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Strength and Durability of Cement-Treated Lateritic Soil

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Abstract: The transportation infrastructure, including low-volume roads in some regions, needs to be constructed on weak ground, implying the necessity of soil stabilization. Untreated and cement-treated lateritic soil for low-volume road suitability were studied based on Malaysian standards. A series of unconfined compressive strength (UCS) tests was performed for four cement doses (3%, 6%, 9%, 12%) for different curing times. According to Malaysian standards, the study suggested 6% cement and 7 days curing time as the optimum cement dosage and curing time, respectively, based on their 0.8 MPa UCS values. The durability test indicated that the specimens treated with 3% cement collapsed directly upon soaking in water. Although the UCS of 6% cement-treated specimens decreased against wetting–drying (WD) cycles, the minimum threshold based on Malaysian standards was still maintained against 15 WD cycles. On the contrary, the durability of specimens treated with 9% and 12% cement represented a UCS increase against WD cycles. FESEM results indicated the formation of calcium aluminate hydrate (CAH), calcium silicate hydrate (CSH), and calcium aluminosilicate hydrate (CASH) as well as shrinking of pore size when untreated soil was mixed with cement. The formation of gels (CAH, CSH, CASH) and decreasing pore size could be clarified by EDX results in which the increase in cement content increased calcium.

Keywords: lateritic soil; low volume road; cement; UCS; durability; FESEM; EDX

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1. Introduction

Increasing population and demands have resulted in vast construction of the transportation infrastructure. Although urbanization has been developed, and most Malaysian people live in urban areas, rural roads are still significant for rural inhabitants to travel and carry their goods conveniently. The total length of roads across Malaysia is about 216,837 km, of which about 25% (i.e., 52,801 km) is unpaved road (i.e., low volume road), constructed conventionally of gravel [1]. Therefore, lateritic soil, which is widespread in tropical countries, including Malaysia, could replace gravel in low-volume roads. Low-volume roads have average daily traffic (ADT) of below 250 vehicles per day [2].

Although lateritic soil can be divided into coarse grain and fine grain, some researchers have used different classification methods. For instance, Lacroix [3] classified laterite soils, based on chemical properties, as true laterites, silicate laterites, and lateritic clays. Afterward, Martin and Doyne [4] and Martin and Doyne [5] categorized laterite soils according to their silica–alumina ratio (SiO_2/Al_2O_3). The ratio is less than 1.33, between 1.33 and 2, and greater than 2 for true laterites, lateritic soil, and non-lateritic, tropically weathered soil, respectively. However, this classification has a deficiency as it does not consider the value of iron oxides (Fe_2O_3), which are one of the major constituents in these soils. Therefore, another ratio was proposed by Martin and Doyne [4] such that they considered the value of ferric oxide along with aluminum oxide in term of the silica–sesquioxide ratio ($\frac{SiO_2}{Al_2O_3+Fe_2O_3}$) [6]. The size of grains depends on the degree of lateralization and weathering degree. The quantity of primary silicates and bases is less in the composition of lateritic soil, while the amount of secondary oxides (i.e., iron oxides, aluminum oxides, or both) is greater in lateritic soil ingredients [7].

Soil characteristics depend on various factors such as constituent and particle size, origin, water content, and microstructure. In other words, the intricate system of soil can be affected by varying chemical, biological, and physical processes [2,8–31]. The vulnerability of structures such as road and railway embankments and beds increase when the soil has a considerable proportion of clay mineral because this type of soil possesses low engineering properties. A high percentage of fine-grained soil particles exist in the majority of residual tropical lateritic soil, resulting in the low engineering characteristics of these types of soils [32]. Therefore, fine-grained, tropical lateritic soils are very susceptible when exposed to the atmosphere. In other words, tropical soils alter their properties with interaction with the atmosphere. For instance, De Carvalho et al. [33] reported the collapse of the roads in the Amazonas state of Brazil due to the swelling of the substructure resulting from water infiltration. Thus, these types of soils need to use methods to improve their characteristics as transportation materials.

Researchers have used varying stabilizers to improve the mechanical and engineering characteristics of soils. For instance, biomaterials (bacteria and enzyme) [34] are utilized in bio-cementation techniques such as microbial-induced calcium carbonate precipitation (MICP) and enzyme-induced calcium carbonate precipitation (EICP) because of their "environmentally-friendly" features [35]. Microbially induced calcite precipitation (MICP) as a biomineralization method has been used for soil stabilization in previous studies [36–39]. A biochemical process occurs in the MICP method to improve soil properties. The process in which microbially induced biochemical processes fill the gaps between soil grains is called bio-logging [36]. Since emerging in 1995, the MICP method has been compatible with green construction requirements [40] such that it has had minimal impacts on the environment compared with conventional methods. However, considering the granular material, the MICP method does not significantly stabilize fine-grained soil [41]. Nevertheless, some studies have been conducted on the effectiveness of MICP in stabilizing fine-grained soil.

For instance, Sharma and Ramkrishnan [37] studied the influence of this method on CL and CH soils, and their results indicated that MICP was increased the UCS of both soils, but the UCS increase of CH was greater when compared to CL soil. Moreover, Choi et al. [42] stated that apart from the environmentally friendly features of MICP, the cost of calcium chloride ($CaCl_2$) made this method uneconomical. The cost and environmental effectiveness of the MICP approach relate to the volume of chemical solution requirements. In stabilizing sub-base material, the MICP method affects the environment 3.4 times more and is about 1.6 times costlier than the conventional cement stabilization method due to its high volume of chemical solution requirements [43]. A study by Islam et al. [39] revealed that, in general, MICP increased the UCS of clay soil, but the enhancing rate of UCS was below the threshold for some subgrade soils. However, the authors [39] indicated that the UCS of clayey soil might be increased beyond the threshold using additional treatment cycles. The enzyme-induced calcium carbonate precipitation (EICP) technique requires the urease enzyme rather than bacteria. Thus, EPIC is utilized to overcome factors such as bacteria–soil adaptability, cost of cultivation, and difficulties in the storage of bacteria that impede the application of MICP [44]. The rates of carbonate precipitation and preparation method affect strength gain in the EICP technique. In general, the efficiency of EICP is lower than the MICP method [45]. Furthermore, the cost of EICP is another concern when using it in practice [46].

Latifi et al. [47] used a sodium silicate-based stabilizer (TX-85) to stabilize tropical lateritic soil. They stated that a 9% TX-85 stabilizer agent increased the compressive strength of lateritic soil almost four times in 7 days, curing it from 270 kPa to 984 kPa. [48] studied the suitability of the mixture of lime, coal fly ash, and ground glass to stabilize residual lateritic soil in Brazil. Their results indicated that UCS increased with the decrease of η/B_{iv}, in which η indicated the porosity and B_{iv} illustrated the volumetric content of pozzolan and carbide lime. The results of a study by Oyediran and Okosun [49] suggested the desirability of 6 to 10% lime content for stabilization of lateritic soil as a road base in Nigeria. However, the authors stated that the suitability of lateritic soil as road base material was different from soil to soil.

Another study by Jiang et al. [50] compared quicklime and calcium carbide residue (CCR) efficacy on a road subgrade's low-plasticity clay soil in China. The results of their study revealed that generally, at the same percentages of 4% and 6%, the influence of the calcium carbide was bigger compared to the quicklime. However, the results indicated that the efficacy of quicklime was dependent on the degree of compaction, while the effectiveness of CCR was not. For instance, considering the 120-day curing time, a UCS of 2250 kPa was obtained using CCR regardless of compaction percentage, while on the other hand, for 6% quicklime, UCS of 1600 kPa and 2200 kPa were achieved for 93% and 96% degrees of compaction, respectively.

Similarly, a study by Kampala et al. [51] explored the influence of CCR and fly ash on silty clay in Thailand. The achieved results highlighted that CCR increased the UCS value, but the durability of CCR-stabilized soil against wetting and drying (WD) cycles was low according to the American Concrete Institute (ACI) and the US Army Corps of Engineers and could not be accepted as a road pavement material. However, 20% fly ash (FA) was the optimum percentage for mixing 7% CCR-stabilized soil to reach strength and durability requirements. Furthermore, the effectiveness of CCR- stabilized subgrade soil has been studied through experimental field tests such as the California Bearing Ratio (CBR), Cone Penetration Test (CPT), plate loading test, and Benkelman beam deflection test [52]. A high-calcium, fly ash-based geopolymer was used to stabilise the marginal lateritic soil for use as the road base and subbase material. [53,54]. Other kinds of materials such as bamboo straw ash, biomass silica (SH85), xanthan gum, fly ash, expanded polystyrene geofoam (EPG), sulfonated oil, waste plastic crumb, and shredded tire rubber have also been utilized in stabilizing subgrade soil and construction of roads [32,55–60]. Furthermore, cement has been studied as a modifier and stabilizing agent in the stabilization of soil as a road material vastly and globally [61–68]. The effect of cement as a stabilizer for the subbase and base of roads for flexible pavement thickness was also studied by [69]. Based on their results, pavement thickness showed a declining trend with an increase in cement content of subgrade soil. Based on Nusit et al. [70], 3% to 7% cement has been suggested for the stabilization of crushed rock road base in Australia. The organic matter in the soil composition delays the hydration process of cement, resulting in low strength and low effectiveness.

In this regard, the results of a study exposed that the pH value and SO_4 concentration in the voids could be used as key indicators for determining the effectiveness of cement-treated soil. In other words, the oil and hydrocarbons postponed the hydration of cement but did not affect its final strength, while on the other hand, a pH value lower than 9 in the pore solution produced by organic acid strongly affected the formation of cementing products and no strength gain was recorded [68]. Thus, the pH value decreased considerably with zinc concentration, resulting in low UCS, E_{50} value, and decreased C-S-H, portlandite, and ettringite compounds in the cement-stabilized soil [71].

Another study by Du et al. [63] ascertained that zinc concentration increase, as a heavy metal, demolished cementation bonding in cement-stabilized soil, resulting in consolidation yield stress and compression index decrease. Mohammadinia et al. [62] inspected the optimum dosages of cement for stabilizing crushed brick (CB), reclaimed asphalt pavement (RAP), and recycled concrete aggregate (RCA) to be used as road base and sub-base materials, based on the local standard requirements of Australia. The results revealed that the required minimum UCS of 4 MPa, based on Australian standards, was achieved using 2% cement with 7 days curing for RAP and 4% cement with 28 days curing for RCA and CB. Razali and Che Malek [1] studied the applicability of cement, lime, and bitumen emulsion stabilizer agents for stabilizing lateritic soil to be used in low volume roadbed. The study revealed that the first two stabilizers were not suitable, whereas the 4% cement was enough to obtain a minimum UCS of 0.8 MPa according to Malaysian standards. In the same way, a research study by Akmal Abd et al. [72] proposed 8% cement for stabilizing of kaolin in order to obtain the minimum UCS of 0.8 MPa, according to Malaysia Public Works Department (MPWD) standards.

The durability of soil against wetting–drying and freezing–thawing cycles is of great importance. In tropical countries like Malaysia that have humid, hot, and rainy weather, durability should be tested against wetting–drying cycles. In contrast, in countries having cold weather, durability testing should be conducted against freezing–thawing cycles. The durability of soil has been studied against wetting–drying cycles [61,73–78] and freezing–thawing cycles [79].

Kampala et al. [51] explored the influence of wetting–drying cycles on calcium carbide residue (CCR) and fly ash (FA)-stabilized silty clay in Thailand. The results revealed that the durability of soil was mainly related to its initial unconfined compressive strength (UCS). Larger initial UCS resulted in more durable soil. The durability of recycled asphalt pavement and fly ash mixture increased against wetting–drying cycles until reaching the 6th cycle; beyond that, the UCS of the mixture decreased because of initiated cracks. [51]. The applicability of high-plasticity Bangkok clay when mixed with bottom ash and lime was investigated for road construction according to Thailand standard [77]. The stabilized Bangkok clay with 50% bottom ash and 12% lime mixture was found to be the most durable condition against wetting–drying cycles. However, the durability of some cement-treated soils was also investigated (e.g., [80]), but yet to be investigated vastly. Furthermore, the durability of some stabilized soils has been investigated based on local road standards in other countries [72,74,75], but the durability of cement-lateritic soil has not been investigated yet considering Malaysia Public Works Department (MPWD) standards for low-volume roads.

In summary, so far, different methods have been discussed, according to their effectiveness, advantages, and disadvantages. As mentioned before, different methods can be utilized in soil stabilization, and particularly in road construction. However, as mentioned earlier, some nontraditional, environmentally friendly stabilizers cannot be replaced with ordinary Portland cement to stabilize transportation subgrade. For instance, some bio-cementation methods such as MICP and EICP are environmentally desirable, but their usage for high-volume earthwork is still questionable because of the high cost. Further, MICP was found to impose more CO2 for high volumes of earthwork than ordinary Portland cement (OPC). In this regard, one can refer to [43] for more detail. Therefore, OPC could still be considered an effective stabilizer agent in the construction of transportation infrastructure, as Al-Jabban et al. [81] stated, based on their research that cement was more effective in improving the engineering properties of fine-grained soil compared to Petrit-T, a by-product obtained from sponge iron manufacturing [82]. Although some studies have been conducted in determining the optimum OPC for low-volume roads according to MPWD standards, the small number of studies and discrepancies between obtained results motivated the conducting of this research. Moreover, previous studies in Malaysia have neglected the durability that is of great importance in road construction. Therefore, this research aims to study the mechanical, durability, and microstructure behavior of lateritic soil treated with ordinary Portland cement (OPC).

2. Materials and Methods

The lateritic soil used for the current research study was collected from Universiti Teknologi Malaysia, Johor campus. The sampling pit was at 1°33′32.9″ N, 103°38′39.4″ E coordinates. The soil collected was first stored outside the lab for drying in the air and then was left inside the oven for two days to become completely dry. The oven drying temperature was selected as equal to 60 ± 5 degrees Celsius to avoid temperature effects on the soil characteristics [83–85]. Next, the oven-dried soil was passed through a 2 mm sieve in order to prepare a homogenous specimen. The color of the sampled soil was reddish, indicating high iron oxides [57]. As shown in Table 1, the soil was classified as plastic silt (MH) and A-7-5 according to the USCS and AASSHTO systems, respectively. The rest of the primary natural soil properties, such as particle grain size, Atterberg limits, maximum dry density, and optimum moisture content of the natural lateritic soil used in this study have been tabulated in Table 1.

Table 1. Characteristics of untreated 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: Mg/m^3	MDD	1.39
Specific gravity	G_s	2.74
Dry unit weight: KN/m^3	γ	13.64
Unconfined compressive strength (UCS) kPa	q_u	200.75
Undrained shear strength: kPa	S_u	100.38

In regard to Table 1, the obtained results are within the ranges found for lateritic soil by other researchers [32,57,86]. The grain size distribution curve of lateritic soil and ordinary Portland Cement (OPC) is illustrated in Figure 1, indicating the high content of fine grains: 61.26% of silt and 8.41% of clay, for lateritic soil. The particle size distribution of soil grains smaller than 75 microns and OPC was carried out using laser diffraction machine model LA960V2 HORIBA according to ISO:13320 (2009) because laser diffraction methods were more reliable and effective [87,88]. The sieving method was adopted for analyzing soil particles larger than 75 microns. The combination of conventional and laser diffraction methods adopted in this study resulted in saving time and high precision [89].

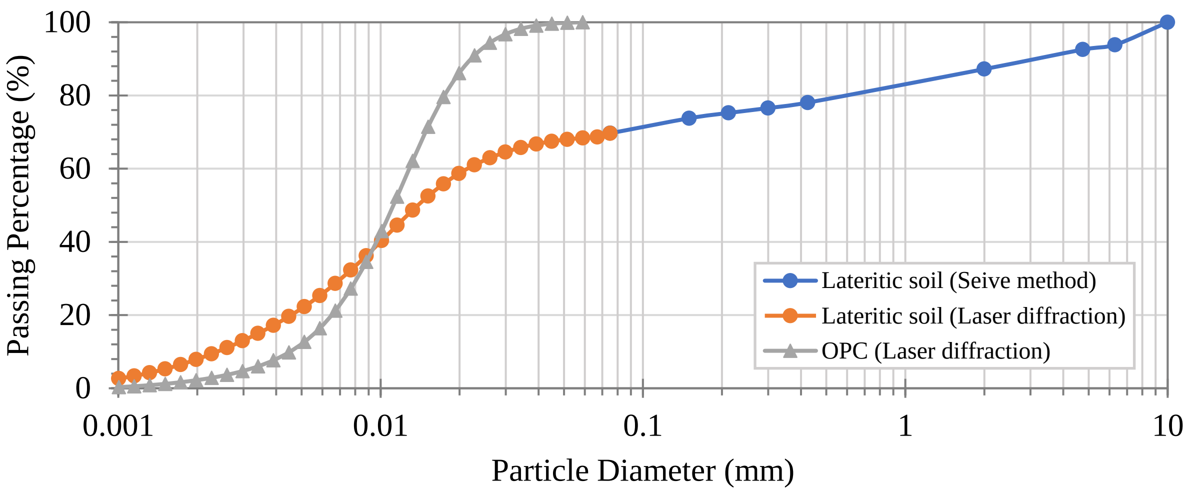

Figure 1. Particle size distribution of natural lateritic soil and OPC.

Ordinary Portland cement, one of the most common agents for stabilization purposes in road geotechnical engineering [90], was selected as a binder element in this research. The

OPC used in this study was CEM I 42.5 N, which was produced by the Holcim company. OPC CEM I was chosen for this study because it had 95–100 percent clinker compared to 65–94 percent for CEM II, meaning that CEM I had higher strength [91]. In addition, by using a higher clinker percent, the targeted strength could be achieved quickly. The particle size distribution of OPC used in this study is illustrated in Figure 1. In addition, the chemical elements of the OPC and lateritic soil used in this research are tabulated in Table 2.

Table 2. Chemical elements of lateritic soil and OPC.

Element	Untreated Wt (%)	Cement Wt (%)
O	61.4	44.6
Al	16.9	2.5
Si	16.1	4.6
Fe	5.2	2.8
K	0.4	1.6
Ca	-	34.4
S	-	8.5
Mg	-	1

In order to prepare the specimens for UCS testing purposes, the standard compaction was carried out according to British standards [92] to determine the maximum dry density (MDD) and optimum moisture content (OMC). Thus, in this research, the unconfined compressive strength (UCS) test was conducted according to British standards [93] to find out the compressive strength (q_u) and undrained shear strength (S_u) of the desired mixed specimens. The specimens were prepared using compaction test results for 3, 6, 9, and 12% cement. For doing so, the sample was prepared at 76 mm height (h) and 38 mm diameter (d) to prevent the effects of the h/d ratio on UCS results [94]. The summary of the testing plan is tabulated in Table 3, while the details of the machine used in this study for UCS testing are depicted in Figure 2.

Table 3. UCS testing plan.

No	Cement (%)	Curing Time (day)
1	0	0
2	3	0, 3, 7, 14, 28
3	6	0, 3, 7, 14, 28
4	9	0, 3, 7, 14, 28
5	12	0, 3, 7, 14, 28

In addition to strength and stiffness, road layer performance dramatically pertains to durability tests [75]. In regard to the tropical climate of Malaysia, in this study, the durability performance of lateritic soil treated with 3%, 6%, 9%, and 12% Portland cement and cured for 7 days was tested at the end of 1, 2, 4, 7, 12, and 15 wet–dry cycles using the UCS test. The specimens having 38 mm diameter and 76 mm height were immersed into water for 5 h and then put for 42 h into an oven at a temperature of 71 °C ± 3 °C in order to simulate one wetting–drying cycle [95].

To explore the influence of cement on lateritic soil mechanical properties more clearly, microstructure and morphology analyses have been conducted using scanning electron microscopy (SEM) and field emission scanning electron microscopy (FESEM) tests [96]. In other words, to figure out the principal mechanisms of chemical stabilization, conducting microstructural analysis has been effective [57]. For doing so, specimens for the microstructural analysis were prepared from the UCS samples after testing. After that, identical to [96], a small, solid specimen was coated with platinum using a vacuum sputter coating before starting the FESEM test. Furthermore, the EDX experiment was conducted to study the quantitative analyses [97] of untreated and cement-treated lateritic soil.

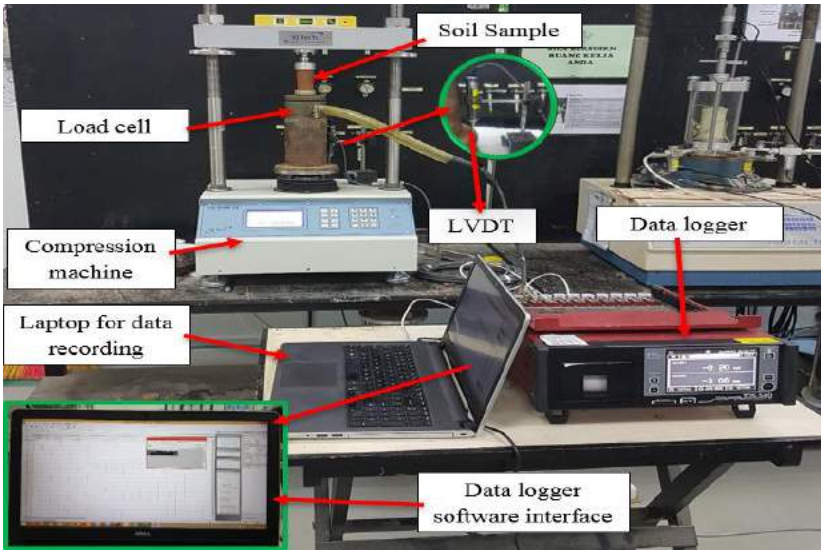

Figure 2. Equipment used for UCS testing.

3. Results and Discussion

3.1. Compaction

From Figure 3, it is seen that MDD and OMC increase with cement percentage. The increasing trend of MDD and OMC with the increase of cement content in this study is consistent with previous research [98,99]. The influence of cement on the compaction properties of fine lateritic soil is clearly demonstrated in Figure 4. The MDD and OMC for untreated soil were obtained equal to 1.39 g/cm^3 and 28%, respectively. After mixing the cement to 3, 6, 9, and 12 percent, the MDD increased to 1.419 g/cm^3, 1.447 g/cm^3, 1.460 g/cm^3, and 1.479 g/cm^3, respectively, as shown in Figure 4. Similarly, the OMC increased to 29.5, 30, 30.5, and 31% by adding 3, 6, 9, and 12% cement, respectively.

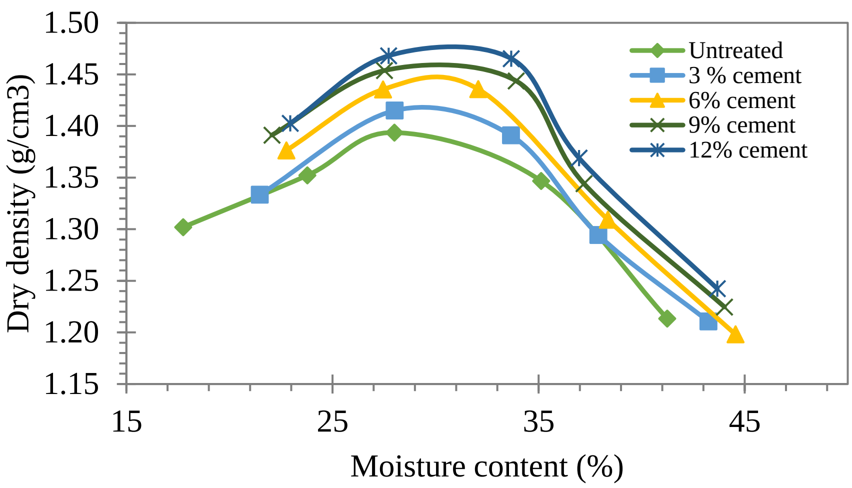

Figure 3. Compaction curves.

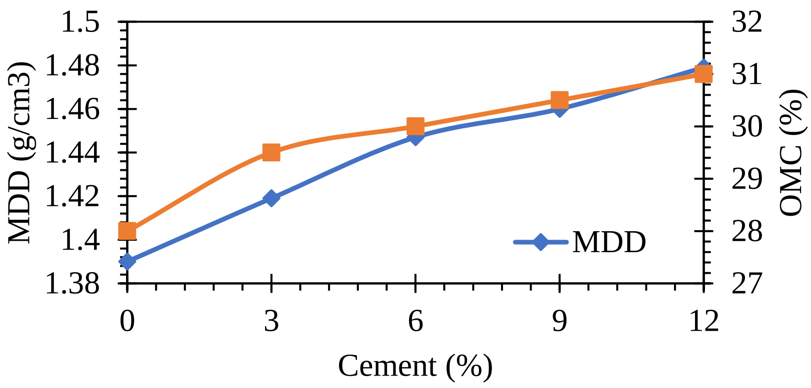

Figure 4. MDD and OMC with respect to cement content.

3.2. Unconfined Compressive Strength

The stress–strain curves are depicted in Figure 5, and it can be readily understood that the shear strain decreased with the increase of cement content and curing time. In contrast, the unconfined compressive strength increased with increasing cement content. For instance, considering 7 days curing time, the untreated UCS of 200.74 kPa improved to 391.35 kPa, 1233.15 kPa, 1737.52 kPa, and 1899.6 kPa for 3%, 6%, 9%, and 12% cement, as shown in Figure 5c Strength gain due to cement is attributed to decreased soil porosity when adding cement [80]. Conversely, the strain decreased from 2.58% for untreated to 2.08%, 1.56%, 1.37%, and 1.19% for 3%, 6%, 9%, and 12% cement content within 7 days curing. The results obtained for the ductility change with increasing cement and curing time in this research were compatible with [2,70,82,100] in that the authors indicated higher brittleness for high cement content and more curing time. Similarly, in the current study, the ductility changes of a specimen mixed with 3% cement, with a curing time, were not considerable, whereas the ductility significantly decreased for 6%, 9%, and 12% cement. This fact can also be seen in the specimens' failure shape when treated with 3% cement in Figure 6a, wherein the failure plane is in a bulging shape such as that of the untreated samples. Whereas, for 6%, 9%, and 12% cement, the samples were sheared in an inclined plane, as illustrated in Figure 6. The failure plane pattern obtained in this research is compatible with the research conducted by [86]. Although the overall UCS results shown in Figure 5. demonstrate that compressive strength was enhanced with cement content and curing time, the effectiveness of 3% cement was not significant. This behavior could be attributed to the low pH value, whereby the cement could not improve soil strength effectively at a pH value smaller than 12.4 [82].

The UCS results in Figure 7 show that the 6% cement was adequate for stabilizing the lateritic soil to achieve a minimum UCS of 0.8 MPa, according to Malaysia Public Works Department (MPWD) standards. The result was consistent with the research of [7], in which between 2% and 6% cement was suggested for stabilization of Colombian lateritic soil, to be applied for construction of low- to medium-volume roads. Although the UCS results for 6% cement-treated specimens in 0- and 3-day curing were under the target value (800 kPa), for 7-day curing, they increased above the target value in Figure 7. Therefore, the 7-day curing time was sufficient to achieve minimum UCS results for 6% cement according to MPWD, as shown in Figure 7.

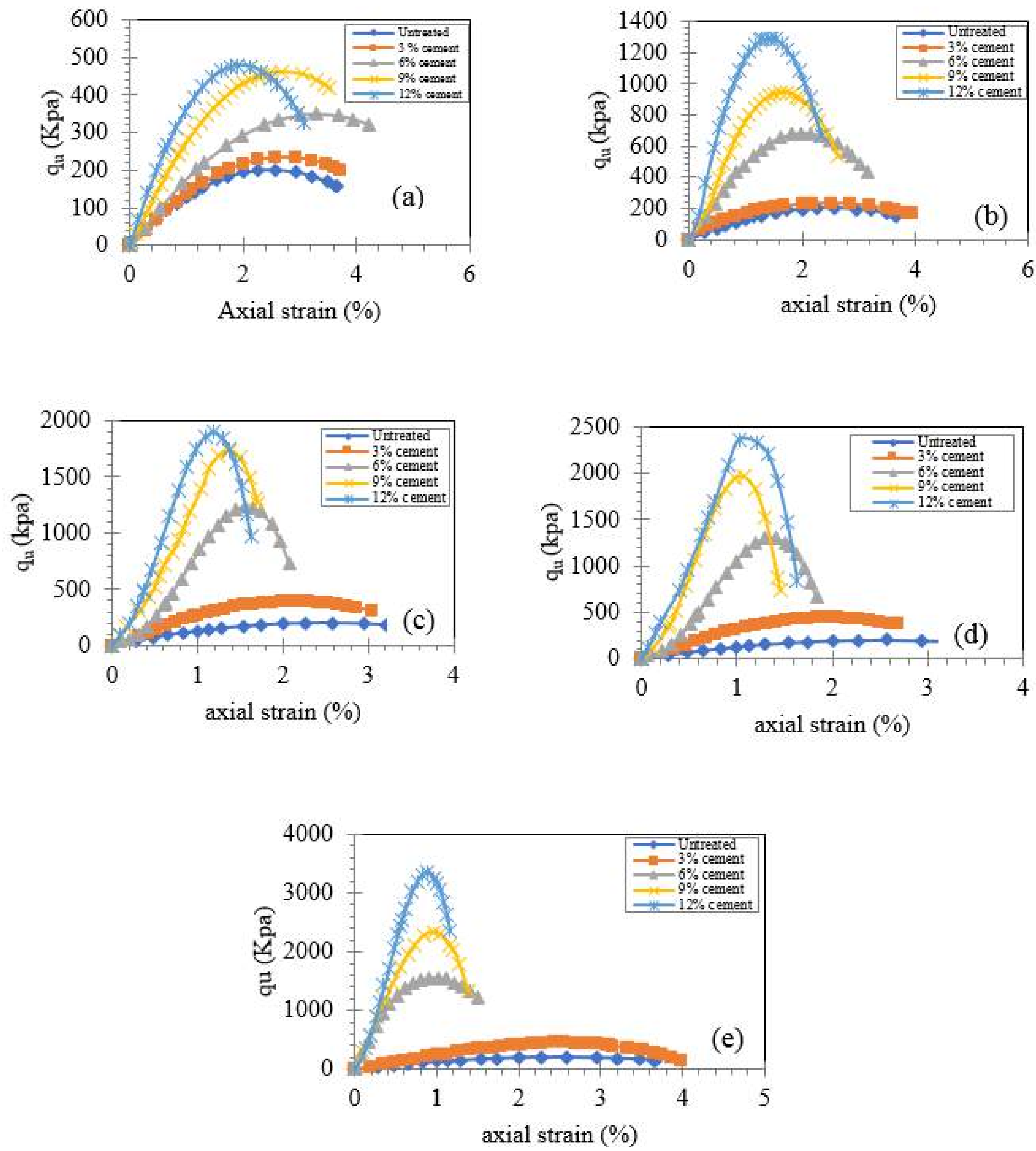

Figure 5. UCS results for different curing times: (**a**) 0 days, (**b**) 3 days, (**c**) 7 days, (**d**) 14 days, (**e**) 28-days.

Figure 6. Failure plane for 28-day curing: (**a**) bulging shape (**b**) inclined shape.

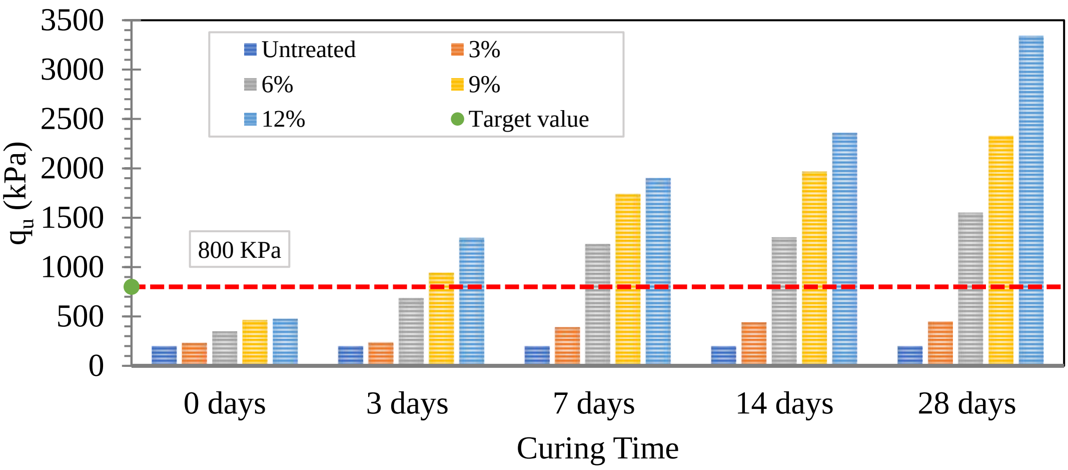

Figure 7. UCS due to curing time for different cement contents.

Moreover, regression analysis was carried out for UCS results according to cement content for 0, 3, 7, 14, and 28-day curing times, as depicted in Figure 8. The results in Figure 8 indicate a square root value of above 0.91 for all curing times. Regarding Figure 8, the UCS value of all specimens treated with 3, 6, 9, and 12 % cement is under the target line for 0 curing time. This issue indicates the importance and effectiveness of curing time. However, from Figure 8, one can understand that even around 4.5% cement at 7 days curing results in 800 kPa, but it is of considerable importance to use a cement dose above the minimum threshold because of the durability of subgrade under wetting and drying cycles. In other words, the UCS of cement-treated lateritic soil decreases under wetting and drying cycles [61]; hence, in this research, 6% cement is suggested to stabilize the lateritic soil in the application of low volume roadbed.

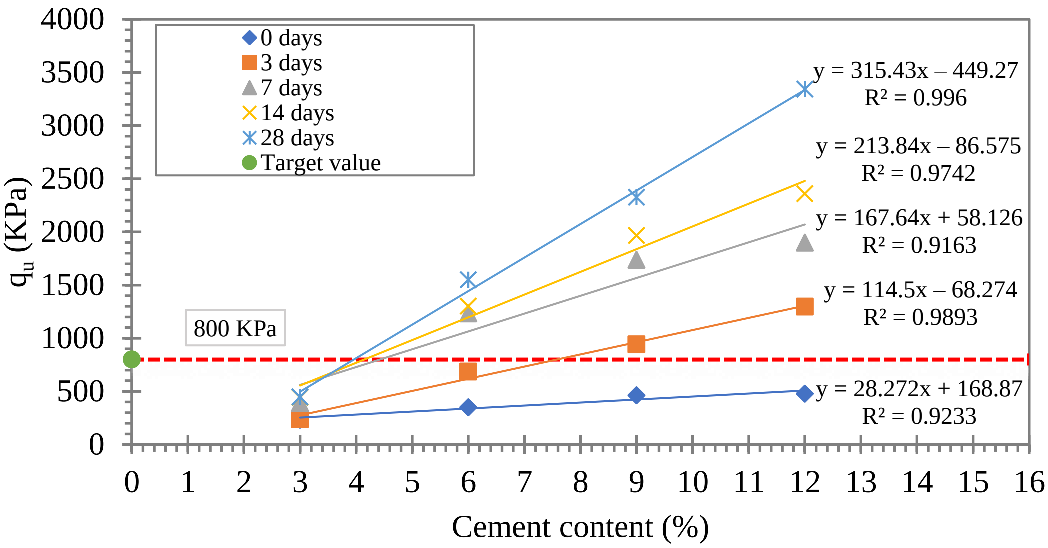

Figure 8. Relationship between UCS and cement content for different curing times.

Given a comparison of the results obtained for UCS in this research with other studies in which other types of stabilizers were used, it can be easily see—n that that the cement is more effective than other types of stabilizer agents. For instance, research by Sharma and Ramkrishnan [37] exposed that the use of microbial-induced calcite precipitation (MICP), increased by 1.5–2.9 times the UCS of intermediate- and high-compressible soil, while in this research, the 7% cement increased by 9.5 times the UCS of untreated lateritic soil under 7 days curing. Similarly, in a study by Latifi et al. [47], the UCS of lateritic soil increased from 270 kPa to 984 kPa by using 9% TX-85 for 7 days of curing, while in the current research, over 7 days of curing, 9% OPC enhanced the UCS of lateritic soil from 200.75 to 1732.52 kPa. Further, the UCS increase in the current research was much higher than the UCS increase in the research by Bhurtel and Eisazadeh [77], in which lime was used for treating Bangkok clay. Upon considering these comparisons, it can be easily understood that the effectiveness of OPC is much larger than other kinds of stabilizers such as lime, MICP, and TX-85.

3.3. Effect of Curing Time on Cement Stabilized Laterite

The influence of curing time on soil strength can clearly be explained with the strength development index (SDI). The SDI can be obtained according to Equation (1) [77].

$$SDI = \frac{q_{u(tr)} - q_{u\ (unt)}}{q_{u\ (unt)}} \quad (1)$$

where $q_{u(tr)}$ = unconfined compressive strength of treated-lateritic soil and $q_{u\ (unt)}$ = unconfined compressive strength of the untreated specimen.

Figure 9 depicts SDI results for treated soils with 3%, 6%, 9%, and 12% cement at 0, 3, 7, 14 and 28 days. The target value of SRI = 2.99 was calculated according to the untreated UCS value (i.e., 200 kPa) and the target UCS value (i.e., 800 kPa). Thus, considering the target SRI = 2.99, the lateritic soil could not achieve the target UCS = 800 kPa at 0 days curing for all 3%, 6%, 9%, and 12% cements; at 3 days curing for 3% and 6% cement; and at 7, 14, and 28 days curing for 3% cement. By looking at Figure 9, one of the effective parameters in cemented soil is curing time. However, the slow growth rate of UCS for a small amount of cement is due to the slow hardening process and complex reaction [101]. The regression analysis of UCS for 3%, 6%, 9%, and 12% cement according to curing time is portrayed in Figure 10. In the same manner, Figure 10 also indicates that 3% cement does not result in a target value of UCS of 800 kPa, even at 28 days, as it located under the red-colored target line. Therefore, according to MPWD standards, 6% cement and 7 days curing are suggested as the optimum cement percentage and curing time.

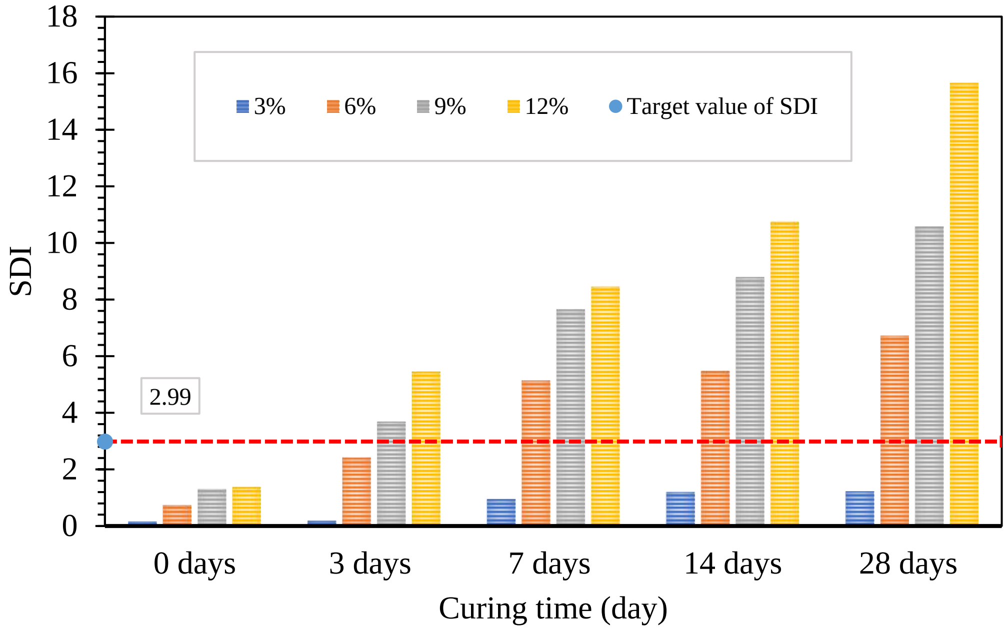

Figure 9. Strength development index (SDI) due to curing time.

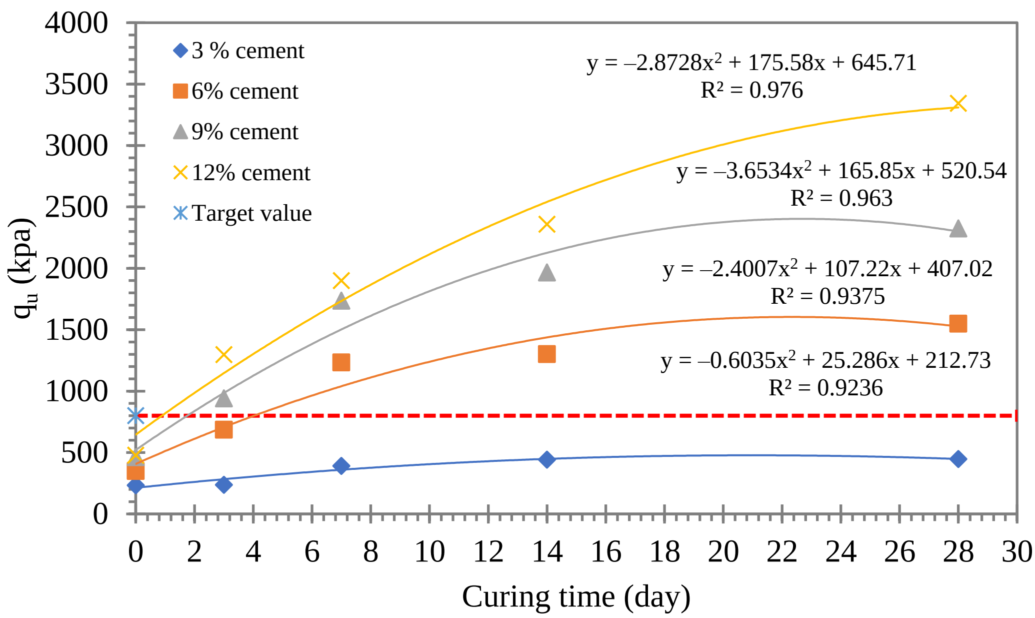

Figure 10. Relationship between UCS and curing time for different cement contents.

3.4. Effect of Cement Content on Soil Stiffness

The influence of cement on soil stiffness can be evaluated with initial and secant moduli. The secant moduli were considered at half of the maximum unconfined compressive strength in this study, the same as in previous studies [2,81,102]. Figure 11 represents the relationship of secant moduli (E_{50}) and the unconfined compressive strength (q_u) of soil treated with 3%, 6%, 9%, and 12% cement at 0, 3, 7, 14, and 28 days curing. In regard to Table 4, the obtained equation for E_{50} in this study was within the range of previous studies, particularly the study carried out by Rashid et al. [2] in Malaysia.

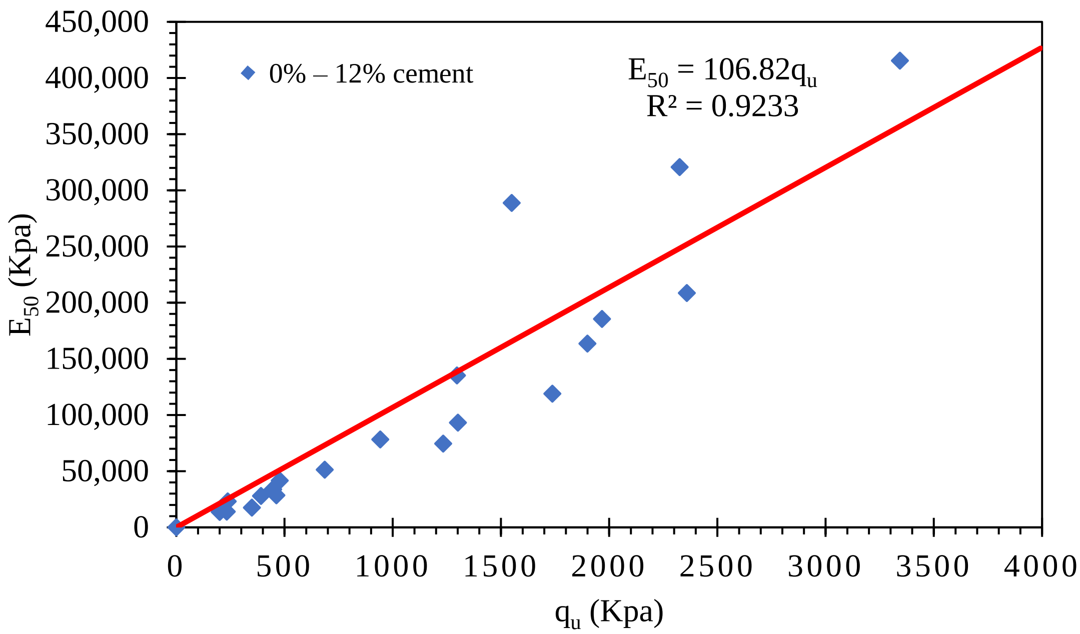

Figure 11. Relationship between elastic modulus (E50) and UCS.

Table 4. Comparison of secant moduli (E50) with previous studies.

Material	Stiffness, According to UCS	Reference
Cement-treated (3–12%) lateritic soil in Malaysia	$E_{50} = 106.82\ q_u$	Current study
Cement-treated (7–13%) silt, silty clay, and laterite in Malaysia	$E_{50} = (100–326)\ q_u$	[2]
Cement-treated (1–7%) sandy clayey silt in Sweden	$E_{50} = (16–85)\ q_u$	[82]
Cement-admixed (5–20%) Bangkok clay in Thailand	$E_{50} = 150\ q_u$	[102]
Cement-stabilized (10%) and cement kiln dust-stabilized (10–13%) high-plasticity soft Bangkok clay in Thailand	$E_{50} = 113\ q_u$	[103]
Cement-stabilized (10–20%) marine clay in China	$E_{50} = (150–275)\ q_u$	[104]
Cement-treated (3–9%) laterite soil in Cameroon	$E = 117.39\ q_u - 36.812$	[86]

3.5. Durability

The wetting–drying cycles impacted the UCS of treated lateritic soil. The durability results of 3%, 6%, 9%, and 12% cement-treated specimens for 7 days curing are depicted in Figure 12. In regard to Figure 12, the 3% cement-treated specimens collapsed swiftly after soaking into the water, indicating the insufficiency of cement and its short service life against wetting–drying cycles. The 3% cement-treated specimen collapse may have happened because of big pores, which resulted in more water absorption, and subsequently, the collapse occurred due to the total loss of interparticle forces. The specimens treated with 6% cement represented a decreasing trend for UCS against wetting–drying cycles as in previous studies results [49,59,72,77]; the UCS decreased from 1233.15 kPa for 0 cycles to 1220.25 kPa, 1199.15 kPa, 1134.1 kPa, 1024 kPa, 937.6 kPa, and 883.85 kPa for 1, 2, 4, 7, 12, and 15 cycles, respectively.

The UCS-decreasing trend against wetting–drying cycles was ascribed to cement-bonding degradation [73]. Furthermore, Bhurtel and Eisazadeh [77] stated that strength reduction against wetting–drying results from back pressure caused by absorbed pore water and softening of specimens because of soaking into water. On the contrary, 9% and 12% cement-stabilized specimens exhibited an increasing trend, denoting cement adequacy to react with soil particles in water's presence. The increasing trend of UCS for 9% and 12% under WD cycles (i.e., durability) was similar to the durability results obtained by Hoy et al. [105] for recycled asphalt pavement flay ash (RAP-FA) composition. The inclination of UCS under wetting–drying cycles for 12% cement was larger than that for 6% cement, but the drastic increase of UCS for treated soil with 12% cement continued until two cycles; afterward, the slope decreased, as seen in Figure 12.

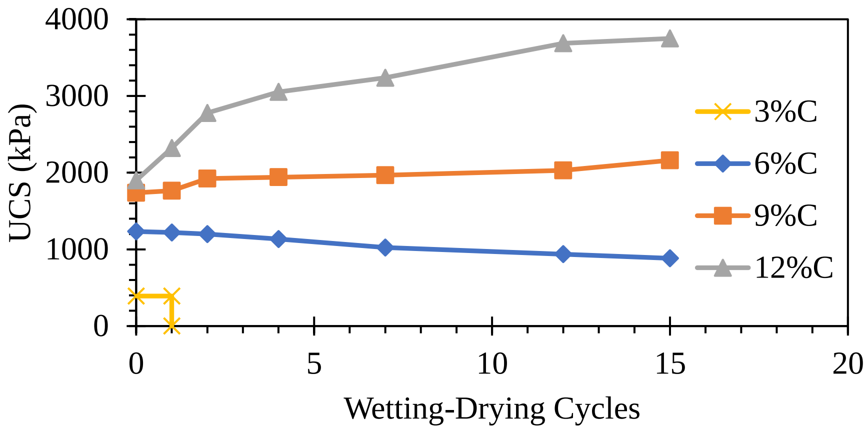

Figure 12. Durability test results.

The increasing UCS against WD cycles was attributed to pozzolanic chemical reactions, in which more calcium aluminate hydrate (CAH) and calcium silicate hydrate (ASH) production was obtained [105], as illustrated in Figure 13. Moreover, the obtained results in this research can be supported by Ye et al.'s [106] results, in which the UCS of expansive soil treated with iron tailing sand and calcium carbide slag first increased until three WD cycles and then decreased after. Furthermore, the cement-treated lateritic soil composed of melanin debris increased UCS against WD cycles until three cycles and then decreased [76]. Overall, the durability results indicated that the treated lateritic soil with low cement percentages resulted in just short-term stabilization, while treated lateritic soil with high cement percentages resulted in both short- and long-term stabilization. Considering MPWD standards, the stabilized soil with 6% cement can maintain the minimum UCS value of 800 kPa under the predetermined wetting–drying cycles in this research, indicating long service life.

3.6. Microstructure Analysis

The influence of ordinary Portland cement (OPC) on lateritic soil at the micro-level was performed using FESEM and EDX methods. The FESEM results of untreated lateritic soil, ordinary Portland cement (OPC), and 7-day curing-treated lateritic soil with 3%, 6%, 9%, and 12% cement are illustrated in Figure 13a–f, respectively. The untreated lateritic soil consists of minerals in platy forms, resulting in big pores as shown with black spots in Figure 13a like previous studies [107–109]. When clayey particles contacted moisture, they dispersed and floated, resulting in large pores [110]. Whereas the FESEM result of pure ordinary Portland cement (OPC) showed small pores with accumulated and needle-like structures, indicating calcium silicate (CS) and calcium aluminate (CA), as seen in Figure 13b. The structure of untreated lateritic soil changed with the addition of OPC. Lateritic soil mainly consists of alumina (Al_2O_3) and silica (SiO_2) [76,111], while OPC considerably consists of calcium ions [86], as shown in Table 2, in terms of chemical elements, of which the highest values, belonging to aluminum and silicon in soil and calcium in OPC, were 16.9%, 16.1% and 34.4% respectively. The stabilization process with the addition of cement to the soil was performed in two stages: cement hydration (short term) and pozzolanic reactions (long term). These two stages resulted mainly in soil stabilization by calcium-based stabilizers such as cement [112]. The hydration of cement resulted in the production of calcium hydroxide (slaked lime) $Ca(OH)_2$, and then pozzolanic reactions occurred as the following [113]:

$$A_xS_y + mCH + nH \rightarrow CSH + CAH \quad (2)$$

Pozzolan (alumina/silica) + lime + water → calcium silicate hydrates + calcium aluminate hydrates.

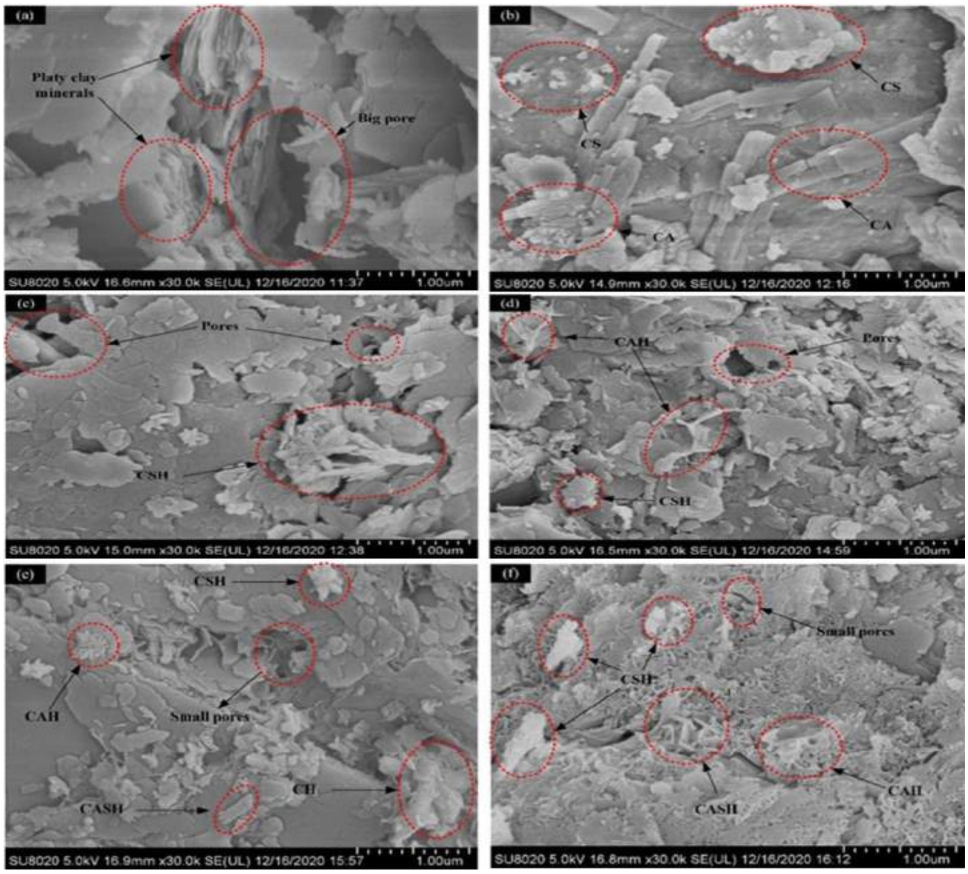

Figure 13. FESEM results at 7 days curing: (**a**) untreated, (**b**) OPC, (**c**) 3% cement, (**d**) 6% cement, (**e**) 9% cement, (**f**) 12% cement.

The increasing cement content and curing time resulted in more hydration and pozzolanic reactions [98]. Thus, the agglomerated parts, indicating the calcium aluminate hydrate (CAH), calcium silicate hydrate (CSH), and calcium aluminosilicate hydrate (CASH) increased with cement content because of pozzolanic reactions between the calcium ions of cement and the silica and alumina of the lateritic soil [114,115]. The gel (CSH, CAH, CASH) products were attributed to the high percentages of amorphous Si and Al in the lateritic soil and Ca in OPC [97]. Furthermore, the cement content modified the pore size and pore distribution of the untreated lateritic soil. The pore size decreased with cementitious bonding force increase [98], created by cement content. The results were consistent with the results found by [69] for cement-treated lateritic soil. In order to explore the microstructure results in more detail, the FESEM pictures were analyzed with Image J software, and the results in Figure 14a–f exhibit that the cement content decreased the pore size, as shown in black spots.

Overall, the UCS increase with cement was attributed to decreasing pore size, resulting from cementitious materials produced because of cement reactions with soil in the presence of water, as shown in Table 5 [116].

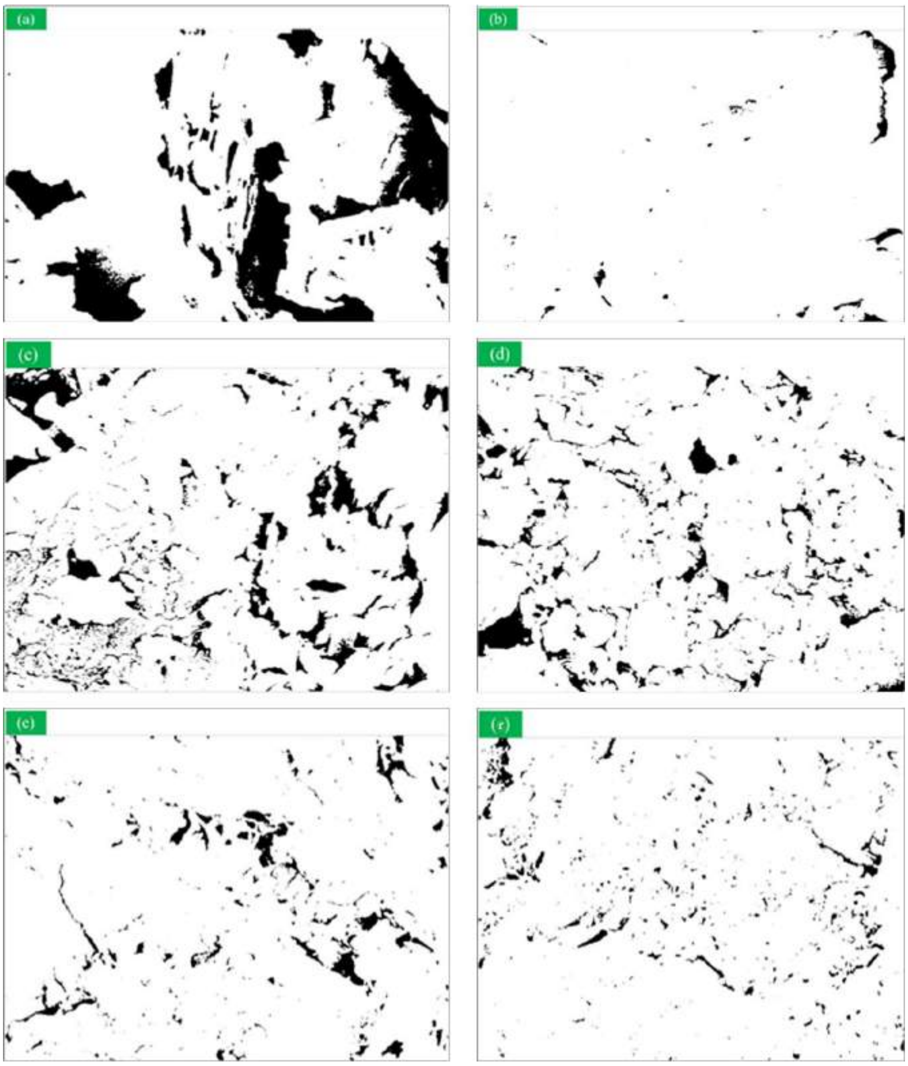

Figure 14. Pore space analysis using image processing of (**a**) untreated, (**b**) OPC, (**c**) 3% cement, (**d**) 6% cement, (**e**) 9% cement, (**f**) 12% cement.

Table 5. Computed parameters of pores and cracks (black spots) of images in Figure 14.

Sample	Count	Total Area (μm^2)	Average Size (μm)	Area (%)	Mean (μm)	Perimeter (μm)	Circularity
Ordinary Portland cement	138	0.216	0.002	1.41	254.687	0.127	0.796
Untreated	168	3.021	0.018	19.713	254.754	0.374	0.778
Cement-treated lateritic							
3%	1884	2.196	0.001	17.894	254.642	0.103	0.812
6%	1414	2.031	0.001	13.348	254.646	0.127	0.779
9%	953	1.228	0.001	8.009	254.854	0.126	0.738
12%	1402	0.813	0.00058	6.626	254.891	0.081	0.807

The chemical elemental-based quantitative analysis of untreated and cement-treated specimens cured for 7 days is portrayed in Figure 15a–e. Given Figure 15a, the untreated lateritic soil in this study was rich in oxygen (O), aluminum (Al), and silicon (Si), having weight percentages of 61.4%, 16.9%, and 16.1%, respectively. The next chemical element having a high value (5.2%) in the composition of untreated soil was iron (Fe). The addition of cement to natural lateritic soil caused calcium (Ca) production, as illustrated with the red circle in Figure 15b–e. The more cement, the higher the weight percentage of calcium [117].

For instance, the 3% cement-stabilized soil resulted in 1.1% calcium (Ca) (Figure 15b); next, it increased to 2.5%, 2.7%, and 8.5% for 6%, 9%, and 12% cement, respectively (Figure 15c–e). The obtained results through EDX testing in this paper were in great agreement with the results of previous studies [86,117]; the high weight percentage of calcium resulted in more gel production (CAH, CSH, CASH) in cement-treatedsoil [114]. Thus, the enhancement of UCS with an increase in cement content could be attributed to the production of calcium.

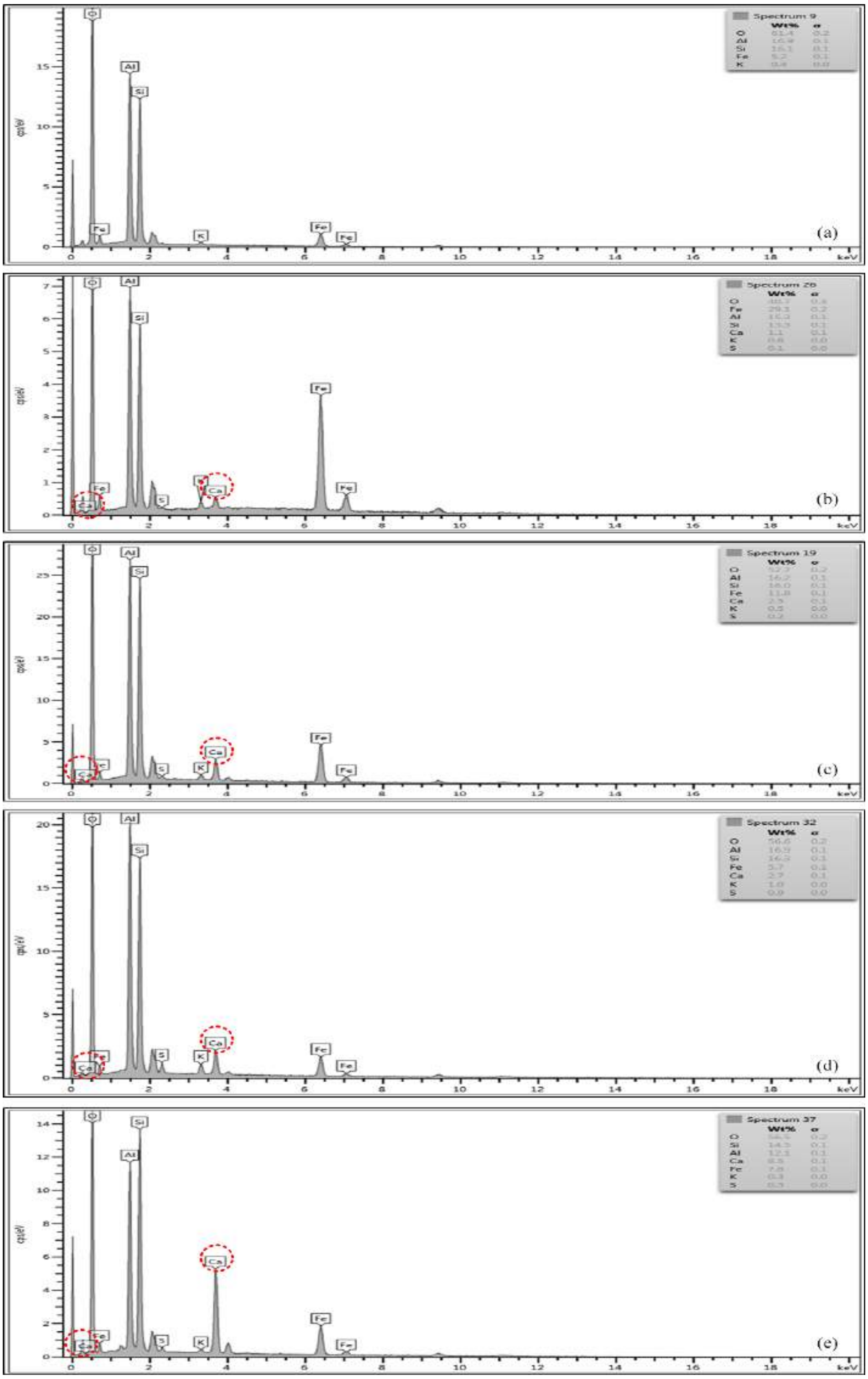

Figure 15. EDX results with 7 days curing for (**a**) untreated, (**b**) 3% cement, (**c**) 6% cement, (**d**) 9% cement, (**e**) 12% cement.

4. Conclusions

Considering Malaysia Public Works Department (MPWD) standards, the obtained results indicated that untreated lateritic soil could not be utilized as road pavement for low-volume roads unless stabilized with cement. In general, according to the obtained results, the following conclusions can be drawn:

1. The maximum dry density (MDD) and optimum moisture content (OMC) of lateritic soil increase with cement content.
2. The unconfined compressive strength of lateritic soil increases with cement percentage and curing time.
3. Considering Malaysia Public Works Department (PWD) standards, 6% cement cured in 7 days was found sufficient to obtain a UCS of more than 800 kPa for low-volume road construction.
4. The strength development index (SDI) equals 2.99 based on the unconfined compressive strength (UCS = 200.74 kPa) of untreated lateritic soil and the MPWD's threshold value (UCS = 800 kPa).
5. The elastic modulus of lateritic soil increased with cement content, indicating that lateritic soil's ductility decreased with increasing cement content. Furthermore, an equation was proposed for E_{50} according to unconfined compressive strength results;
6. The durability results revealed that the lateritic soil treated with 3% cement entirely collapsed after one wetting–drying cycle. On the contrary, the specimens treated with 6% cement withstood against 15 WD cycles. However, the UCS of 6% cement-treated specimens decreased against WD cycles, but at the end of the 15th cycle, the UCS result was more than 800 kPa. On the other hand, the UCS results exhibited an increasing trend against WD for 9% and 12% cement-treated lateritic specimens, indicating long-term pozzolanic reactions.
7. The microstructure analysis depicted that the CSH, CAH, and CASH were produced because of the pozzolanic reaction between alumina–silica of the soil and calcium ions of the cement or lime in the presence of water. Subsequently, the pore and crack size decreased with an increase in cement content, indicating increasing mechanical properties.

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Conflicts of Interest: The authors declare that we do not have any commercial or associative interest representing a conflict of interest in connection with the work submitted.

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