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Enhancing Soil Stabilization: The Influence of Cement and Polymer Additives on the Strength and Performance of Soil-Cement Composites for Unpaved Roads

Thitibhorn Phantachang[1*], Chusak Kererat[2], Sahalaph Homwouttiwong[3]

[1] Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna, Chiang Mai 50300, Thailand
[2] Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Rattanakosin, Prachuap Khiri Khan 77110, Thailand
[3] Department of Civil Engineering, Faculty of Engineering Mahasarakham University, Maha Sarakham 44150, Thailand

Corresponding Author Email: Thitibhorn@rmutl.ac.th

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ABSTRACT

The stabilization of clayey sand for unpaved roads was investigated to enhance geotechnical properties using cement and polymer additives. Soil samples classified as well-graded sand with clay (SW-SC) were subjected to laboratory analysis to evaluate strength, durability, and load-bearing capacity. Cement incorporation at varying percentages significantly improved unconfined compressive strength (UCS), with the highest value of 2340 kPa observed at a 10% cement content. However, excessive cement additions were found to increase soil brittleness, highlighting the necessity for optimized mix designs. The inclusion of polymers at 6% and 8% concentrations further enhanced the UCS while mitigating the brittleness associated with higher cement proportions. Curing time contributed substantially to strength development, with polymer-modified soil-cement mixtures demonstrating superior performance compared to those without polymers. Optimum moisture content (OMC) conditions were critical, as maintaining moisture slightly above the OMC (+2%) yielded maximum strength gains, whereas deviations resulted in reduced performance. California Bearing Ratio (CBR) tests revealed that cement-stabilized soil with 5% to 9% cement achieved soaked CBR values that were 12.1 to 18.5 times greater than untreated soil, meeting or exceeding standards for base materials in unpaved road construction. The combined use of cement and polymers improved the durability, load-bearing capacity, and mechanical performance of soil-cement composites, offering a sustainable and effective approach for enhancing unpaved road subgrades. These findings emphasize the significance of carefully balancing cement and polymer proportions, moisture conditions, and curing periods to achieve optimal outcomes. This study delivers significant insights into the development of high-performance soil stabilization techniques tailored for unpaved road applications.

1. INTRODUCTION

Unpaved roads are essential for supporting agricultural activities by providing critical access between rural and urban areas. For sustainable development, particularly in remote regions, road construction methods must be cost-effective, low-tech, and capable of ensuring long-term durability and performance. Additionally, improving access for vehicles and agricultural machinery in these areas can significantly enhance productivity and income. Unpaved gravel or earth roads are often sufficient for this purpose, especially in rural and agricultural provinces, as they meet basic technical requirements while keeping construction and maintenance costs low. However, the increased load from larger and heavier vehicles can lead to surface damage, including excessive settlement and rutting. Soil-cement stabilization offers a cost-effective and technically viable solution for enhancing the strength and longevity of these unpaved roads.

The soil-cement stabilization technique has been successfully utilized as a pavement base material, a foundational layer for shallow foundations, and for slope protection in earth dams. Additionally, it has been employed to improve the stability of railways and as a base course layer for both paved and unpaved roads [1-5]. Furthermore, crushed rocks become unsuitable for road construction when the quarry has a significant distance from the construction site as it increases transportation costs and environmental impact. Soil-cement is an alternative for improving shear strength and bearing capacity while reducing settlement of native soils. Produced with the addition of Portland cement, it is an attractive solution due to its cost-effectiveness, rapid construction, satisfaction of required basic technical qualities, and good performance.

Research indicates that soil properties and pavement performance can be effectively improved through soil-cement stabilization. Felt [1] conducted experimental studies on soil-cement mixtures to assess the impact of cement content on strength and durability. The results indicated that the addition of cement to granular materials reduces soil plasticity and improves the strength-bearing capacity. Ashraf et al. [6] further revealed that cement content significantly impacts strength and durability, with optimal content typically ranging from 6-10% by weight. Compressive strength increases with cement content up to 8%, with slower gains beyond that point. Curing time also plays a role in strength development, with longer periods resulting in higher strength. Durability tests, including freeze-thaw and wet-dry cycles, demonstrated that cement-stabilized soils exhibit improved resistance to environmental factors [6, 7]. Compared to other stabilization agents, such as lime and fly ash, cement consistently shows superior performance across various soil types [7, 8]. However, for many soils, multiple stabilization options may be effective, and pre-construction testing is recommended to determine the most suitable agent [8].

Polymer-based chemical soil stabilization is an effective approach for enhancing soil properties and performance, producing encouraging results in improving soil strength and durability. Rezaeimalek et al. [9] investigated poorly graded natural sand stabilized with a liquid polymer, which significantly improved fatigue test performance, resulting in specimens that exhibited perfectly elastic behavior with no signs of failure. Similarly, Iyengar et al. [10] utilized styrene-acrylic polymers, demonstrating acceptable short-term performance and durability in stabilized sand specimens, with minimal strength loss after aging and excellent fatigue resistance. Phummiphan et al. [11] reported that high-calcium fly ash-based geopolymer can effectively stabilize marginal lateritic soil. The study highlights the success of using geopolymer based on fly ash (FA) as an environmentally friendly pavement material. Additionally, polymer-stabilized soils exhibit superior compressive strength compared to unstabilized and cement-stabilized soils, particularly in Qatari subgrade soils. Polymer stabilization in pavement subgrades has been shown to significantly reduce rutting, making it a valuable option for perpetual pavements in high-traffic areas [10]. These findings suggest that polymer-cement stabilization is a promising technique for enhancing soil performance across various applications and environmental conditions.

Laboratory mechanical tests have been conducted to assess the performance of soil-cement and polymer stabilization, focusing on their mechanical behavior and bearing capacity. Studies commonly utilize UCS and CBR tests to evaluate the performance of soil-cement stabilization in laboratory settings. Clare and Shearwood [12] investigated the effects of organic matter components on soil-cement stabilization using UCS tests. Haralambos [13] studied the impact of cement stabilization on five different soil types with varying cement proportions. The findings indicated that soil type plays a crucial role in the rate of increase in UCS as cement content rises. Additionally, curing time and the OMC of the soil stabilization process were found to influence strength. Pongsivasathit et al. [5] carried out a laboratory investigation to assess the impact of cement content on the strength of various soil stabilizing agents, focusing on sand and clay specimens. The study employed tests such as unconfined compressive strength (UCS), California bearing ratio (CBR), third-point load, and plate load tests. The results indicated that increasing the cement content led to improved values of UCS, CBR, resilient modulus (M_r), and subgrade reaction modulus (K) in the stabilized soil samples. Etim et al. [14] employed the periwinkle shell ash (PSA) mixed with lateritic soil for use as road pavement materials. Laboratory testing was performed on UCS, CBR and compaction parameters. It can be concluded that a PSA-lateritic mixture can be used as a sub-base for light traffic roads. Kererat et al. [15] examined the potential of using a blend of bottom ash, Portland cement, and para rubber latex as an alternative material for road construction. Two sizes of bottom ash were tested, and mixtures with varying proportions of cement and latex were examined for their UCS tests, skid resistance, and durability in wet and dry conditions.

Existing research on cement soil stabilization has primarily focused on major highways or paved roads, with limited testing on soil stabilization for unpaved roads. This is particularly important for developing countries, where it could offer significant benefits for agriculture and accessibility. This study aims to present the performance of selected soil-cement and soil-cement polymer stabilizers used on unpaved roads, specifically their impact on material strength. The effectiveness of these stabilizers was evaluated by examining the influence of cement and polymer content, curing time, and OMC on soil strength. Performance was assessed based on compaction characteristics, UCS, and CBR test results.

2. TESTING MATERIAL

This study provides a detailed description of the materials used for soil-cement and soil-cement polymer stabilization.

2.1 Soil

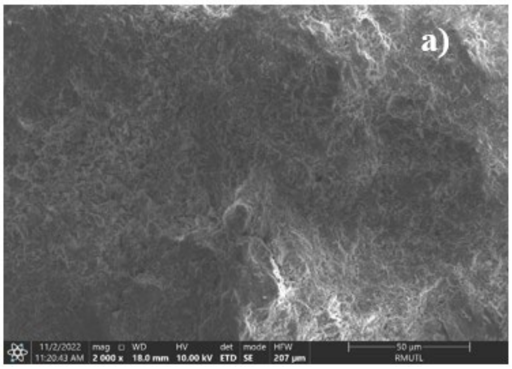
The soil used in this study was categorized as well-graded sand with clay. Disturbed soil samples were collected from a borrow pit located near rice farms in the rural agricultural region of Chiang Rai Province, Thailand. Excavation was carried out at a depth ranging from 0.50 to 1.00 m below the ground surface to minimize the presence of organic matter and ensure sample consistency for testing. Figures 1(a) and (b) present Scanning Electron Microscope (SEM) images of soil at 2000x and 1000x magnification, respectively. Figure 1(c) illustrates the soil passing through a 4.7 mm (No. 4) sieve, both before and after compaction. The post-compaction image reveals increased rock fracturing and a reduction in particle thickness, attributed to the compaction effort. The mineralogical composition of the soil was assessed using X-Ray Diffraction (XRD) analysis, as illustrated in Figure 2. The XRD pattern indicates a prominent peak at $2\theta = 26°$, corresponding to the presence of iron (III) oxide-hydroxide, FeO(OH). Soils containing FeO(OH) are typically rich in iron and are referred to as lateritic or ferrallitic soils, commonly found in tropical and subtropical regions where intense weathering leads to the concentration of iron and aluminum oxides.

2.2 Cement

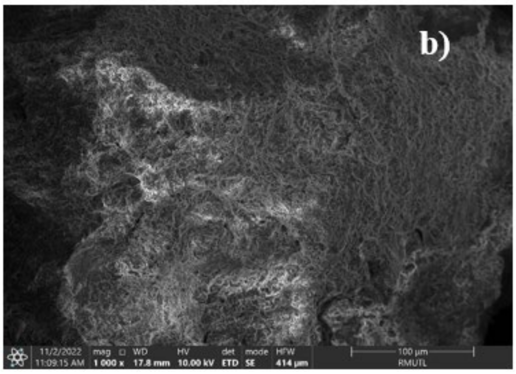
For the soil-cement stabilization and soil-cement polymer experiments, Portland cement type I, a commercially available product, was utilized. The cement exhibited a specific gravity of 3.15 g/cm^3.

2.3 Water

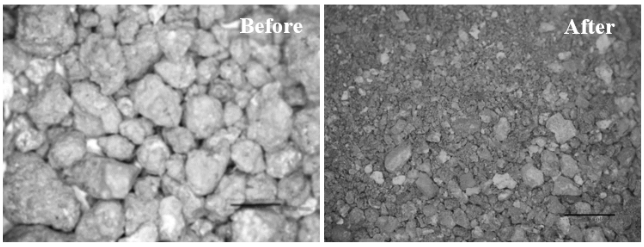
The water used in the experiments served for both the compaction process and cement hydration. The water quality met the standards for potable water, being free from alkalis, acids, or organic impurities.



a) SEM image of soil in 2000x magnification



b) SEM image of soil in 1000x magnification



c) Soil passing a 4.75-mm sieve (No. 4) before and after compaction

Figure 1. Images of soil samples excavated from Chiang Rai Province, Thailand

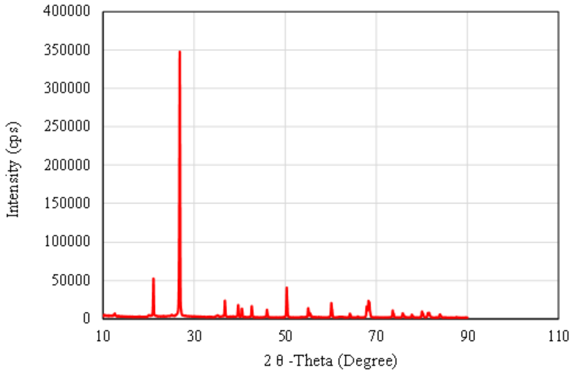


Figure 2. Mineralogical composition of the soil assessed using XRD analysis

2.4 Polymer

The styrene-butadiene copolymer latex (SBR) used in this study was a commercially available product sourced from Thailand. The purpose of the polymer stabilizer was to act as a chemical additive, improving the modulus of elasticity, flexibility, strength, and durability of the soil-cement mixture. Table 1 summarizes the typical characteristics of the commercial SBR.

Table 1. Typical properties of the commercial SBR

Characteristics	Values or Descriptions
Appearance	White liquid
Specific gravity	1.00-1.02
pH at 25^{o}C	11.0-12.5
Viscosity	1,200-2,000 cps
Solid content (%)	5%

3. EXPERIMENTAL PROGRAM

The experimental program was conducted in two phases. The first phase involved analyzing the engineering properties of the untreated soil. In the second phase, the mechanical properties of soil, soil-cement, and soil-cement polymer, with varying cement content, were evaluated using the compaction, UCS, and CBR tests. All experimental procedures were conducted in compliance with the standards of the American Society for Testing and Materials (ASTM) and the specifications of the Department of Highways (DOH) in Thailand.

3.1 Compaction test

The soil compaction tests were performed following the Standard Proctor Test (SDD) according to ASTM D698 and the Modified Proctor Test (MDD) in accordance with ASTM D1557-07. Soil samples were prepared in a mold with dimensions of 101.6 mm in diameter and 116.0 mm in height. For the SDD, the sample was compacted in three layers, each receiving 25 blows per layer. For the MDD, the sample was compacted in five layers, also with 25 blows per layer. These tests were conducted to determine the maximum dry density (γ_{drymax}) and OMC. Eq. (1) represents the dry unit weight at the zero air void curve [16].

$$\gamma_{zav}=\frac{G_s\gamma_w}{1+\frac{wG_s}{S_r}} \tag{1}$$

where, γ_{zav} is the zero air void unit weight, γ_w is the unit weight of water, e is the void ratio, and G_s is the specific gravity of soil solids.

3.2 Unconfined compaction test

The UCS test was performed following ASTM D1633 for soil-cement and soil-cement polymer samples, which were molded to a diameter of 101.6 mm and a height of 116.0 mm. Soil-cement samples were mixed with cement at varying percentages (0%, 2%, 4%, 6%, 8%, and 10%) of the dry weight of the soil. The soil-cement and soil-cement polymer samples were prepared by thoroughly mixing the original soil, cement, and water to obtain a homogeneous mixture. Each batch was mixed with water at the optimal content to achieve maximum dry density. Three specimens were made for each cement content, and the entire preparation process was completed within 1.5 hours.

UCS tests were performed on the samples after a 7-day curing period. The specimens were tested under strain-controlled conditions, with an axial load applied at a strain rate of 1% per minute using a universal testing machine (UTM). Figure 3 shows the sample preparation. The specimens were initially wrapped in plastic sheets, as shown in Figure 3(a), to ensure uniform curing. After curing for 7, 14, and 90 days at room temperature to assess the long-term performance of the cement-stabilized samples as recommended by previous studies [17, 18] the specimens were submerged in water for 2 hours before testing, as depicted in Figure 3(b). The UCS testing setup and failure of samples are illustrated in Figure 4. The load-displacement curve was recorded, and the ultimate UCS (q_u) was calculated using the appropriate formula as Eq. (2) [16].

$$q_u = \frac{P_u}{A} \tag{2}$$

where, q_u is the ultimate UCS (kPa), P_u is the ultimate load (kN), and A is the area (m^2).

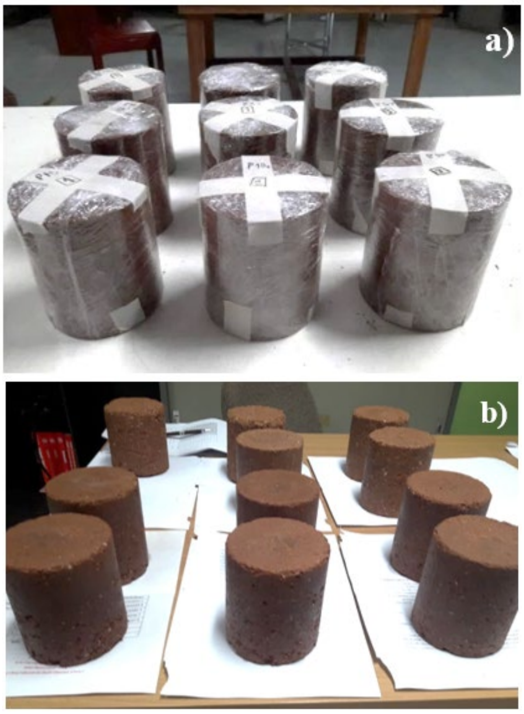


Figure 3. Preparation of soil-cement and soil-cement polymer samples

3.3 CBR test

The CBR test is a commonly utilized strength assessment for aggregates and construction materials, aimed at evaluating the strength of soil subgrades and base course materials. This test provides an indirect measure of soil shear strength, influenced by compaction effort and soil moisture content. Both soaked and unsoaked CBR tests were conducted in accordance with ASTM D1883-07 standards. The soil specimens were compacted into molds with dimensions of 152 mm in diameter and 178 mm in height, utilizing a rammer weighing 4.536 kg dropped from a height of 457.2 mm, following the Maximum Dry Density (MDD) method. Figure 5 provides a depiction of the CBR test setup.

Figure 4. Unconfined compression test setup and failure of samples

Figure 5. CBR testing setup

4. RESULTS AND DISCUSSION

4.1 Basic properties of soils

The geotechnical index properties of the Chiang Rai soils are summarized in Table 2. According to the Atterberg limit and grain size distribution test results presented in Figure 6, the soil used in this study was classified as well-graded sand with clay (SW-SC) based on the Unified Soil Classification System (USCS) and as A-2-6 according to the American Association of State Highway and Transportation Officials (AASHTO) classification.

Figure 7 displays the compaction curves for various compaction energies. The results from the SDD test show a maximum dry density ($\gamma_{\mathrm{drymax(SDD)}}$) of 17.8 kN/m^3 with an optimum moisture content (OMC) of 15%. In comparison, the MDD test produced a maximum dry density ($\gamma_{drymax(MDD)}$) of 19.7 kN/m^3 with an OMC of 11.5%. Furthermore, the MDD test for soil containing 9% cement showed a $\gamma_{drymax(MDD)}$ of 19.3 kN/m^3 with an OMC of 11.3%. The compaction curves show that increased compaction energy results in higher maximum dry density and lower OMC. The MDD test results suggest that the compaction effort aligns closely with the zero air voids curve, indicating that the compaction achieved during the soil compaction process is highly efficient, minimizing the amount of air present in the soil voids.

Table 2. Index characteristics of the Chiang Rai soil sample employed in this research

Description	Testing results
Basic properties	
● Specific gravity (G_S)	2.73
● Natural water content (W_n) (%)	9.70
Grain size distribution	
● Coefficient of uniformity (C_u)	26.15
● Coefficient of curvature (C_c)	1.99
Atterberg limit test	
● Liquid limit test (W_{LL}) (%)	36.70
● Plastic limit test (W_{PL}) (%)	22.39
● Plastic index (PI)	14.31
Soil classification	
● USCS	SW-SC
● AASHTO	A-2-6
Standard proctor test and MDD	
● OMC (%)	15.0, 11.5
Maximum dry density ($\gamma_{dry\ max}$) (kN/m^3)	17.8, 19.7
CBR test	
CBR (%)	13.98
UCS test	
UCS (ksc)	4.06

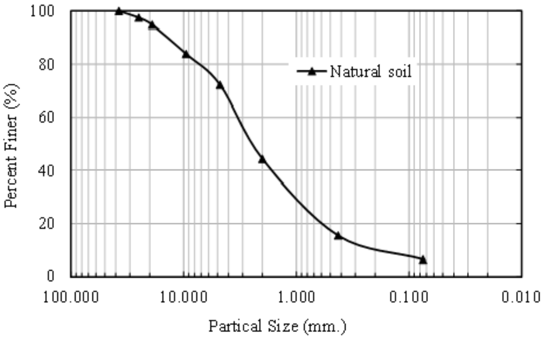


Figure 6. Grain size distribution curve for the soil sample

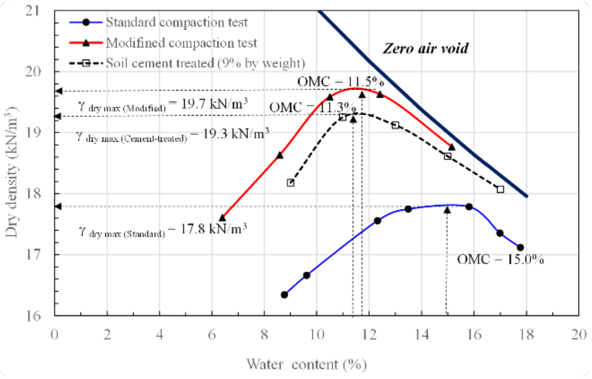


Figure 7. Compaction curves for untreated soil and soil-cement stabilized samples

4.2 Effect of cement and polymer on the strength behavior of soil

4.2.1 UCS of soil-cement stabilized

The stress-strain curves are a common technique used to evaluate the failure point and behavior of materials under load. Figure 8 shows the stress-stress curves results for untreated soil (0% cement) and soil-cement samples with cement contents of 2%, 4%, 6%, 8%, and 10% after a 7-day curing period. The compressive strength at failure for the different cement contents was 398 kPa, 666 kPa, 1314 kPa, 1654 kPa, 1815 kPa, and 2340 kPa, respectively. The increase in compressive strength with different cement contents can be represented as factors of 1.6, 3.3, 4.2, 4.6, and 5.9 times, respectively, compared to the untreated soil. Generally, the stress-strain curves show improved performance with increased cement content up to 4%. The UCS values increase significantly with cement addition. However, the curves also indicate a sharp decline in strength after reaching peak compressive strength, which suggests a brittle failure behavior in the treated soil. It is important to highlight that the initial tangent stiffness, evident in the early section of the stress-strain curves for treated soils, increases considerably as cement content rises.

The relationship between cement content and UCS in Figure 9 demonstrates a linear trend where UCS increases with higher cement content. This relationship can be accurately described by a linear regression equation by Eq. (3).

$$q_u = 192.78(c\%) + 400.67 \tag{3}$$

where, q_u is the ultimate UCS (kPa), and $c\%$ is the percentage of cement content by weight of dry soils.

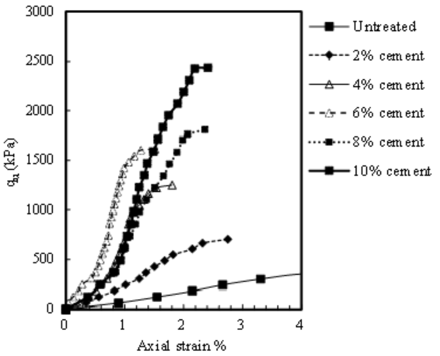


Figure 8. Stress-strain curves for untreated soil and soil-cement samples after 7-day curing

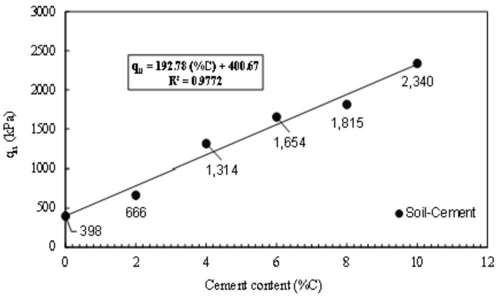


Figure 9. Variation of compressive strength of soil-cement stabilization after 7-day curing

Based on Eq. (3), the required percentage of cement content for soil-cement and soil-cement polymer mixtures can be determined. The DOH specifies that the UCS after seven days of curing for cement-stabilized lateritic soil and cement-stabilized crushed rock should not be less than 1.7 MPa (17.3 ksc) as recommended by Pongsivasathit et al. [5]. Using the regression analysis, the calculated cement content required to achieve this UCS is 6.83%, with a coefficient of determination (R^2) of 0.977 (92%). For practical field applications, an additional 20% cement is recommended to ensure extra strength. Consequently, the cement content for soil-cement mixtures can be set at 9% of the weight of dry soil.

4.2.2 UCS of soil cement stabilizer with polymer

To evaluate the effect of polymer content on the UCS of soil-cement stabilization, soil-cement mixtures with 9% cement content were prepared with polymer additions of 2%, 4%, 6%, and 8% by weight of the dry cement. UCS tests were performed following a seven-day curing period. Figure 10 displays the stress-strain curves for the soil-cement polymer samples after a 7-day curing period.

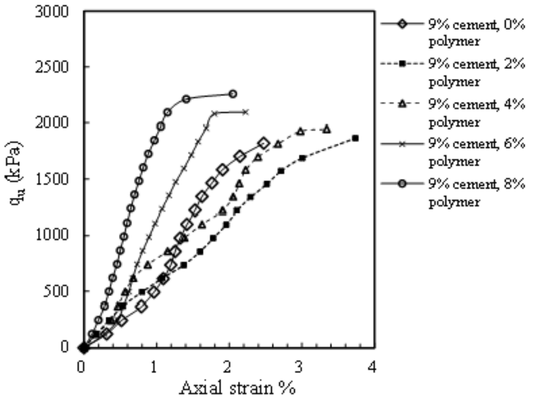


Figure 10. Stress-strain curves for soil-cement polymer samples after 7-day curing

It is observed that the addition of polymer to soil-cement stabilization has minimal impact when the polymer content is at 2% and 4%. However, increasing the polymer content to 6% results in a notable improvement in UCS, as the stress-strain curve reflects a significant increase in strength. At 8% polymer content, the soil-cement mixture exhibits brittle behavior, with failure occurring at a relatively short axial strain. Figure 11 illustrates a comparative analysis of the stress-strain relationships among untreated soil, soil-cement stabilized soil, and soil-cement stabilized soil with polymer. The inclusion of polymer as a chemical admixture clearly enhances both the UCS and material stiffness at equivalent cement content levels.

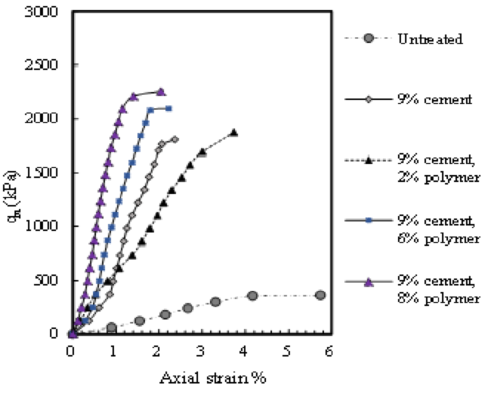


Figure 11. Variation of stress-strain curves for untreated soil, soil-cement with 9% cement, and soil-cement polymer with 2%, 6%, and 8% polymer content by weight of dry soil after 7-day curing

4.2.3 Effect of curing time on soil-cement stabilized and polymer-modified soil-cement stabilized

Figure 12 illustrates the changes in compressive strength of soil-cement and soil-cement polymer mixtures with varying cement content percentages following a 7-day curing period. The stress-strain curves for soil-cement polymer contents of 0%, 2%, 4%, 6%, and 8% of the cement weight are presented in Figure 10, indicating a significant improvement in strength compared to soil-cement samples without polymer. The compressive strengths achieved are 1,741, 1,887, 1,989, 2,071, and 2,282 kPa, reflecting corresponding increases of 37%, 62%, 83%, and 136%, respectively. The UCS of both soil-cement and soil-cement polymer mixtures increases with curing time due to the progressive effects of cement hydration, ion exchange, and soil particle agglomeration. This trend mirrors the UCS behaviour observed in traditional soil-cement stabilization but with significantly higher strength gains in the polymer-modified specimens. These findings align with previous studies, which demonstrated that waterborne polymer additives substantially improved the UCS of sandy soils, particularly those susceptible to liquefaction, as found in the previous studies of Ateş and Bao et al. [8, 19].

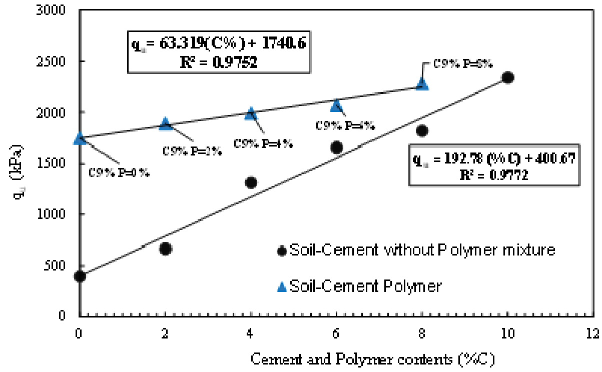


Figure 12. Variation of compressive strength of soil-cement and soil-cement polymer with different percentages of cement content after 7-day curing

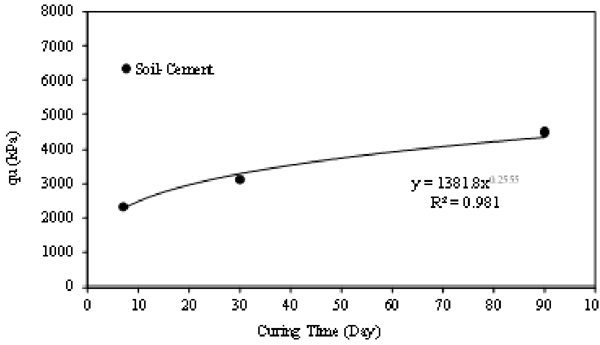


Figure 13. Average compressive strength of soil-cement (9% cement content) showing the effect of curing time at 7, 28, and 90 days

Figure 13 illustrates the long-term effects of curing time on soil-cement stabilization, showing the average UCS of soil-cement with 9% cement content and emphasizing the strength development at 7, 28, and 90 days of curing. The observations indicate a gradual increase in UCS after 28 days, attributed to ongoing hydration reactions. A similar trend is observed in the UCS results for soil-cement polymer mixtures in Figure 14.

The correlation between average UCS and curing time for soil-cement polymer mixtures with 2%, 4%, and 10% polymer content is illustrated for curing periods of 7, 28, and 90 days. The data show a similar trend in soil-cement stabilization, where the UCS increases with extended curing time. This is due to the hydration reaction of the cement, which strengthens the soil by forming chemical bonds that enhance its structural integrity and load-bearing capacity, as supported by recent research studies [20-22].

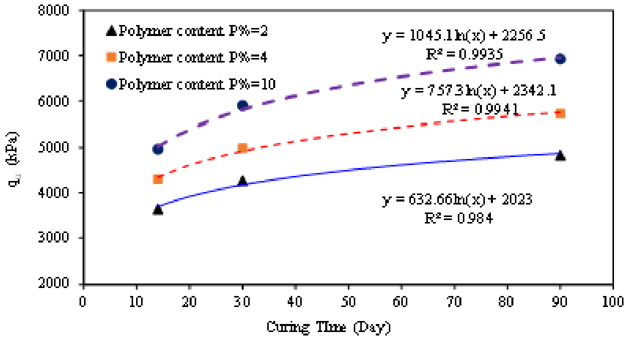


Figure 14. Average compressive strength of soil-cement polymer contents with the effect of curing time at 7, 28, and 90 days

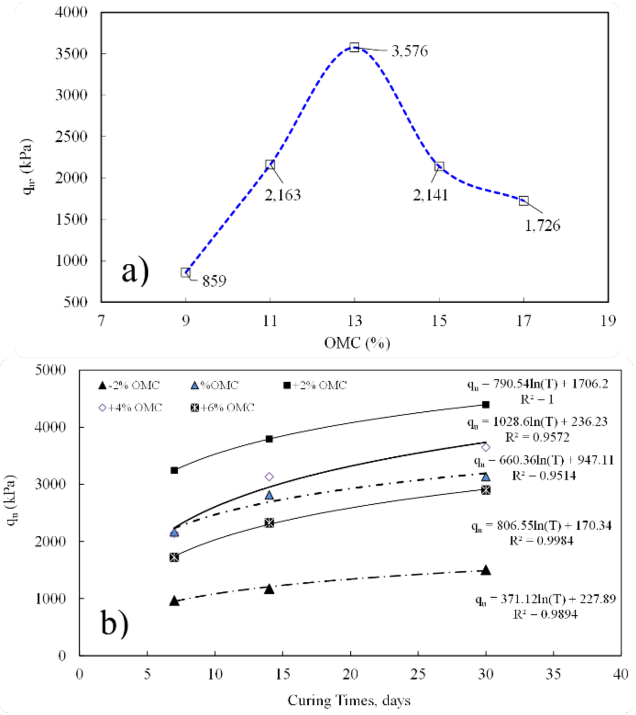


Figure 15. Mean UCS with varying OMC considering the effect of curing time at 7, 14, and 28 days

4.2.4 Effect of OMC and curing time on soil-cement stabilized

The moisture content in soil-cement stabilization plays a crucial role in determining its properties. Figure 15(a) illustrates the UCS of soil-cement at various moisture levels after a 7-day curing period. With the soil-cement stabilization at the OMC measured at 11.3%, the UCS is 2163 kPa. When the water content decreases to -2% of OMC, the UCS decreases to 857 kPa (-60%), indicating that insufficient water for the hydration process results in ineffective mixing of cement with soil. Conversely, with an additional water content of +2% of OMC, the UCS increases to 3,756 kPa (65%). Moreover, OMC exceeding 4 to 6% demonstrates decreased UCS values in the soil-cement stabilized.

This trend is observed both in the short term and over extended periods, as demonstrated in Figure 15(b). The variation in UCS values at different moisture levels highlights the significance of having adequate water for the cement hydration process, which is essential for soil-cement to develop strength in both short and long curing times.

4.3 CBR test of soil cement stabilization

The CBR test results, as shown in Figure 16, show the comparison of the performance of untreated soil under both unsoaked and soaked conditions. In the unsoaked condition, the CBR value for untreated soil was 45%, which significantly decreased to 11% when soaked. This substantial reduction highlights the vulnerability of untreated soil to moisture, resulting in diminished strength and bearing capacity.

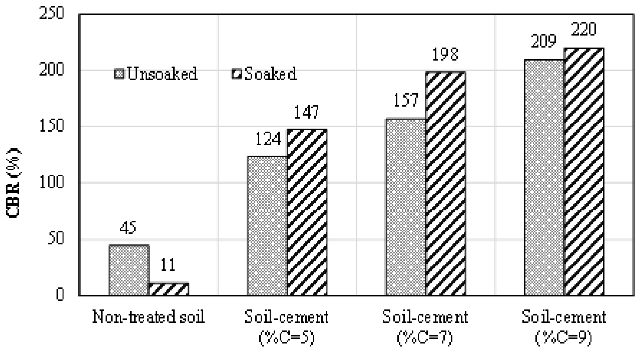


Figure 16. CBR of untreated soil and soil-cement samples under different testing conditions

In contrast, the CBR tests for soil-cement stabilization were conducted with cement contents of 5%, 7%, and 9%. The CBR values for the unsoaked condition were 124%, 157%, and 209%, respectively, indicating increases of 1.8, 2.5, and 3.7 times compared to untreated soil. For the soaked condition tests, the CBR values were 149%, 198%, and 220%, corresponding to 12.1, 16.6, and 18.5 times the values of untreated soil. This significant improvement in strength can be attributed to the hydraulic properties of Portland cement, which sets and hardens through a chemical reaction with water, allowing soil-cement samples to achieve notable strength gains even under soaked conditions.

According to the DOH specifications, the required CBR values are 20% for sub-base materials and 80% for base materials. While untreated soil meets the criteria for the sub-base material, soil stabilized with 5% cement content achieves a CBR value sufficient for use as a base material in road construction. This underscores the effectiveness of cement stabilization in enhancing soil strength and its suitability for various construction applications. Additionally, addressing the drastic drop in CBR value under soaked conditions mitigates concerns about potential issues such as reduced load-bearing capacity, instability, and rutting in unpaved roads, especially during rainy periods. This emphasizes the necessity of soil stabilization for road construction in environments prone to heavy rainfall to ensure pavement performance and longevity.

5. DISCUSSION

Based on current research observations, the chemical reaction in soil-cement stabilization—a mixture of cement, soil, and water—begins with cement hydration, producing calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H), and calcium hydroxide ($Ca(OH)_2$). This is followed by the pozzolanic reaction between lime and soil particles, forming additional C-S-H and C-A-H bonds that strengthen and compact the soil. These reactions increase UCS with higher cement content, with hydration completing in 28 days, while the pozzolanic reaction takes longer and UCS continues to improve with extended curing time, as demonstrated in similar studies [11, 23]. Furthermore, the pozzolanic reaction can occur in sandy soil during cement stabilization, but its effectiveness depends on the mineral composition of the sand. Sandy soils generally have fewer clay particles, which means they may have a lower natural pozzolanic activity compared to clay-rich soils.

In the study of soil-cement stabilizers with polymer, significant improvements in UCS were observed with 9% cement content as the polymer content increased, particularly within 6-8% of the cement weight. This finding differs slightly from the recommendations of Ateş [8], where the addition of cement (10-40%) and polymer (1-4%) was found to improve UCS values in sand samples after 7 and 14 days of curing. It was observed that longer curing time led to improved UCS values due to the chemical reactions from the pozzolanic process and the presence of additional chemical binders in the polymer. However, the cost of road construction using this method may not be economically viable for unpaved roads.

It can be observed that OMC significantly impacts UCS values and strength development. Maintaining moisture levels at +2% of the OMC benefits UCS strength, particularly with longer curing time. The OMC allows for maximum compaction of the soil-cement mixture and provides sufficient moisture to facilitate the hydration reactions of cement. This prevents excess water, which could lead to cement leaching or dilution of the mixture. Consequently, these conditions ensure that chemical reactions are efficient, resulting in higher UCS and improved durability of the stabilized soil.

In terms of CBR values, the CBR in soaked conditions showed gradual improvement. This significant strength gain can be attributed to the hydraulic properties of Portland cement, which sets and hardens through a chemical reaction with water, allowing soil-cement samples to achieve notable strength even in soaked conditions. The study indicates that soil-cement stabilization increased CBR values by 5% to 9%, significantly improving the quality of the soil material, making it a cost-effective solution for soil stabilization consistent with the results observed in the study by Pongsivasathit et al. [5].

Future research on soil-cement and soil-cement with polymers should focus on long-term durability under environmental stresses, such as wet-dry cycles, chemical exposure, and the impacts of climate change on unpaved road surfaces, as highlighted in previous studies [24, 25]. Additionally, the effects of polymers on permeability and drainage, as well as their performance under dynamic loads like traffic and seismic activity, require further study. Large-scale field trials are also needed to validate lab findings in real-world conditions. These areas offer key opportunities to improve soil stabilization techniques.

6. CONCLUSIONS

The laboratory study was conducted to examine the engineering properties of soil enhanced with Portland cement and polymer for unpaved roads. Based on the test results and data analysis, the following conclusions and recommendations can be made:

a) Soil-cement stabilization enhances UCS values through cement hydration and pozzolanic reactions, improving soil stability as the cement content and curing time are increased.

b) The incorporation of 6-8% polymer significantly increases UCS while also enhancing the modulus of elasticity, flexibility, strength, and durability. Further studies are needed to explore these improvements in more detail.

c) Results indicate that maintaining moisture slightly above the OMC (+2%) is critical for achieving maximum compaction and strength in soil-cement mixtures.

d) Soil-cement stabilization with 5-9% cement content results in a 12.1 to 18.5-fold increase in the CBR values under soaked conditions, greatly improving the performance of unpaved roads.

Future studies should focus on long-term durability, polymer effects under wet and dry cycle tests, drainage behavior, dynamic loading conditions, and large-scale field trials specifically for unpaved roads.

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