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Evaluation of cement stabilised residual soil on macro- and micro-scale for road construction

Mohammad Jawed Roshan[1,2*], Ahmad Safuan Bin A. Rashid[3], Muhammad Azril Bin Hezmi[3], Mohammad Nazir Nejabi[2], Siti Norafida Bt.Jusoh[3], Sakina Tamassoki[2] and Roslizayati Razali[3]

*Correspondence: jroshan2020@gmail.com; mj.roshan@kpu.edu.af

[1] Department of Civil Engineering, ISISE, University of Minho, Campus de Azurim, 4800-058 Guimaraes, Portugal
[2] Faculty of Transportation Engineering, Kabul Polytechnic University, Kabul 1001, Afghanistan
[3] Department of Geotechnics and Transportation, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

Abstract

Lateritic soil is a kind of residual soil widespread in tropical countries. This soil usually possesses acceptable engineering properties to be laid under the construction projects. However, it needs treatment for transportation infrastructure such as railway and road subgrade and embankment, particularly when it is in fine-grained form. Thus, cement, one of the very common stabiliser agents in soil stabilisation, was selected to study its influence on lateritic soil at macro- and micro-levels. In order to achieve this goal, UCS, durability, FESEM and EDX tests were conducted. The results obtained indicate that the UCS increase occurs with an increase in cement content and curing time. It was also found that the shear modulus increases with cement content and curing time. The durability test results disclosed that 3% cement is not enough for soil stabilisation when used for projects in the areas subjected to cyclic wetting-drying cycles. The durability test results revealed that the UCS decreased for specimens treated with 6% cement, while on the other hand, the UCS increased for samples treated with 9% and 12% cement. The FESEM results revealed that the soil micro-structure changed with the addition of cement and curing time. The EDX results presented the chemical elements change upon adding cement and increasing curing time. Overall, it was found that cement-stabilised residual soil can be used for road construction. However, the cement percentage needed to stabilise residual soil differs depending on the standards.

Keywords: Lateritic soil, Residual soil, Cement, Micro-structure, FESEM, EDX

Introduction

Lateritic soil, mostly produced by chemical weathering, forms a large portion of residual soils in tropical and subtropical countries [1]. Apart from transportation infrastructures such as railways and roads, the lateritic soil may be utilised without treatment for the project constructions. The main reason for most roads facing failure in tropical countries has been the lateritic soils with poor quality [2]. Although the lateritic soils are significantly used for road construction in tropical countries, heavy rains make them impassable over rainy seasons [1]. For instance, the lateritic soils covering the land in East and Central Thailand do not meet the required standard of base and sub-base [3]. Since the transportation infrastructure bed is subjected to wetting-drying or freezing-thawing cycles, stabilising lateritic soil is of great importance and needs to be selected wisely. For instance, it was found that the stability of railway embankments constructed with lateritic soil decreases under rainfall infiltration [4]. Furthermore, the failure of a road built on lateritic soil because of heavy rainfall has been reported in many countries [2, 5].

The stabilisation process enhances the durability and strength and reduces the swell and consolidation due to altering the soil's physical, chemical, or physical and chemical characteristics [6]. Many techniques such as chemical, physical, mechanical and biological methods have been utilised so far [7–10]. In addition to these methods, although recently quarry fines usually are employed to improve the gradation, compaction, plasticity and strength of natural soil, the mixture of soil with quarry fines is very susceptible to contact with water [11]. In order to overcome this challenge, chemical stabilisation is often used to improve the stability and durability of soils [12]. For instance, a mixture of 6% cement and 8% quarry dust (optimal mixture) was used to improve the strength of lateritic soil as a pavement material [13].

Chemical modification is often used to improve the soil characteristics up to desired value owing to easy field mixing and implementation procedures [14]. In a chemical approach, the soil is modified using certain chemical stabiliser agents [15]. The stabiliser agents are divided into two categories: traditional agents (lime, cement and fly ash) and non-traditional agents (e.g. polymers, enzymes and ionic solutions) [16]. Of these two categories, the traditional stabilisers are widely used in soil stabilisation because of the existing uncertainties in using nontraditional stabilisers [17]. Furthermore, though calcium-based stabilisers are responsible for considerable environmental pollution and greenhouse emissions, they are still commonly used in soil stabilisation owing to their considerable advantages [18].

Although varying techniques and stabiliser agents such as cement [19–22], lime [23–26], fly ash [3, 27], bottom ash [28], MICP [29, 30], activated carbon [31], EICP [32, 33] and waste materials [34, 35] have been employed in the stabilisation of soil, cement is of common, particularly for transportation infrastructures [36]. Cement is widely used because of its advantages, such as low cost, remarkable integrity and strong water stability [37]. Furthermore, [38] mentioned that lime and cement are used widely because of their abundant availability. In summary, the cost, sufficient mechanical characteristics and availability make cement more common in geotechnical projects [39]. Considering the equal amount of stabiliser agents, in general, cement is more advantageous than lime or other kinds of calcium-based stabilisers because of its effectiveness in soil strength gain [40].

The use of cement as a soil stabilisation agent was first started in 1915 to construct streets in the USA [41]. Since then, cement has been used more than other kinds of stabiliser agents because of some advantages. For instance, the calcium carbide residue or carbide lime which is a by-product resulting from the production of acetylene gas can be utilised for soil stabilisation purposes [42]. Chindaprasirt et al. [43] have utilised carbide lime to stabilise the marginal lateritic soil. Although the results obtained indicated that the addition of carbide lime results in increased UCS, elastic modulus and CBR, the soil that stabilised with it may not be resistant to water like soils stabilised by cement. For instance, adding cement into lateritic soil and sand continuously increased both soaked and unsoaked CBR [44]. In contrast, the CBR of fly ash-stabilised soil increased in unsoaked and decreased in soaked conditions. Thus, this issue indicates the suitability of cement-stabilised soil for places where the moisture condition is high. In addition, the overall effectiveness of traditional agents over non-traditional agents was detected; the traditional stabilisers enhance the strength of soils more than non-traditional methods [16]. For instance, the applicability of fine-grained cement-stabilised lateritic soil for base and sub-base construction has been proved [45]. The addition of cement has resulted in increased UCS, shear modulus, tensile strength, CBR, and shear parameters due to the increment of denseness, small pores and high amount of hydration compounds resulting from the chemical reaction between cement ingredients and soil minerals. A long time ago, the cement was used for tailings to ease their handlings to landfills [46], but currently, cement-stabilised tailings can be employed for some purposes in the field of geotechnics [13]. Overall, cement can be employed to stabilise all types of soils except those having more than 2% organic content and a pH value lower than 5.3 pH value [18].

The shear strength of soil decreases under wetting-drying cycles (w/d). Thus, durability against wetting-drying cycles, a parameter indicating soil stability under cyclic rainfall and drying seasons, is of great importance. The natural lateritic soil may fail when contacted with water, indicating the instability of lateritic soil under rainfall. For this reason, the durability of lateritic soils has been studied when mixed with some stabiliser agents, particularly cement. For instance, [47] explored the durability of cement-stabilised lateritic soil. The achieved findings rendered the high mass loss for low cement-treated lateritic soil. Similarly, [48] also conducted the durability test for lateritic soil mixed with cement and sand. Their findings represented a smaller than 5% loss of mass for compacted lateritic soil mixed with sand and cement after 12 wet-dry cycles, indicating the stability of this stabilised lateritic soil. The influence of wet-dry cycles on cement-stabilised lateritic soil was explored in Thailand [49], where the lateritic soil (LS) was first mixed with melanin debris (MD) (a waste produced from the manufacturing of plate and cups) at varying blends (LS: MD) and then was mixed with cement. The acquired findings manifested the increase of UCS for cement-stabilised lateritic-melanin debris blends up to three wet-dry cycles, beyond which the UCS decreased under further wet-dry cycles. Compared to cement, soil stabilization using other stabilisers like lime is not beneficial and effective for projects subjected to frequent wetting-drying cycles [40]. For instance, [50] presented the loosing of strength for lime-treated soil under wetting-dryin cycles. Therefore, cement is an effective stabiliser to resist the negative influence of environmental factors such as wetting-drying and freezing-thawing cycles.

In order to assess the viability of soils as construction materials, mechanical, chemical, and mineralogical studies need to be carried out [51]. Although previous research studied the influence of cement on varying soils, the mechanism of cement stabilisation still needs to be systematically studied at macro- and micro-levels for better understanding. Besides, the durability of cement-stabilised lateritic soil against wet-dry cycles must be carried out properly to overcome the deficiency of previous studies [52, 53]. Therefore, this research aims to explore the influence of the cement on mechanical behaviour, the changes in chemical compositions and changes in the micro-texture of the lateritic soil. In order to obtain these goals, UCS, durability, FESEM and EDX tests are performed.

Table 1 Basic characteristics of lateritic soil

Properties	Symbol	Value
Liquid limit %	L_l	70.3
Plastic limit %	P_l	42
Plasticity index %	P_i	28.3
Gravel %	-	12.79
Sand %	-	17.54
Silt %	-	61.26
Clay %	-	8.41
Soil classification		
USCS		MH
AASHTO		A-7-5
Optimum moisture content: %	OMC	28
Maximum dry density: $^{Kg}/_{m^3}$	MDD	1390
Specific gravity	G_s	2.74
Dry unit weight: $^{KN}/_{m^3}$	γ	13.64
Unconfined compressive strength (UCS) kPa	q_u	200.8

Table 2 Characteristics of used cement

Type	Initial setting time (minute)	Loss on ignition (LOI) %	Insoluble residue (IR) %	Chloride (Cl) %	Compressive strength at 28-day curing (MPa)
CEM I 42.5 N	140	0.97	1.24	0.03	52.4
British Standard	EN 196-3:2007 Clause 6	EN 196-2:2007 Clause 7	EN 196-2:2007 Clause 9	EN 196-2: 2007 Clause 14	EN 196-1: 2007
-	Not less than 60	Not more than 5	Not more than 5	Not more than 0.1	Not less than 42.5 not more than 62.5

Methods

The lateritic soil used in this study possesses a reddish colour vastly deposited in tropical and subtropical countries due to laterisation and weathering processes. The characteristics of untreated natural soil used in the current research are illustrated in Table 1.

Based on the ASTM C150 standard, cement is divided into eight categories, while EN197 is classified into five classes (CEM I, II, III, IV, V) [54]. Furthermore, considering 28-day strength, each type has three grades (32.5MPa, 42.5MPa, and 52.5MPa), and according to the strength gain rate, the cement is categorized into normal strength gain (N), early strength gain (R) and slow strength gain (L or S) [55]. In this research, CEM, I 42.5 N, which is pure ordinary Portland cement (OPC) (having 95–100% clinker compared to other types) and normally used for soil stabilisation globally owing to being resistant against sulphate attack, was utilised. The properties of OPC used in this study are tabulated in Table 2.

The grain size distribution (GSD) of soil and cement obtained using laser diffraction [56] and sieve analysis in the current research study is depicted in Fig. 1. To analyse the efficacy of cement on the lateritic soil at the macro- and micro-level, UCS, durability, FESEM and EDX tests were carried out for both treated and untreated specimens.

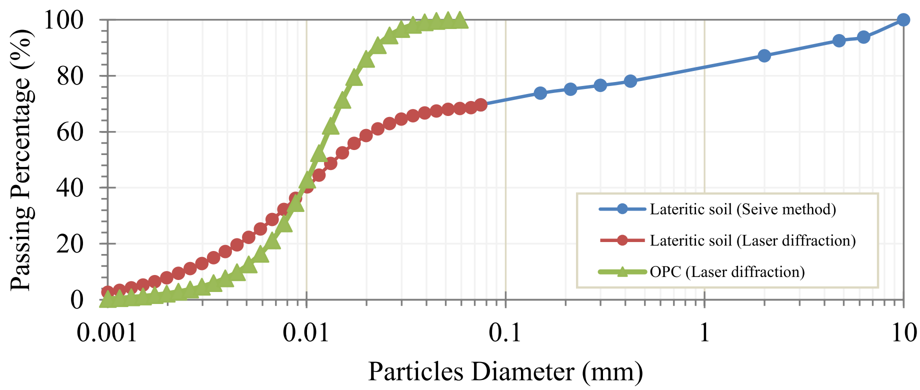


Fig. 1 Grain size distribution (GSD)

Figure 2 illustrates the overall procedures adopted in this research, from specimen preparation to desired experiments. In the first step, the soil and cement were weighed according to the MDD. Then, the soil and cement were thoroughly mixed in the dry state, and the water obtained based on OMC was added to the mixture because it has been found that the cement is more effective when the moulding water is close to OMC [57]. After mixing, the monotony and homogeneity of the mixtures were visually observed. It is worth noting that the MDD and OMC were varying for natural soil and soils stabilised by specific cement content. Detailed information regarding the compaction properties of soil used in this study has been discussed in a previously published paper [58]. The specimens were prepared using static compaction. The prepared specimens were then wrapped with plastic film to avoid moisture loss and placed inside the cans. The prepared cylindrical specimens (H/D=2) were stored in an automatically controlled humidity and temperature chamber (27±2°C) until the required curing period. After achieving the curing period, the UCS test was conducted according to British Standard [59]. For the durability test based on ASTM-D 559-03 [60], the 7-day cured specimens were first subjected to the desired wetting-drying cycles and then the UCS test was conducted. According to ASTM-D 559-03, one wetting-drying cycle consists of 5 h immersing into the water to wet and 42 h placing into the oven at 71° C ± 3°C to dry the specimens. After the last wet-dry cycle (i.e., last wetting stage), each sample was placed on the surface for 2 h to ensure consistency before conducting the UCS test. For FESEM and EDX tests, the specimens were provided from the broken parts of UCS samples, similar to a previous study conducted by Zhang et al. [61]. The FESEM was carried out using the HITACHI SU8020, a machine equipped with an energy-dispersive X-ray spectrometer to conduct the EDX test.

Results and discussion

Unconfined compressive strength (UCS) and durability

The UCS results illustrate the increased trend both for cement content and curing time, as shown in Fig. 3. The strength gain of soil stabilised with cement is obtained through short-term (cation exchange, particle restructuring or flocculation and agglomeration) and long-term mechanisms (Pozzolanic reaction and cementitious hydration) [36, 62]. The short-term strength is obtained in hours, while the strength resulting from the

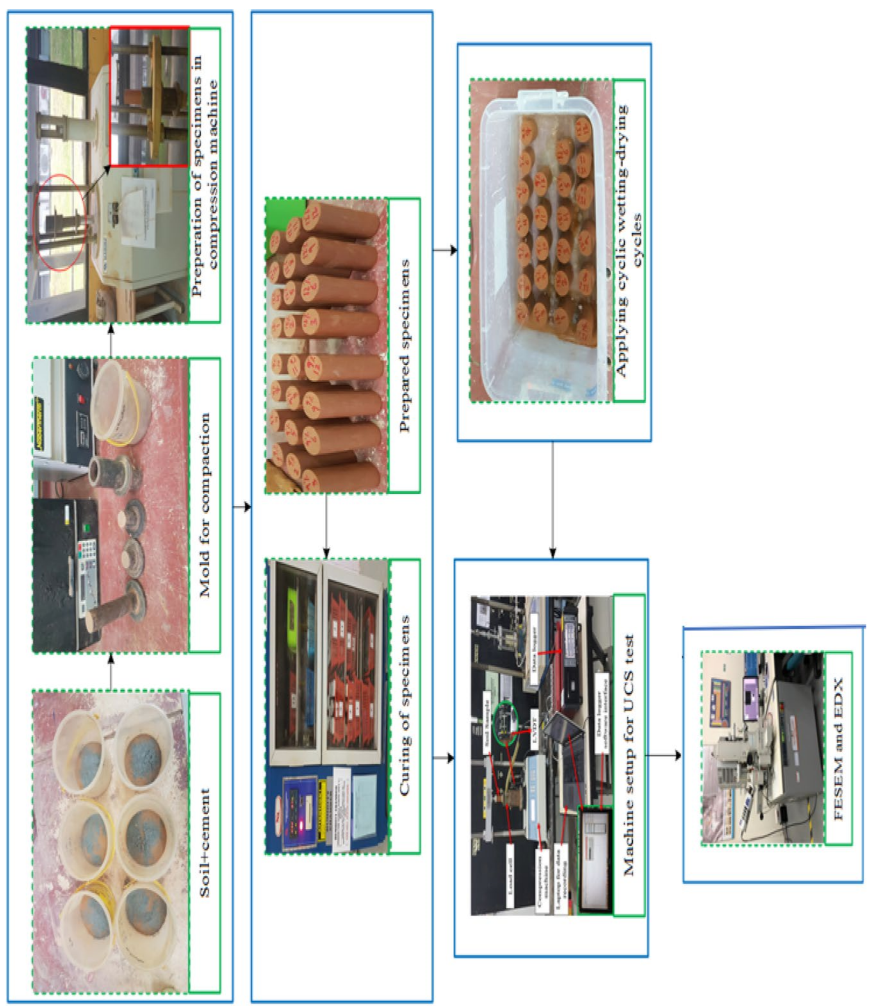


Fig. 2 Testing procedure

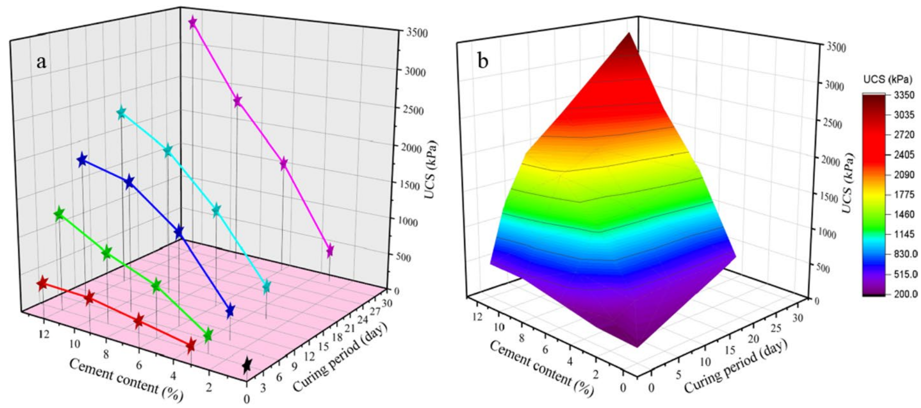


Fig. 3 UCS results versus cement content (0, 3, 6, 9, 12%) and curing time (0, 3, 7, 14, 28 days) **a** scatter plot and **b** surface plot

pozzolanic reaction takes a day or a month and the strength resulting from cementitious hydration takes months or years [63]. Thus, an increase in strength such as UCS resulting from curing time is attributed to the pozzolanic reaction and cementitious hydration processes [36]. Being activation of chemical reactions in the soil can be perceived through strength development with curing time so that when there is no strength gain with curing time, the chemical reaction is passive [64]. Moreover, the pH of soil increases in the existence of OH^{-} (alkalinity increases), resulting in strong and lasting pozzolanic reaction and cementitious hydration in which the Ca^{+2} provided by cement enters to chemical reaction with Si an Al of soil. As a result of these reactions, produced hydrated gel such as CSH, CSH and CASH are the main factors of strength gain upon mixing cement with soil [40] stated that CASH is produced when there is a sufficient amount of lime. This issue may also be valid for cement since both cement and lime are calcium-based stabilisers in which calcium is the main contributor to the production of hydrated gel. Thus, providing a sufficient amount of cement is of great importance to achieve the desired and long-lasting strength [40]. In the light of this issue, the UCS and secant modulus of soil (E_{50}) increase with the increase in cement content and curing time, as illustrated in Figs. 3 and 4, respectively. The obtained results in this study are consistent with the results reported by [65] on fine lateritic soil such that the larger increase in UCS occurred with a higher percentage of cement (6% and 9%) similar to this study in which the considerable increase in UCS occurred upon addition of 6%, 9% and 12% cement. For instance, in a previous study [65], 7-day cured specimens showed 2510 kPa and 3610 kPa UCS for 6% and 9% cement, while in this study, the UCS of 6%, 9% and 12% cement for 7-day cured samples were recorded 1233.1 kPa, 1737.5 kPa and 1899.6 kPa, respectively. Moreover, the addition of cement resulted in two types of failure behaviour of lateritic soil in compressive strength, ductile and rigid. The adding 3% cement increased the UCS slightly, as shown in Fig. 3, thus resulting in ductile failure behaviour (in bulging shape) like untreated specimens. In regard to Fig. 3, the addition of 6%, 9% and 12 % cement into the soil increased the UCS considerably, thus resulting in a rigid type of failure (in a sliding plane). For instance, at 28-day curing, the UCS increased from 200.8 kPa to 447.6 kPa, 1549.3 kPa, 2325.7 kPa and 3343.1 kPa for 0%, 3%, 6%, 9% and 12% cement, respectively. The rigid behaviour of a high dosage of cement

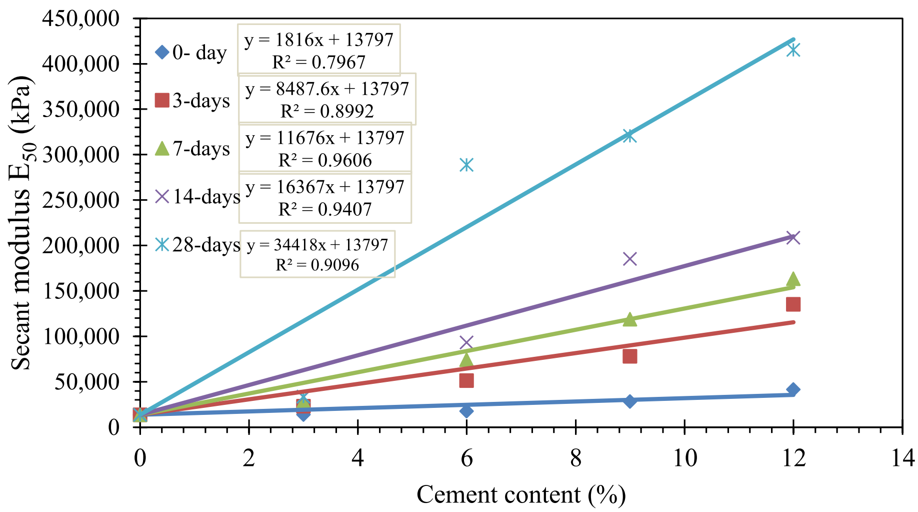


Fig. 4 Relationship between secant modulus and cement content for varying curing time

stabilised soil is a common trend since they often behave in a condition between soil and rock [66]. The failure behaviour of stabilised soil in this paper agrees with that observed in [45, 67]. Similar to the previous study's findings [68], the cement stabilised specimens in the current study illustrated strength softening behaviour.

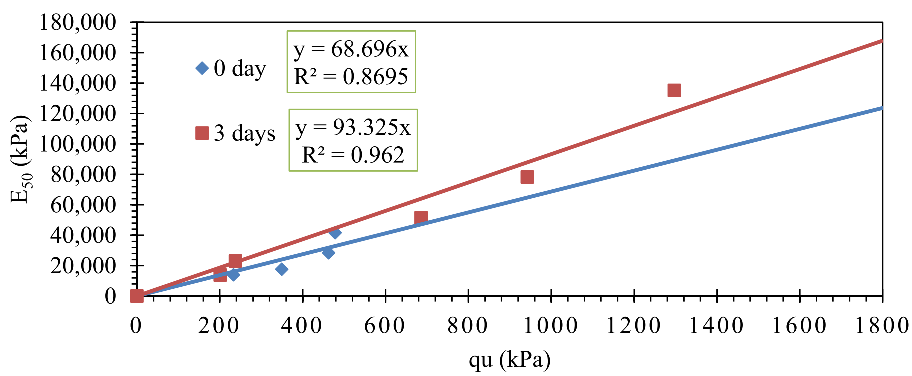
Although the increase in UCS results from the cement content and curing time, the increase of UCS of 3% cement stabilised specimens changes slightly, unlike that of other percentages, as shown in Fig. 3. This result is consistent with the results obtained by [69], in which the change in shear strength of a particular plasticity clay stabilised by 2% quicklime has been almost steady with curing time, indicating the unsatisfactory amount of chemical stabilisers that are already consumed and the chemical reactions have stopped. Further, the obtained results for 3% cement stabilised specimens by which the UCS of natural soil increased slightly are comparable with the results revealed by [45]. In addition, noteworthy is the reduction of strength improvement over time such that the strength gain decreases by curing time, as seen in Fig. 3. Over time, the reduction of strength development is attributed to the formed thicker calcium silicate hydrate crystals, preventing the water molecules from reacting with un-hydrated tricalcium silicate. Moreover, it can be attributed to the insufficiency of water owing to dry conditions or evaporation caused by exothermic reactions [39].

The elastic and plastic deformation of stabilised soil can be analyzed by using the secant modulus (E_{50}) [70]. Hence, the rigidity of lateritic soil increases with cement content and curing time, as can be perceived from the secant modulus (E_{50}) in Fig. 4. The secant modulus increases with curing time after the addition of cement, as shown in Fig. 4. In regard to Fig. 4, the regression equation of secant modulus (E_{50}) with respect to cement content (x) for 0-day curing has been found y=13797+1816x, whereas for 28-day curing, it was found y=13797+34418x, this indicates that the secant modulus increases with cement and for constant cement, and it enhances with curing time. The production of hydrated gels (hydration products) such as CSH, CAH and CASH fills the void of soil stabilised by cement, consequently increasing strength and rigidity [71].

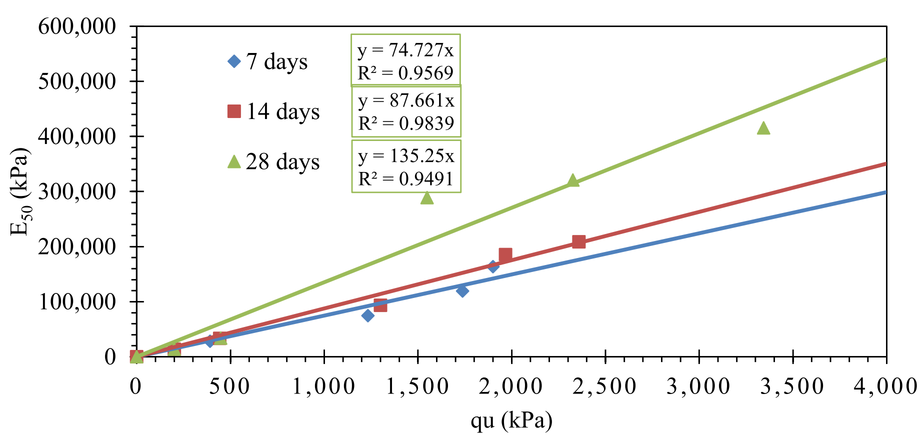
Figure 5 presents the relationship between UCS and E_{50}. Regarding Fig. 5, the E_{50} increases with increasing UCS value. The cement content and curing time increase results in increased UCS and, hence, increased E_{50}.

The untreated lateritic specimens degraded after immersing in the water, indicating their deficiency against water. The results obtained are in accordance with the findings achieved by Bouras et al. (2021), in which the UCS of untreated plastic silty soil specimen could not be measured after immersing into the water due to degradation. The durability of cement stabilised soils under wetting-drying cycles depends on cement content. The soil stabilised with high cement content is more durable than soils stabilised with low cement content. Given this issue, the 3% cement stabilised sample failed under one wetting-drying cycle, as seen in Fig. 6.

The compressive strength of 6% cement-stabilised samples decreased with increasing wetting-drying cycles, whereas the compressive strength of 9% and 12% cement-stabilised specimens increased with increasing wetting-drying cycles, as shown in Fig. 7. The results obtained are consistent with the findings of [38], in which the compressive strength of cement stabilised low plasticity clay (CL) increased with



(a)



(b)

Fig. 5 Correlation between secant modulus and unconfined compressive strength **a** 0-day and 3-day curing and **b** 7-day, 14-day, and 28-day curing

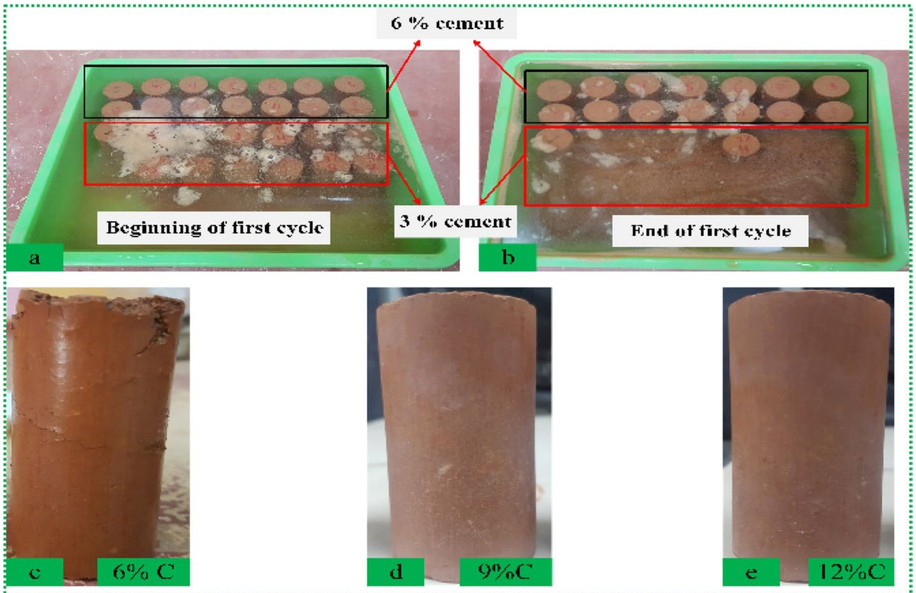


Fig. 6 Durability **a** beginning of the 1st cycle, **b** end of the 1st cycle, **c** 6% cement-treated specimen at the end of the 15th cycle, **d** 9% cement-treated specimen at the end of 15th cycle, and **e** 12% cement-treated specimen at the end of the 15th cycle

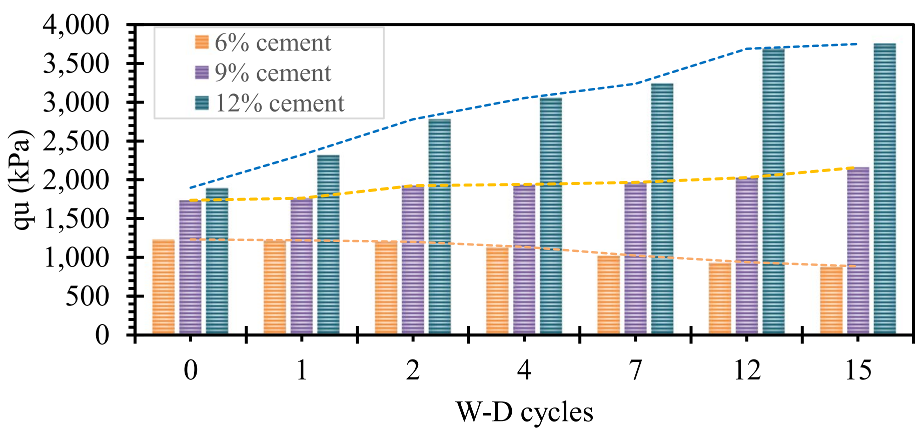


Fig. 7 Durability results of 7-day cured specimens

increasing cyclic wetting-drying cycles. Besides, the current findings can be supported by the results of another study [72] in which the 3% treated soil illustrated a slight disintegration while stabilised soil with more than 3% cement showed a stable condition after submerging for 72 h into the water. The decreasing strength trend of low cement stabilised soil under cyclic wetting-drying cycles is attributed to cracking during drying and ingression of water during wetting. On the other hand, the increasing strength of high cement content stabilised soils under cyclic wetting-drying cycles is attributed to the hydration of un-hydrated cement particles in the presence of water, resulting in the formation of hydration products (CSH, CAH). Furthermore, the findings of [67], in which the strength of cement stabilised clayey sand (SC) increased with increasing moisture content up to a specific value, confirm the current study's results. Similarly, the finding of [73], in which the UCS of cement stabilised soil prepared at water content higher than the OMC was more significant than that prepared at water content lesser than OMC, could support the findings of durability in the current study.

Considering the amount of cement, generally, the durability results on specimens at 7-day curing illustrated three varying trends, collapsing, decreasing and increasing trend of UCS. Specimens stabilised with 3% cement collapsed under one wetting-drying cycle, as shown in Fig. 6. This behaviour is attributable to the less produced hydration compounds and large pores, thus implying that 3% cement is not enough to modify the natural lateritic soil. As seen in Fig. 6, the 3% cement-modified specimens collapsed at the end of the 1st cycle, while specimens stabilised with 6%, 9% and 12% cement are stable at the end of the 15th cycle. In regard to Fig. 6, at the end of the 15th cycle, 9% and 12% cement-stabilised samples are very stiff and in good condition, but those stabilised with 6% cement show some sign of deterioration. Although the UCS of 6% cement stabilised samples decreases with increasing wetting-drying cycles, the specimens still have UCS=883.85 kPa at the end of the 15th wetting-drying cycle, indicating less water ingression into the pores and consequently the deterioration of strength. On the other hand, the trend of lateritic soil stabilised with 9% cement and 12% cement at 7-day curing is completely different under cyclic wetting-drying cycles. Similar to previous studies that showed the increasing trend of UCS under certain wet-dry cycles [38, 74, 75], in the current studies, the UCS of specimens stabilised by 9% and 12% cement increases with increasing wetting-drying cycles, indicating the high effectiveness of stabilised soil over time. In other words, the high cement content results in a high amount of hydration products (CSH, CAH) in the presence of water, thus resulting in increased compressive strength rather than strength degradation over wet-dry cycles. However, owing to the stopping of the hydration process and water ingression into voids, the UCS will illustrate a decreasing trend after a certain wet-dry cycle. For instance, the UCS of 9% cement stabilised specimens was 1737.52 kPa before starting to apply the wetting-drying cycles (0-day wetting-drying cycle), then at the end of the 1st, 2nd, 4th, 7th, 12th and 15th cycles, and it increased to 1764.37 kPa, 1923.16 kPa, 1940.81 kPa, 1967.27 kPa, 2029.02 kPa, and 2161.34 kPa, respectively, as depicted in Fig. 7. The increasing trend of 9% and 12% cement-stabilised specimens with wetting-drying cycles is attributable to the tiny pore avoiding the ingression of water and viability of chemical reaction between cement and soil minerals resulting in a higher amount of hydration compounds. For high-cement content, the 5 h immersing and 42 h drying work as curing time, resulting in increased strength after each w/d cycle. Overall the findings of this research can be supported by previous studies' results [38, 49, 75, 76]. In the previous studies, the UCS of stabilised soils showed an alternate increase and decreased trend during wetting-drying cycles. For instance, a previous study by Aziz et al. [38] yielded a sudden increase of UCS after the first wet-dry cycle and an alternate increase and decrease of UCS for the rest of the wet-dry cycles. It is noteworthy that an overall increase of UCS of stabilised soil under repeated wet-dry cycles has been recorded for cement-stabilised soil [38]. In another study by Hoy et al. [75], the compressive strength of fly ash geopolymer stabilised recycled asphalt pavement increased during six wet-dry cycles and then decreased after 6th wet-dry cycle. Similarly, the UCS of stabilised increased during three wet-dry cycles and followed a reduction trend afterward [74]. In the current study, the UCS of 9% and 12% cement-stabilised soil did not illustrate a decreasing trend during the 15 wet-dry cycles. However, it may decrease after the 15th wet-dry cycle as a slight difference in UCS of 12% cement-stabilised soil is seen between the 14th and 15th wet-dry cycles (Fig. 7). In order to explore the durability of cement-stabilised lateritic soil under wet-dry and freeze-thaw cycles in detail, future studies are suggested.

FESEM and EDX

The soil micro-structure obtained using the FESEM technique is illustrated in Fig. 8. The results of FESEM in this study are greatly in agreement with that obtained by [77], in which the pores have been filled with hydrated compounds or gels produced by the chemical and pozzolanic reaction between minerals of soils and cement ingredients, and the pore size decrease develops more with curing time. Similarly, [78] also found that pore size and volume of plasticity clay (CH) decrease with increasing cement content and curing time. The reduction of voids and pore spaces and increasing strength are attributed to the formation of hydration gels (cementitious products) particularly CSH and CASH [71]. Similarly, cement stabilised soft marine clay's

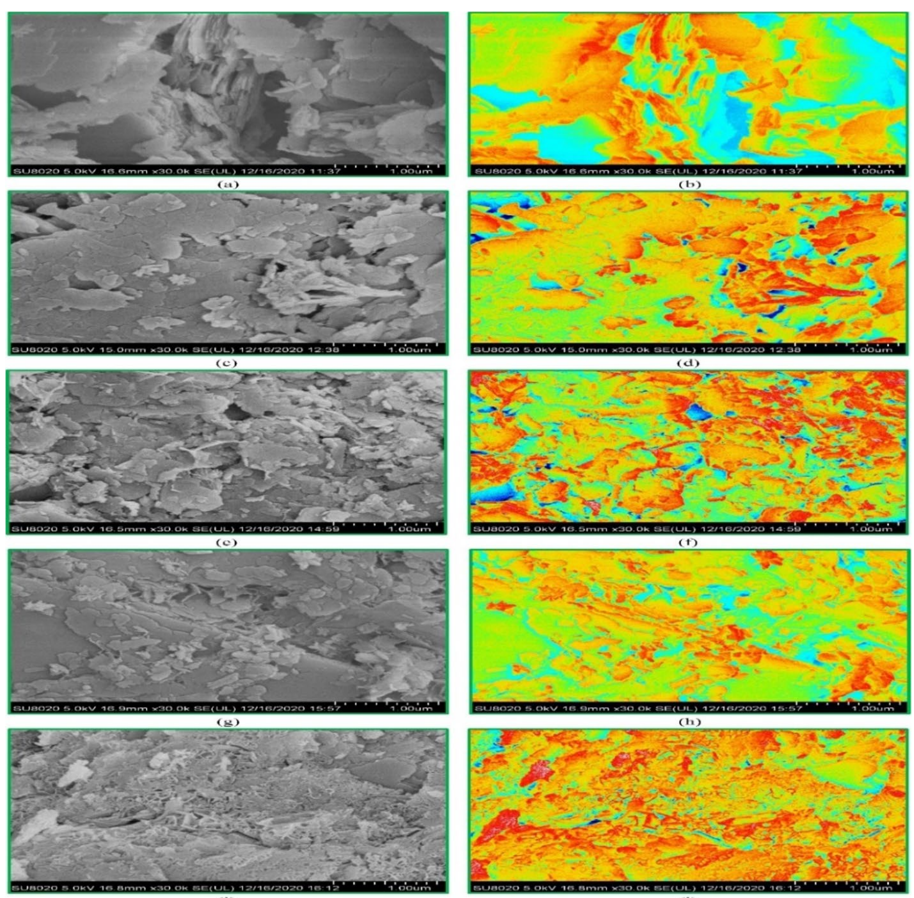


Fig. 8 Micro-structure analysis of un-stabilised lateritic soil and varying cement-stabilised lateritic soil at 7-day curing time: **a**, **b** untreated; **c**, **d** 3% cement; **e**, **f** 6% cement; **g**, **h** 9% cement; and **i**, **j** 12% cement

increasing UCS and decreasing permeability with increasing cement content have been ascribed to the produced CSH and CASH [79]. Therefore, the total pore area decreases with increasing cement content and curing time, as depicted in Fig. 9.

The strength of soils stabilised with cement increases because of calcium-based minerals produced by the addition of cement, and the strength increase continues with curing time [80]. The production of hydrated gels, filling of the pore by produced gels and enlarging the soil-cement cluster bonding are the reasons for increasing strength owing to increasing cement content and curing time [77].

The results obtained through EDX testing are illustrated in Fig. 10. In regard to Fig. 10, calcium is observed from the higher peak of EDX for stabilised soil compared to that of un-stabilised soil, indicating the reason for the strength gain of stabilised soil [29]. Further, the occurrence of hydration and pozzolanic reactions can be realized from the existence of calcium peaks, which indicates the strength gain. In other words, the strength gain owing to the addition of calcium-based stabilisers such as cement can be realized from the micrographs obtained by EDX.

The strength gain due to chemical reactions such as hydration and pozzolanic reaction upon the addition of cement can be evaluated by the Ca: Si and Al: Ca ratios such that the strength increases with the enhancement of Ca: Si and decrease of Al: Ca [71]. Further, the strength gain of soils stabilised with calcium-based stabilisers can be evaluated with respect to Ca: Si and Al: Si ratios [81], as seen in Fig. 11. The increase in Ca: Si ratio increases strength, whereas the increase in Al: Si ratio results in decreased strength. Thus, the higher Ca: Si ratio and lower Al: Si ratio demonstrate more cementitious compounds and higher strength.

Similar to [45], as depicted in Fig. 12, the weight of Ca increases with increasing cement content and curing time, implying an increase in mechanical properties. Moreover, the strength gain of cement stabilised soil is predicted based on the Ca/(Al+Si) ratio, as seen in Fig. 13. Regarding Fig. 13, the Ca/(Al+Si) ratio increases with increasing cement content and curing time. Such a growth results in the increased bonding efficiency, and thus, the increased strength of the stabilised soil [70].

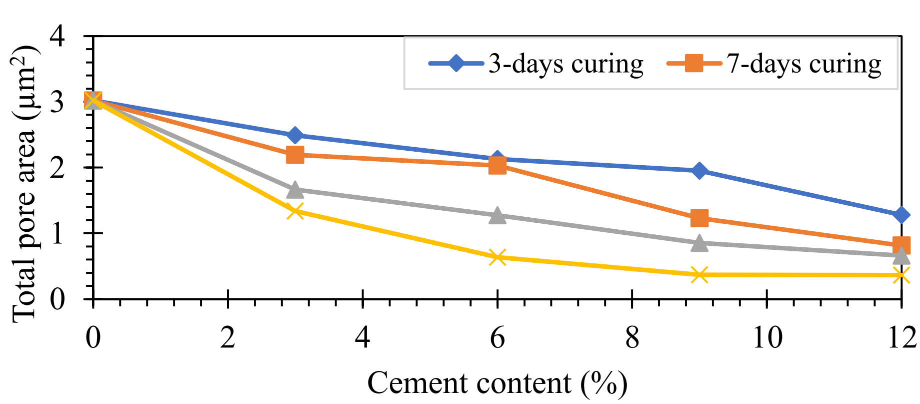


Fig. 9 Total pore area with respect to cement content and curing time

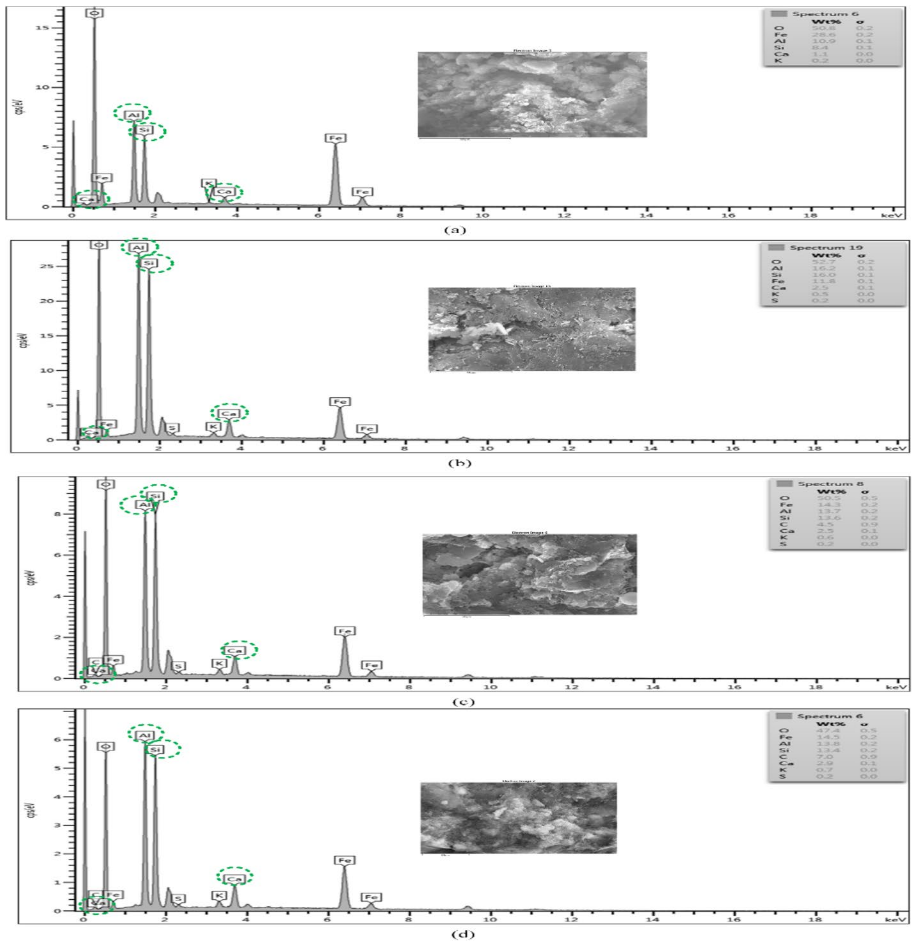


Fig. 10 EDX results of 6% cement-treated lateritic soil. **a** 3-day curing, **b** 7-day curing, **c** 14-day curing, and **d** 28-day curing

Applicability of cement stabilised residual soil for transportation infrastructures

The construction of roads using high-quality materials is of great importance. However, the lack of high-quality natural materials necessitates low-quality materials, such as fine-grained soils, to be used in transportation layers. Therefore, soil stabilization is necessary to make the low fine-grained soil usable in constructing transportation layers.

Although cement can be counted as a commonly utilised additive, the CO_2 emission resulting from Portland cement manufacturing (i.e. decarbonization of limestone, fossil fuel consumption, electricity needs for cement factory and transportation) is roughly 10% of all CO_2 [82]. However, a comparison study disclosed that the cement is cheaper and causes lesser CO_2 than microbial-induced calcite precipitation (MICP) in large-scale projects [83]. In addition, considering the structure of the rural roads, [84] have compared the lifetime and cost of the crushed layer overlaid by a thin asphalt layer and cement-treated lateritic soil overlaid by a thin asphalt layer. They found that using cement-treated lateritic soil instead of crushed rock for the base layer can prolong the life span and decrease the cost of construction, indicating the effectiveness of cement-stabilised lateritic soil as a base course for road construction.

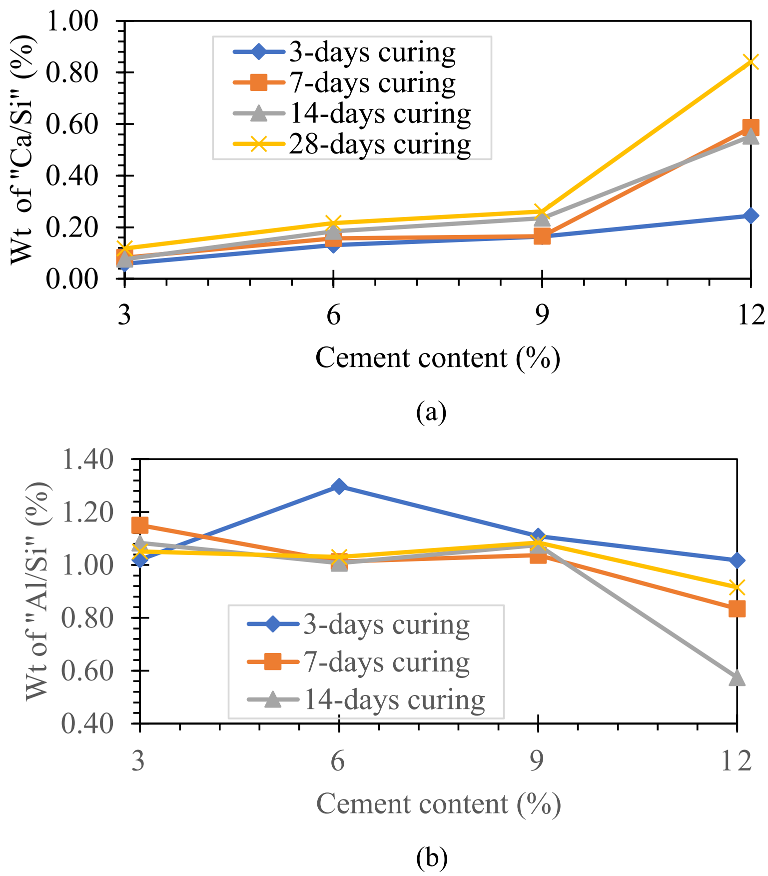


Fig. 11 Weigth of Ca with respect to cement content and curing time

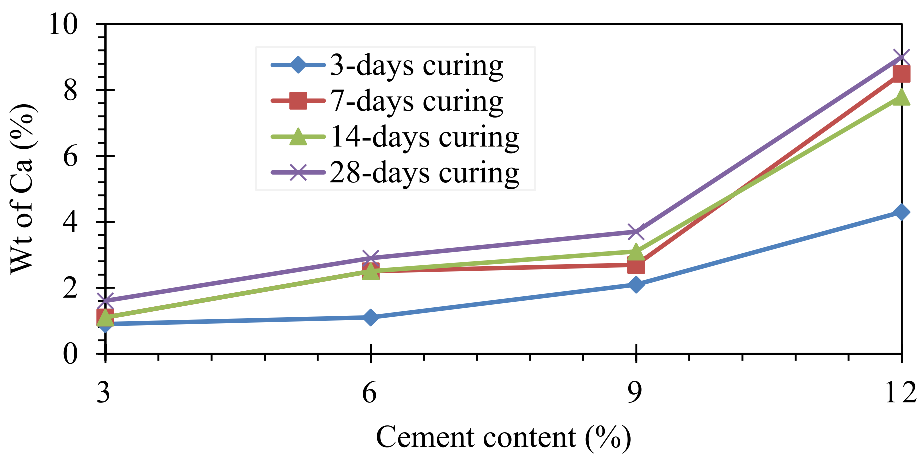


Fig. 12 Weight of Ca/(Al+Si) with respect to cement content and curing time

The threshold strength of cement stabilised soil as transportation layer material varies according to standards worldwide. The requirements for cement-stabilised soil as transportation layers materials are tabulated in Table 3 according to various

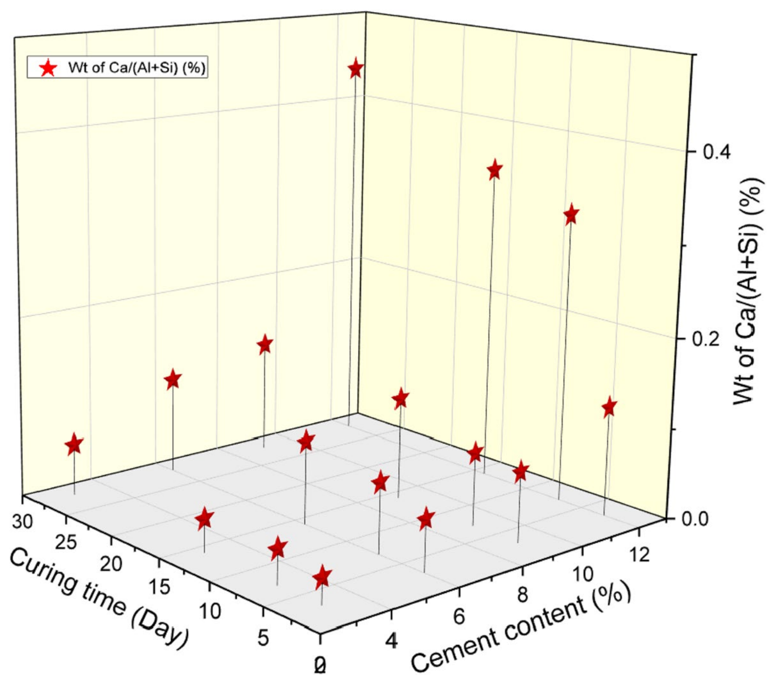


Fig. 13 **a** Ca:Si ratio with respect to cement content. **b** Al:Si ratio with respect to cement content

Table 3 UCS threshold of cement-stabilised soil as road material according to various standards

No	Type of structure	Parameter	Standard	Reference
1	Sub-base coarse	7-day UCS (0.75–1.5 MPa)	India	[85]
2	Low traffic volume road	7-day UCS (0.8 MPa)	Malaysia	[86]
3	Road base	7-day UCS (>1.8 MPa)	France	[45]
3a	Road sub-base	7-day UCS (>1.2 MPa)		
4	Medium-high traffic volume road	7-day UCS (2.068–5.516 MPa)	Portland Cement Association (PCA)	[87]
5	Subbase and subgrade	7-day UCS (1.72 MPa)	AASHTO	[88]
5a	Base	7-day UCS (5.17 MPa)		
6	Base in cold regions	UCS (4.1 MPa)	Federal Highway Administration (FHWA)	[89]
6a	Subgrade	7-day UCS (1.4 MPa)		
7	Bound pavement materials	28-day curing and 4 h submerging into water before testing UCS (2 MPa) The stabilisers must be >3%	Australia	[90]
8	High-speed railway roadbed	5% Cement was proved to be adequate to control frost-heaving	China	[91]

countries' standards. Therefore, the comparisons of the results obtained in this study according to various standards are illustrated in Fig. 14.

The minimum UCS threshold value in Fig. 14 is based on 7-day curing specimens. Regarding Fig. 14, it is seen that the UCS of untreated residual soil and 3% cement-stabilised are situated under threshold lines, indicating their inapplicability for road layers. Although 6% cement-stabilised soil cured at 7 days fulfils the requirements of standard

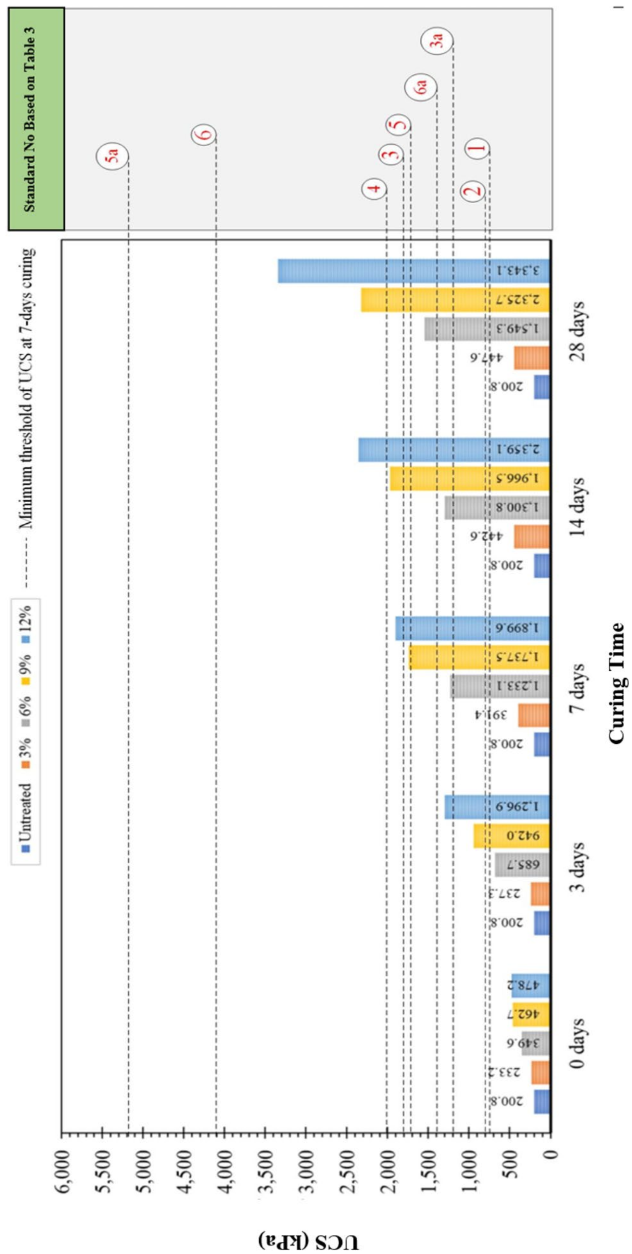


Fig. 14 Comparison of UCS based on various standards as mentioned in Table 3

no. 1, 2, and 3a, it is not enough for standard no. 3, 4, 5, 5a, 6, and 6a. Therefore, the requirement of standard no. 6a, 5, and 3 are achieved with 9% cement, and 12% cement-stabilised soils, respectively. The threshold line of standard no. 4, 5a, and 6 are located upper than the UCS value of 7-day cured samples. This issue, therefore, indicates that cement dosages (3%, 6%, 9% and 12%) used in this research are insufficient according to standard no. 4, 5a, and 6.

Conclusions

This research study explored cement-stabilised fine-grained lateritic soil (i.e. residual soil). The applicability of the cement-stabilised soil is discussed based on various standards worldwide. In general, the following conclusions can be summarised according to the findings:

1. The UCS of the natural soil improved by adding cement and increasing curing time. Accordingly, the elastic modulus is improved with increasing UCS.
2. The durability test yielded the collapse (i.e. zero UCS) of untreated soil and 3% cement-stabilised soil after immersing and one wetting-drying cycle.
3. The UCS of 6% cement stabilised soil decreased with wetting-drying cycles because of interparticle bonding degradation and ingression of water into voids.
4. The UCS of 9% cement and 12% cement stabilised soil yielded an increased trend with wetting-drying cycles. This trend can be attributed to high interparticle bonding that results from cement hydration, leading to prevent water ingression into voids.
5. The UCS value increases with increasing Ca content, Ca/(Al+Si) ratio, and Ca: Si. Besides, the UCS value increases with decreasing Al: Si value. Therefore, these ratios are a suitable chemical indicators for improving soil upon adding cement.
6. The cement-stabilised lateritic soil is applicable for road construction. However, the optimum percentage of cement in stabilised soil varies according to the types of road layers and standards.

Although it was found that the cement is applicable for road construction and the optimum cement varies according to the various standards, further studies need to be carried out to correlate the optimum cement based on the type of clay and minerals.

Abbreviations

UCS	Unconfined compressive strength
FESEM	Field emission scanning electron microscopy
EDX	X-ray spectroscopy
CSH	Calcium silicate hydrate
CAH	Calcium aluminate hydrate
CASH	Calcium aluminate-silicate hydrate
EICP	Enzyme-induced carbonate precipitation
MICP	Microbially induced calcium carbonate precipitation

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Authors' contributions

The conceptualization, data collection and writing of the original draft were performed by MJR. The validation and design of the work were performed by ASAR. Review and editing were performed by MAH, MNN and SNJ. The analysis of the data and interpretation were performed by ST and RR. The authors contributed to the manuscript and have read and approved the final version.

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Availability of data and materials

The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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