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Formulation of Geopolymer Stabilized Soil with Different Sodium Silicate to Sodium Hydroxide Ratios Based on Physical and Mechanical Properties

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ABSTRACT

This study investigates the formulation of geopolymer stabilized soil using varying sodium silicate (Na_2SiO_3) to sodium hydroxide (NaOH) ratios, focusing on the physical and mechanical properties of lateritic soil. In this work, fly ash-based geopolymer binders were prepared at contents of 3%, 5% and 7% of the total mix mass and activated with an alkaline activator comprising sodium silicate solution and a 10 M NaOH solution at Na_2SiO_3-to-NaOH mass ratios of 2.0, 2.5 and 3.0. The physical properties of the soil were characterized through Atterberg limit, particle density, particle size distribution and compaction tests in accordance with BS 1377:1990, while the mechanical performance was evaluated using the unconfined compressive strength (UCS) test after 0, 7 and 28 days of curing. The soil was classified as sandy silt of intermediate plasticity, with a maximum dry density of 1.735 Mg/m^3 at an optimum moisture content of 18.39%. The results showed that a 5% geopolymer binder with an Na_2SiO_3/NaOH ratio of 2.5 achieved the peak UCS of 0.2173 MPa after 28 days of curing, showing comparable strength to the 7% binder content (0.2143 MPa) while providing a more efficient mix design. The findings highlight the importance of optimizing both the binder content and the alkaline activator ratio in geopolymer stabilization, offering a sustainable alternative to conventional methods for enhancing soil strength in geotechnical engineering applications.

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1. INTRODUCTION

Soil stabilization has long been a necessary practice to enhance the engineering properties of weak soils, improving their strength, durability and performance under load [1]. Traditionally, binders such as cement and lime have been used extensively for this purpose; however, their high environmental costs, particularly the substantial carbon dioxide emissions and energy-intensive production processes, have driven the search for more sustainable alternatives [2]. Geopolymers derived from industrial by-products such as fly ash are increasingly recognized as environmentally friendly substitutes that improve soil properties while reducing environmental impact [3]. The valorisation of industrial and agricultural by-products in construction materials has likewise been demonstrated in cement-based systems, for example through the partial replacement of cement with rice straw ash in self-compacting concrete [4]. The capacity of geopolymers to strengthen soils and withstand environmental deterioration, especially under demanding conditions, has attracted considerable research interest.

Fly ash-based geopolymers are formed through the chemical reaction between an aluminosilicate source and an alkaline activator, typically a combination of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) [5]. During geopolymerization, silica and alumina are dissolved from the precursor material to form a dense network of sodium aluminosilicate hydrate (N-A-S-H) gels that binds soil particles and improves compressive strength and cohesion [1]. This dense aluminosilicate gel also underpins the high compressive and bond strength reported for fly ash-based geopolymer mortars and repair materials [6]. The Na_2SiO_3 to NaOH ratio plays a crucial role in this process, affecting the workability, compressive strength and overall stability of the stabilized soil. Previous studies have shown that ratios of approximately 2.0 to 2.5 typically produce the highest strength by facilitating effective polymerization and reducing porosity [7,8], whereas ratios that are too high or too low can hinder geopolymerization and lead to weaker materials [9]. Comparable behaviour has been reported for local Malaysian soils, where fly ash geopolymer stabilization of Kedah soil achieved its highest compressive strength at an Na_2SiO_3 to NaOH ratio of 2.5 [10]. Curing conditions, particularly temperature and duration, also significantly influence strength development, with longer curing allowing the reactions to progress further [7]. In addition, the alkaline activator dosage should be tailored to the mineralogy and particle size distribution of the soil to achieve optimal stabilization outcomes [11]. The use of fly ash as the primary precursor not only enhances mechanical properties but also promotes sustainability by recycling industrial waste and reducing reliance on conventional cement [5].

Although the influence of the alkaline activator on geopolymer concrete has been widely reported, systematic data on the combined effect of binder content and Na_2SiO_3/NaOH ratio on lateritic soils remain limited. Therefore, this study was designed with three primary objectives. First, it determines the physical properties of lateritic soil, including its plasticity, particle size distribution, particle density and compaction characteristics, which govern how the soil behaves under different conditions. Second, it identifies the Na_2SiO_3 to NaOH ratio that maximizes the compressive strength of geopolymer stabilized lateritic soil at binder contents of 3%, 5% and 7%. Third, it assesses the broader implications of these findings for soil stabilization performance in geotechnical engineering applications. By examining the interaction between geopolymer binder content, activator ratio and curing time, the study aims to develop a more efficient and sustainable method for stabilizing weak soils that is particularly relevant to construction and infrastructure development.

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2. MATERIALS AND METHODS

This study evaluated the physical and mechanical properties of lateritic soil stabilized with a fly ash-based geopolymer at different Na_2SiO_3 to NaOH ratios.

2.1 Materials

The lateritic soil used in this study was collected from a construction site in Kangar, Perlis, Malaysia, at the geographical coordinates of 6°24′56.5″ N and 100°11′23.8″ E. The collected soil was placed in bags and transported to the soil laboratory for storage and subsequent preparation. The fly ash was classified as Class F in accordance with ASTM C618, based on the combined SiO_2, Al_2O_3 and Fe_2O_3 content of 89.82% and a CaO content of 3.51%. It was obtained from a local supplier in Manjung, Perak, and originated as a by-product of coal combustion for electricity generation.

The alkaline activator comprised sodium hydroxide and sodium silicate solutions. For the 10 M formulation, the NaOH solution was prepared by dissolving NaOH pellets with a purity of 98% in water until the required concentration was achieved. The sodium silicate solution contained 9% Na_2O and 30% SiO_2, corresponding to a total solid content of approximately 39% and a molar SiO_2/Na_2O modulus of approximately 3.44. The quantities of Na_2SiO_3 and NaOH reported in Table 1 refers to the masses of the respective solutions rather than the masses of the dry chemical constituents.

Table 1. Formulation of geopolymer mixtures with varying Na_2SiO_3 to NaOH ratios (binder content expressed as a percentage of the total mix mass; fly ash to alkaline activator mass ratio ≈ 0.35; Na_2SiO_3 and NaOH masses refer to solutions)

Na_2SiO_3:NaOH ratio	**Geopolymer binder (%)**	**Fly ash (g)**	**Na_2SiO_3 (g)**	**NaOH (g)**	**Soil (g)**	**Water (g)**	**Total binder (g)**
– (control)	0	–	–	–	126.30	23.20	–
2.0	3.0	1.20	2.19	1.10	122.49	22.50	4.49
2.0	5.0	1.90	3.72	1.86	119.96	22.10	7.48
2.0	7.0	2.70	5.18	2.59	117.44	21.60	10.47
2.5	3.0	1.20	2.35	0.94	122.49	22.50	4.49
2.5	5.0	1.90	3.98	1.59	119.96	22.10	7.47
2.5	7.0	2.70	5.55	2.22	117.44	21.60	10.47
3.0	3.0	1.20	2.46	0.82	122.49	22.50	4.48
3.0	5.0	1.90	4.18	1.39	119.96	22.10	7.47
3.0	7.0	2.70	5.82	1.94	117.44	21.60	10.46

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2.2 Testing Programme

The physical and mechanical properties of the soil–fly ash mixtures were determined through laboratory testing in accordance with BS 1377:1990, Methods of Test for Soils for Civil Engineering Purposes. The classification tests, comprising the Atterberg limits (liquid limit, plastic limit and plasticity index), particle density and particle size distribution, were conducted in accordance with BS 1377-2 [12]; the compaction test used to establish the maximum dry density and optimum moisture content followed BS 1377-4 [13]; and the unconfined compressive strength (UCS) test used to quantify the strength improvement of the soil after geopolymer addition followed BS 1377-7 [14].

2.3 Mix Design and Sample Preparation

Sodium hydroxide pellets were dissolved in water to prepare a 10 M solution, which was left undisturbed for a minimum of 24 hours to ensure complete dissolution and homogeneity. Sodium silicate solution was then combined with the NaOH solution at Na_2SiO_3 to NaOH mass ratios of 2.0, 2.5 and 3.0. The fine matrix fraction of the soil, passing the 425 μm sieve in accordance with standard sample preparation for fine-grained soil testing, was mixed with fly ash of the same particle size, together with the alkaline activator and distilled water. This pre-treatment satisfies the maximum particle size requirement for the 38 mm diameter UCS specimens and ensures homogeneous remoulded samples; its implications for field applicability are discussed in Section 3.6.

The mixtures were proportioned such that the geopolymer binder, defined as the combined mass of fly ash and alkaline activator (Na_2SiO_3 + NaOH solutions), constituted 3%, 5% or 7% of the total mix mass, which was kept constant at approximately 149.5 g per batch. The fly ash to alkaline activator mass ratio was maintained at approximately 0.35 for all mixtures, and the added water was adjusted so that the total liquid content remained consistent across the series. The resulting mix proportions are given in Table 1.

Each mixture was compacted into cylindrical moulds measuring 76 mm in height and 38 mm in diameter in three equal layers, with 27 blows applied to each layer. Following compaction, the specimens were extruded and cured for 0, 7 and 28 days. Specimens designated for 0-day curing were tested immediately, whereas the remaining specimens were sealed in plastic wrapping and stored in an incubator at 27 ± 2 °C until the specified testing age. Three replicate specimens were tested for each mixture and curing period, and the mean values are reported.

The UCS test was conducted using the load frame method, which is suitable for saturated and cohesive soils. Each specimen was centrally aligned on the loading device, the deformation dial gauge and proving ring were positioned, and the dial gauge was set to zero. A continuous load was applied at a rate of 0.5 mm per minute, with readings taken every ten seconds until failure. The highest reading was recorded as the compressive strength of the sample.

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3. RESULTS AND DISCUSSION

This section presents the results of the study on geopolymer stabilized soil, focusing on the physical and mechanical properties of the lateritic soil at different Na_2SiO_3 to NaOH ratios and geopolymer binder contents. The aim was to identify the most effective formulation for achieving the highest compressive strength within the range of variables tested. The findings highlight the importance of curing time, binder content and activator ratio in determining the effectiveness of geopolymer stabilization, providing valuable insights for construction and geotechnical applications.

3.1 Physical Properties of Lateritic Soil

The physical properties of the lateritic soil were analysed to assess its behaviour under various stabilization conditions, and the results are summarized in Table 2. The average moisture content from the cone penetration test yielded a liquid limit of 48.16%, with Fig. 1 showing that moisture content increases with greater penetration depth. The plastic limit, determined in accordance with BS 1377-2 [12], was 36.11%, giving a plasticity index of 12.05%. Based on the Atterberg limit results, the fine fraction of the soil is classified as silt of intermediate plasticity (MI).

Table 2. Physical properties of lateritic soil

Property	**Unit**	**Value**
Particle density	Mg/m^3	2.46
Specific gravity	–	2.46
Liquid limit	%	48.16
Plastic limit	%	36.11
Plasticity index	%	12.05
Sand content	%	54.73
Silt content	%	45.26
Clay content	%	0.01
Coefficient of uniformity, Cu	–	3.31

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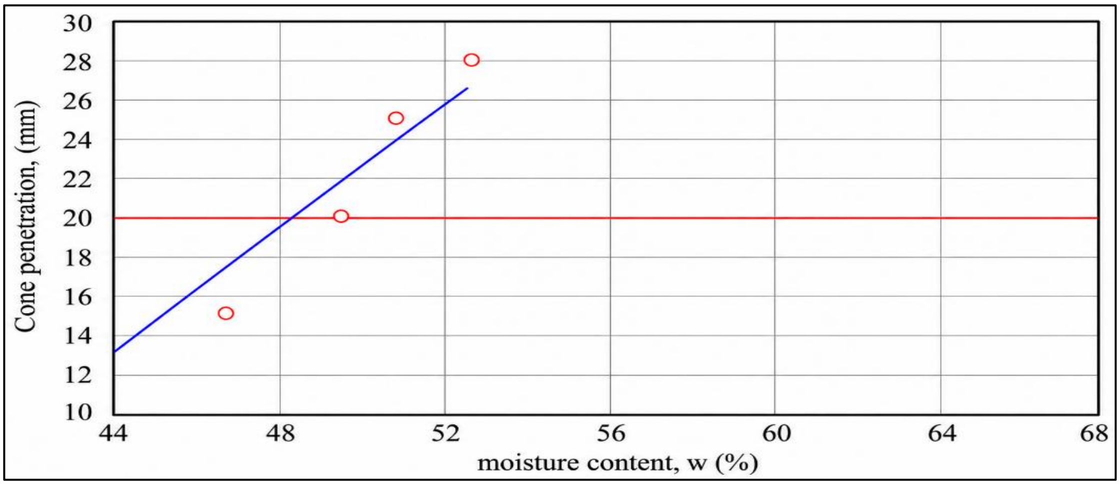

Fig. 1. Penetration curve of lateritic soil

The particle density was determined from three trials with consistent measurements of 2.41, 2.45 and 2.50 Mg/m³, giving an average particle density of 2.46 Mg/m³, which corresponds to a dimensionless specific gravity of 2.46. The particle size distribution in Fig. 2 shows that the soil consists predominantly of fine particles, with 54.73% sand, 45.26% silt and only 0.01% clay based on sieve and hydrometer analyses. Combining the grading with a liquid limit of 48.16%, a plasticity index of 12.05% and a coefficient of uniformity (Cu) of 3.31, the soil is classified overall as sandy SILT of intermediate plasticity (MIS) in accordance with the British Soil Classification System referenced in BS 1377-2 [12], making it suitable for applications requiring moderate plasticity and cohesion.

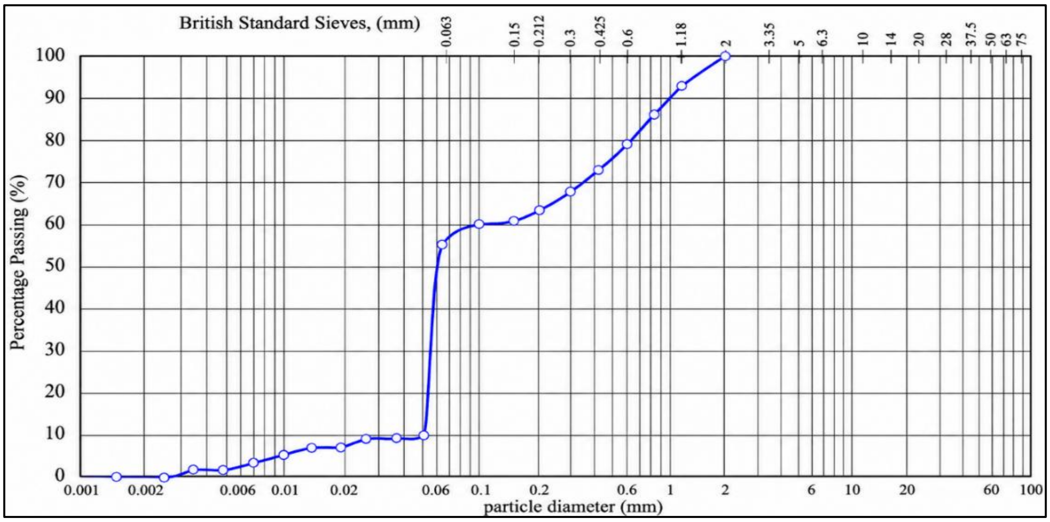

Fig. 2. Particle size distribution of lateritic soil

The composition of 54.73% sand, 45.26% silt and 0.01% clay are favourable for geopolymer stabilization, as sandy and silty soils typically offer better particle reactivity with alkaline activators than clay-rich soils. The particle density of 2.46 Mg/m³ and coefficient of uniformity of 3.31 indicate a moderately dense and reasonably graded soil that supports good compaction and strength development. These characteristics show that the soil is suitable for geopolymer treatment, particularly in applications such as subgrade improvement or low-traffic pavement layers, for which fly ash-based geopolymer mix designs have also been optimized as low-carbon alternatives to conventional rigid pavement materials [15]. For soils with low clay content, increasing the alkaline activator dosage is recommended to enhance geopolymerization, because the additional silicate compensates for the limited aluminosilicate sources in the soil and promotes the formation of a stronger geopolymer matrix. This approach is supported by Disu and Kolay [11], who highlighted the importance of adjusting the alkaline activator ratio to the soil's mineralogy and particle size distribution for optimal stabilization outcomes.

3.2 Compaction Characteristics

The compaction test results in Table 3 establish the relationship between dry density and moisture content for the lateritic soil, determined in accordance with BS 1377-4 [13]. Five samples were prepared with water additions ranging from 11% to 27%, producing measured moisture contents between 11.32% and 30.60%. The bulk density initially increased to a maximum of 2.07 Mg/m³ before declining as the water content rose beyond approximately 23%. The calculated dry density reached a peak of 1.735 Mg/m³, corresponding to the maximum dry density, at an optimum moisture content of 18.39%. Beyond this optimum, the dry density decreased because excess water occupied the voids between soil particles and reduced the compaction efficiency. These values were subsequently used to prepare the UCS specimens at their optimum compaction state.

Table 3. Compaction characteristics of lateritic soil

Parameter	**Unit**	**Value**
Maximum dry density	Mg/m³	1.735
Optimum moisture content	%	18.39

3.3 Unconfined Compressive Strength of Untreated Soil

The control samples, containing no geopolymer binder, form the baseline against which the strength of the treated samples at different Na_2SiO_3 to NaOH ratios is compared. As shown in Fig. 3, the compressive strength of the untreated soil increased from 0.1086 MPa at day 0 to 0.1316 MPa at day 7 and 0.1599 MPa at day 28. Because no cementitious binder was present in the control mixtures, this gain cannot be attributed to hydration reactions. Instead, the modest strength gain of the raw soil stored in the incubator is ascribed to minor moisture redistribution and matric suction changes during storage, together with thixotropic regain of interparticle bonding in the remoulded fine-grained soil over the curing period. Comparable strength gains in untreated remoulded soils during curing have been reported by Kumar et al. [16], underscoring the importance of testing control specimens under the same storage conditions as the treated specimens, as was done in this study.

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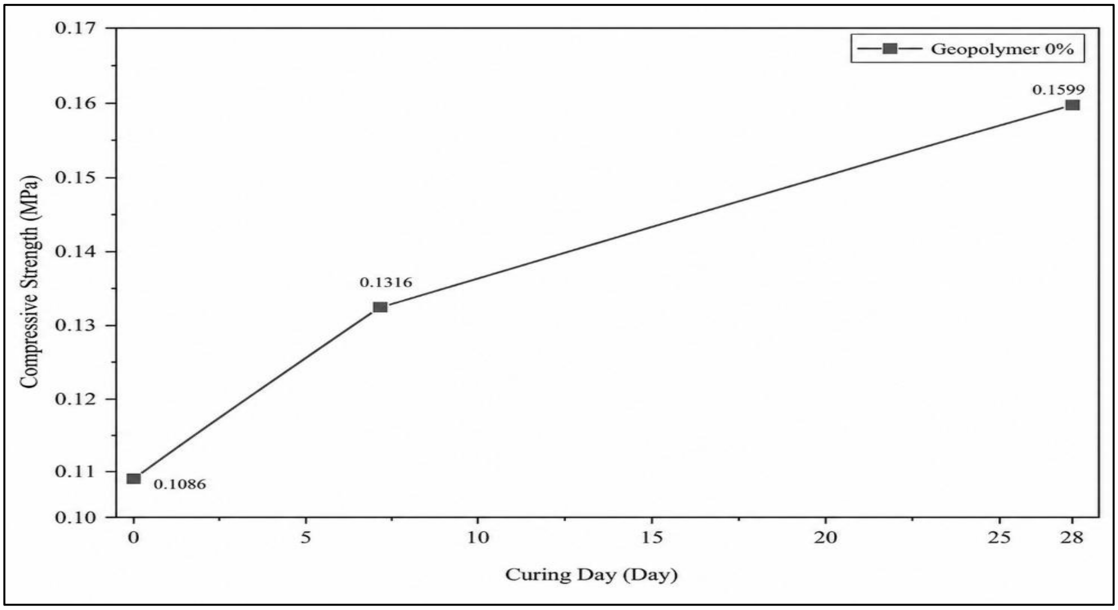

Fig. 3. Unconfined compressive strength (UCS) of the control sample at different curing times

3.4 Effect of Curing Time on Compressive Strength

The mechanical strength development of geopolymer-stabilized soil is strongly influenced by the curing duration. The compressive strength of specimens containing 0%, 3%, 5% and 7% geopolymer binder was evaluated after 0, 7 and 28 days of curing. The strength development for each binder content is presented separately in Figs. 4–6, while a comparative assessment of all mixtures and curing periods is provided in Fig. 7.

As seen in Fig. 4, the compressive strength of samples containing 3% geopolymer binder rises steadily with longer curing for all Na_2SiO_3 to NaOH ratios, indicating that geopolymerization and the associated chemical reactions continue to build strength within the soil matrix between day 0 and day 28. The benefit of the geopolymer binder is evident when compared with the untreated samples, which reached only 0.1599 MPa after 28 days.

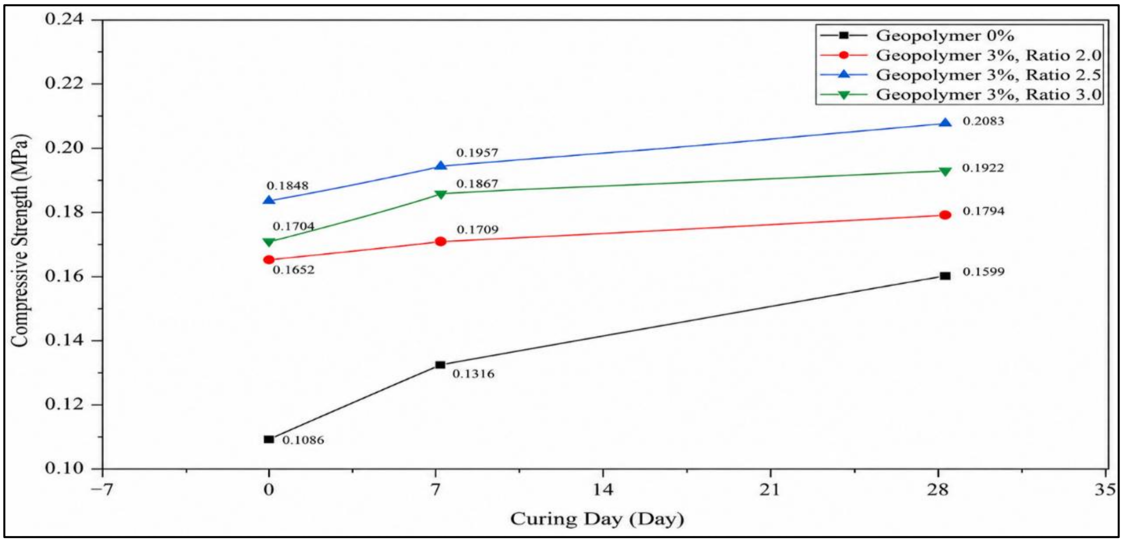

Fig. 4. UCS of 3% geopolymer binder at different curing times

As shown in Fig. 5, samples with 5% geopolymer binder exhibited a steady increase in compressive strength over time, regardless of the activator ratio. Strength values ranged from 0.1666 MPa to 0.1856 MPa on day 0, increasing to between 0.1825 MPa and 0.2173 MPa by day 28. This improvement highlights the role of curing time in enhancing geopolymer bond formation, which increases soil cohesion and particle interlock; according to Heng-yu et al. [17], this produces a denser, more stable and stronger soil structure by day 28. Similar time-dependent development of compressive and bonding strength has been demonstrated experimentally for fly ash-based geopolymer mortars [18].

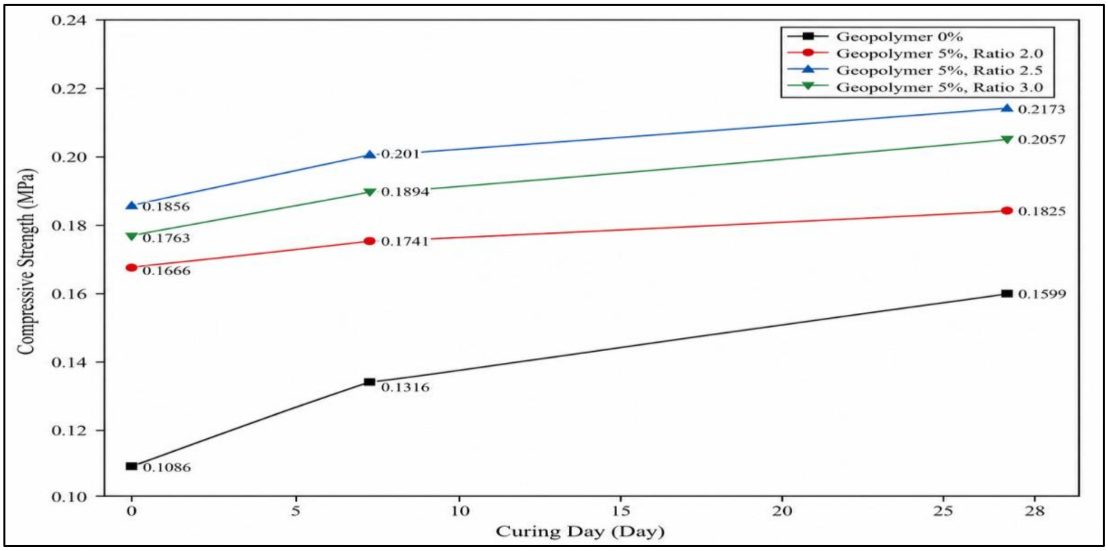

Fig. 5. UCS of 5% geopolymer binder at different curing times

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Fig. 6 shows that the compressive strength of soil stabilized with 7% geopolymer binder likewise increases with curing time, starting at 0.1684 MPa on day 0 and reaching 0.1801 MPa by day 28 at the 2.0 ratio. Although the rate of strength gain is less pronounced than that of the untreated sample, the higher initial strength of the treated soil is attributed to early chemical activation. According to Chen et al. [19], extended curing further promotes the formation of geopolymer gel, contributing to improved mechanical properties of the soil.

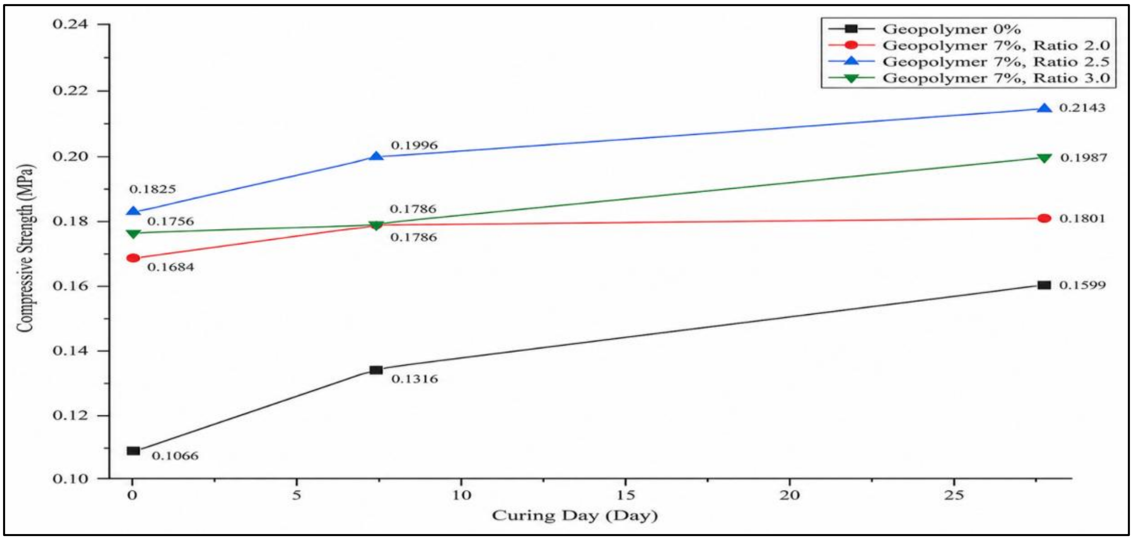

Fig. 6. UCS of 7% geopolymer binder at different curing times

Overall, as illustrated in Fig. 7, curing duration has a clear influence on the UCS of geopolymer stabilized soil, with a consistent pattern of increasing strength from day 0 to day 28 across all samples. This confirms the importance of sufficient curing time for strength development. Castillo et al. [20] similarly reported a strong correlation between curing time and UCS, explaining that longer curing enhances geopolymerization and the formation of a dense N-A-S-H gel network, with most strength development occurring within the first 28 days.

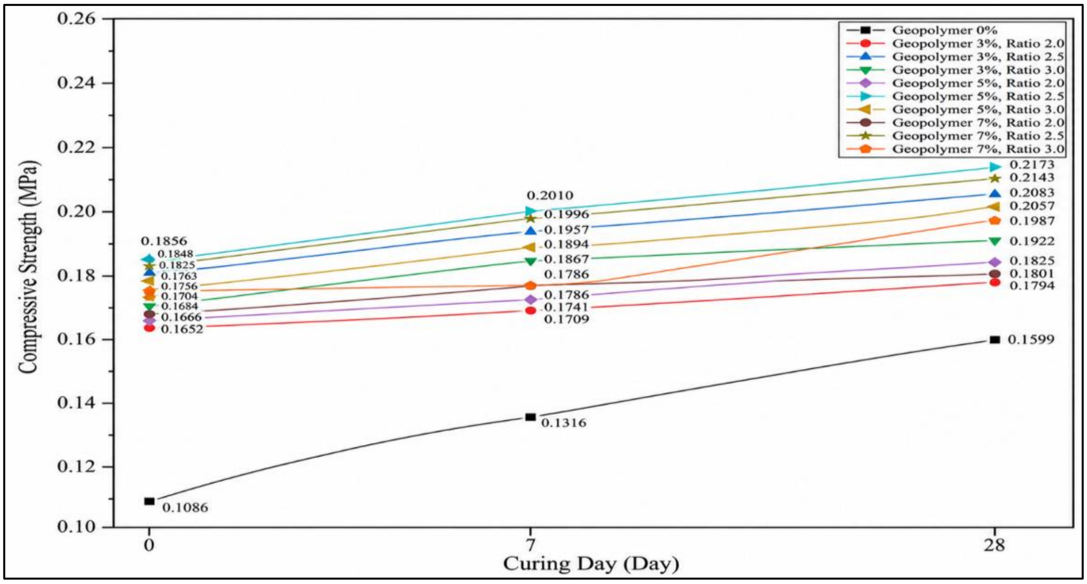

Fig. 7. UCS of all geopolymer binder contents and activator ratios at different curing times

3.5 Effect of Geopolymer Binder Content and Alkaline Activator Ratio on Compressive Strength

The combined influence of binder content (3%, 5% and 7%) and Na_2SiO_3 to NaOH ratio (2.0, 2.5 and 3.0) on strength development can be examined directly from the curing curves in Figs. 4–7, using the untreated sample as the baseline. At the 2.0 ratio, compressive strength increased with binder content on day 0, from 0.1652 MPa (3%) to 0.1666 MPa (5%) and 0.1684 MPa (7%), while by day 28 the 5% binder sample achieved 0.1825 MPa, slightly surpassing the 7% binder sample at 0.1801 MPa. These findings align with Heng-yu et al. [17], who showed that lower binder contents may slow geopolymerization but still improve compressive strength, with the 2.0 ratio allowing gradual strength development.

At the 2.5 ratio, compressive strength increased markedly for all binder contents: on day 28 the untreated sample reached 0.1599 MPa, whereas the 3%, 5% and 7% binder samples achieved 0.2083, 0.2173 and 0.2143 MPa, respectively (Figs. 4–6). These results demonstrate the enhanced effect of the 2.5 ratio in promoting geopolymerization and strength development over time, consistent with Chen et al. [21], who showed that optimal sodium silicate proportions improve compressive strength by enhancing the interaction between the binder and soil particles. At the 3.0 ratio, strength again increased with binder content but tended to plateau, with the 3%, 5% and 7% binder samples reaching 0.1922, 0.2057 and 0.1987 MPa on day 28; Srinivasa Reddy et al. [22] noted similar patterns, highlighting the necessity of determining the ideal binder concentration for successful geopolymerization.

Reading across Figs. 4–7, two consistent trends emerge. First, for every binder content the 2.5 ratio yielded the highest day-28 strength (0.2083, 0.2173 and 0.2143 MPa for 3%, 5% and 7%, respectively), exceeding the corresponding values at both the 2.0 ratio (0.1794–0.1825 MPa) and the 3.0 ratio (0.1922–0.2057 MPa). This is consistent with Castillo et al. [20], who found that the activator ratio strongly affects compressive strength, with the best performance typically observed in the 2.0 to 2.5 range, and with Ahmed et al. [23] and Hartono et al. [24], who reported that an Na_2SiO_3 to NaOH ratio of about 2.5 is favourable for strength development in fly ash-based geopolymers, as well as with Hamzah et al. [10], who observed the highest strength of fly ash geopolymer-stabilized Kedah soil at the same ratio of 2.5. Second, for every activator ratio the compressive strength increased from 3% to 5% binder content but declined slightly at 7%, identifying 5% as the most efficient dosage within the range tested. Beyond 5% binder content, the minor reduction in strength is hypothesised to stem from increased mixture viscosity and unreacted precursor agglomeration, which can impede full gel network formation, as noted in previous microstructural studies [20].

3.6 Most Effective Formulation, Statistical Considerations and Limitations

Within the range of variables tested, the most effective conditions identified in this study are a 5% geopolymer binder, an Na_2SiO_3/NaOH ratio of 2.5 and a 28-day curing period, which achieved the highest UCS of 0.2173 MPa. Increasing the binder content from 3% to 5% improved the day-28 strength by 4.14%, whereas the 5% mixture exceeded the 7% mixture by only 1.38%. A binder content of 5% therefore offers the best balance between mechanical performance, workability and material efficiency, avoiding the additional cost and material consumption associated with higher dosages for little added benefit. These observations are consistent with Castillo et al. [20], who noted that most strength development occurs within the first 28 days as the essential chemical reactions approach completion, and with Heng-yu et al. [17], who observed that longer curing strengthens interparticle bonds.

It should be noted that the difference in compressive strength between the mixtures containing 5% and 7% binder at an Na_2SiO_3/NaOH ratio of 2.5 was marginal, with values of 0.2173 MPa and 0.2143 MPa, respectively. Therefore, the 5% binder content is considered the most efficient dosage within the investigated range based on its consistently favourable performance across the different activator ratios and curing periods. This selection should be interpreted as a practical and material-efficient dosage rather than a statistically distinct optimum. Where replicate data are available, the results should additionally be reported as mean ± standard deviation and supported by a one-way analysis of variance, followed by Tukey's post-hoc test, to determine whether the differences among the binder contents are statistically significant.

Maintaining the alkaline activator ratio at 2.5 is equally important. According to Ahmed et al. [23], raising the ratio above 2.5 reduces workability and strength through poor compaction and increased porosity; the selected ratio therefore ensures a balance between reactivity, moisture content and workability that is essential for forming durable geopolymer bonds. Chen et al. [21] further reported that UCS increases significantly over time as aluminosilicate gels form and bind soil particles, making the 28-day mark particularly significant.

A limitation of this study is that the tested material is the fine matrix fraction of the lateritic soil (passing 425 μm) rather than the whole bulk soil, since Table 2 and Fig. 2 show that 54.73% of the natural soil consists of sand particles up to 2 mm, over half of which was removed by the 425 μm sieving prior to binder mixing. The reported strengths therefore characterize the stabilized fine-grained matrix of the lateritic soil rather than the whole soil as it exists in the field. This pre-treatment was necessary to satisfy the maximum particle size requirement for the 38 mm diameter remoulded UCS specimens and to ensure specimen homogeneity, and it is consistent with standard sample preparation for fine-grained soil testing. Nevertheless, the presence of coarser particles in the field may alter the binder demand and the developed strength, so the absolute UCS values reported here should be applied to full-grading field soils with caution.

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Verification testing on specimens incorporating the natural grading, using larger moulds, is recommended before field implementation.

Beyond mechanical performance, geopolymer stabilization provides an environmentally responsible alternative to cement-based methods by utilizing industrial by-products such as fly ash, reducing greenhouse gas emissions and construction-related waste while enhancing soil strength and durability. The approach supports global sustainability goals and is well suited to long-term geotechnical and infrastructure applications that must comply with environmental standards.

4. CONCLUSIONS

This study achieved its objectives and provides practical insights into the formulation and performance of geopolymer stabilized lateritic soil. First, the physical characterization showed that the soil is a sandy silt of intermediate plasticity (MIS), with a liquid limit of 48.16%, a plastic limit of 36.11%, a plasticity index of 12.05%, a particle density of 2.46 Mg/m^3 (specific gravity of 2.46), a maximum dry density of 1.735 Mg/m^3 and an optimum moisture content of 18.39%. These properties formed the basis for analysing the behaviour of the soil under different stabilization conditions. Second, the study identified the Na_2SiO_3 to NaOH ratio that produces the highest compressive strength in geopolymer stabilized lateritic soil. The 5% geopolymer binder with a 2.5 activator ratio proved to be the most effective formulation within the range tested, achieving a peak UCS of 0.2173 MPa after 28 days of curing and showing comparable strength to the 7% binder content (0.2143 MPa) while providing a more efficient mix design. This ratio maximized compressive strength while providing an effective balance between workability and reactivity, in agreement with previous studies [23, 24] that emphasized the significance of an ideal activator ratio for enhancing the strength and durability of geopolymer stabilized soils. Finally, the findings have important implications for soil stabilization in geotechnical engineering, offering a more efficient and durable method for improving the mechanical properties of lateritic soil. The recommended formulation of 5% geopolymer binder, a 2.5 activator ratio and 28 days of curing provides a sustainable solution for soil stabilization in engineering and construction. Future research should extend this work to specimens incorporating the natural soil grading and larger mould sizes, other soil types, replicate testing with statistical analysis, microstructural verification of the proposed mechanisms (e.g., SEM and XRD), long-term durability studies and field-scale applications to confirm the broader applicability and sustainability of the technology.

5. ACKNOWLEDGEMENTS/FUNDING

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6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Muhammad Sofian Abdullah: Conceptualization, Methodology, Supervision, Validation, Project administration, and Writing – review and editing. Warid Wazien Ahmad Zailani: Conceptualization, Formal analysis, Validation, Supervision, and Writing – review and editing. Anas Ibrahim: Investigation, Resources, Data curation, and Validation. Nazirah Mohd Apandi: Formal analysis, Validation, Visualization, and Writing – review and editing. Noraida Mohd Saim: Methodology, Resources, Validation, and Writing – review and editing. Nurul Rasyidah Ismail: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, and Writing – original draft. All authors reviewed and approved the final version of the manuscript.

8. DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this work, the authors used Claude, developed by Anthropic, solely to improve the readability, clarity, and language quality of the manuscript. After using this tool, the authors carefully reviewed, verified, and edited the generated content as necessary. The authors take full responsibility for the accuracy, integrity, and content of the final publication.

9. DATA AVAILABILITY/SUPPLEMENTARY MATERIALS

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

10. ETHICS STATEMENT

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health and Environmental protocols of Universiti Teknologi MARA.

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