The trend observed in the study is aligned with the studies involving different cement-treated clays [52, 53].

4. Conclusions

Dredged marine soil was reconstituted with different cement contents. The reconstituted samples were used for laboratory tests and results were analysed to determine the physical, microstructural, and mechanical behaviours. The findings of this study are summarised below:

- The cementation significantly affects the physical behaviour of the treated soils. The specific gravity of dredged marine soil decreases from 2.76 to 2.69 when modified with 20% cement content.

- Both the LL and PL of treated soil increased with cement content. However, the rate of increase in the PL was higher, causing a decrease in the PI. However, PI levels recover after a certain amount of cement content.

- The effect of the cement content on cementation and aggregation of the clay particles resulted in larger particle sizes. The effective size (D_{10}) increased to 2.45 µm from 1.454 µm with a cement content of 10%. A similar trend is found for the mean particle size (D_{50}) of cemented soil, which increases from 5.914 to 15.56 µm when treated with 20% cement content.

- Analysis of SEM images supports the results obtained from the gradation analysis. The treated soil had a more flocculated microstructure, with larger particle size and more sizeable voids than the untreated clay. The changes in the microstructure are crucial for enhancing the mechanical behaviour of modified soil.

- The changes observed in the stabilised soil, including improvements in its physical properties, increased particle size, and changes in microstructure, led to a substantial enhancement in strength. This increase in strength was particularly noteworthy, with a nearly seventeen-fold improvement observed when comparing soil treated with 5% cement content and cured for 28 days to soil treated with 20% cement content and cured for 56 days.

CRediT author statement

Bhim Kumar Dahal: Methodology, Data collection, Data analysis, Writing, Editing; Jun Jie Zheng: Conceptualisation, Data analysis, Reviewing, Editing.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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