International Journal of GEOMATE
(Geotechnique, Construction Materials and Environment)
ISSN: 2186-2982 (P), 2186-2990 (O), Japan
Vol. 31, Issue 144, August, 2026, pp.183-191; DOI: 10.21660/2026.144.5605

SOAKED CBR AND MICROSTRUCTURAL ASSESSMENT OF FLY ASH-RICE HUSK ASH-LIME STABILIZED SANDY PODZOL

*Irfan Prasetia[1], Hutagamissufardal[1] and Muhammad Afief Ma'ruf[1]

[1]Department of Civil Engineering, Universitas Lambung Mangkurat, Indonesia

*Corresponding Author, Received: 14 April 2026, Revised: 16 May 2026, Accepted: 26 May 2026

ABSTRACT: Within tropical areas experiencing regular rainfall and seasonal wetness, pavement support under soaked conditions can be significantly reduced. It is primarily attributed to the weakened sandy Podzol subgrade soil due to moisture. To stabilize the sandy Podzol subgrade soil in South Kalimantan, Indonesia, this study examined the soaked performance of a ternary binder involving three components: (i) fly ash, (ii) rice husk ash, and (iii) lime. The untreated soil was classified as well-graded sand (SW) with less than 5% non-plastic fines. At the optimal moisture content determined using the Standard Proctor method, various specimens were compacted, cured for seven days, and soaked for four days prior to California bearing ratio (CBR) testing. The F15LR (15% FA + 5% RHA + 2.5% lime) specimen revealed the highest CBR improvement (4.30% to 7.50%, 74% increase). Fourier transform infrared spectroscopy analysis indicated chemical changes associated with stabilization-related reactions. A more densely bonded matrix was observed in the optimal mixture through scanning electron microscopy analysis. In sandy Podzol subgrade soil, soaked performance was influenced more by binder dosage efficiency and granular packing than by binder quantity alone. Overall, in enhancing pavement subgrade in wet conditions using locally available by-products, this study suggested that the proposed ternary system had high potential.

Keywords: Sandy Podzol, Soaked California Bearing Ratio, Ternary Stabilization, Fly Ash, Rice Husk Ash.

1. INTRODUCTION

Various engineering properties, alongside construction suitability, have been observed for numerous Indonesian soil types [1]. Notably, Podzol soil is a soil type that is commonly found in some areas (Kalimantan, Sumatra, and Papua) [2]. This soil type occupies roughly 64% of the city area in Banjarbaru, South Kalimantan [3]. Globally, Podzol soils also occur in many other countries. In European forests, approximately 12% of the forested area is covered by Podzol soils [4]. Therefore, given both their local prominence and wider global occurrence, a thorough evaluation of sandy Podzol subgrade soil performance, especially under tropical environmental conditions, is necessary.

The sandy texture and low clay content primarily influence the engineering properties of sandy Podzol subgrade soil [2,5]. When dry, considerable strength can also be demonstrated by this coarse-grained sandy soil owing to intergranular friction. Nonetheless, when the condition becomes saturated, the bearing capacity may significantly diminish [6,7]. Consequently, the moisture-sensitive nature of sandy Podzol subgrade soil presents an important concern for subgrade conditions (areas with high rainfall in tropical regions), alongside requiring suitable stabilization techniques. Through the use of binding agents, the soil engineering characteristics can then be substantially improved [8–11]. Currently, this purpose has been achieved using conventional binders (cement and lime). Conversely, there is a growing interest in industrial and agricultural by-products as more sustainable alternatives.

Two promising materials that have been extensively evaluated are fly ash (FA) and rice husk ash (RHA) due to their reactive constituents. For both these materials, they are able to engage in pozzolanic reactions, along with enhancing soil performance [12,13]. Therefore, FA- and RHA-based stabilization can improve subgrade performance while facilitating the beneficial reuse of waste-derived materials. In enhancing the engineering properties of soil regarding cases involving challenging soil conditions, earlier studies also revealed that it could be accomplished when employing binary ash-lime stabilization. Particularly, if RHA-lime mixtures were utilized across various treatment conditions, swelling could be decreased, alongside increasing index and strength-related features [12,13]. Likewise, in improving strength development, it was reported to be achieved through FA-lime systems [14,15]. Binder dosage and lime-ash proportioning were noted to be performance-influencing factors. Accordingly, for the engineering advantages of ash-lime stabilization, it could be achieved through a suitable equilibrium between ash content and lime dosage.

Although FA, RHA, and lime are among the materials commonly used, previous studies have focused on single additives or binary combinations [8,16–18], while evidence on the combined use of all three materials remains limited, especially for clean coarse-grained subgrade soils. In such soils, improvement is not governed solely by the reduction of plasticity, but may also be influenced by factors such as particle contact, packing preservation, and bonding at grain contacts. Moreover, although RHA has been investigated in several stabilization studies, previous research has generally focused on processed or more controlled RHA materials [12,13,18]. Evidence on the use of untreated locally sourced RHA as a stabilizing material is inadequate (even though it holds significant importance for construction in rural and resource-limited settings).

Regarding these gaps, this study examines the soaked performance of a ternary binder consisting of FA, locally sourced RHA, and lime to stabilize a sandy Podzol subgrade soil from South Kalimantan, Indonesia. Emphasis is placed on FA dosage, wet-condition bearing performance, and granular packing characteristics. Fourier transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) were used to provide supportive evidence for interpreting the stabilization response of the applied ternary binder.

This paper is organized as follows. Section 2 presents the research significance. Section 3 explains the materials, mix design, specimen preparation, and testing procedures. Section 4 contains the geotechnical characteristics, soaked CBR performance, FTIR and SEM analyses, engineering interpretation of the research data, practical implications, and limitations of the study. Finally, Section 5 summarizes the main findings of this study.

2. RESEARCH SIGNIFICANCE

Regarding the significance, a moisture-vulnerable sandy Podzol subgrade soil under soaked conditions was attained via the ternary FA-RHA-lime stabilization system. Particularly, the method entailed the field-relevant application of untreated local RHA. The studied soil was a clean coarse-grained subgrade soil. It was examined with emphasis on the relationships between performance, contact stability, and granular packing.

This study offers valuable insights for determining an efficient binder dosage that enhances wet-condition subgrade support for tropical pavement applications. The use of FA and untreated local RHA also provides practical value by encouraging the efficient use of locally available by-products and potentially reducing reliance on cement-assisted treatment. Therefore, through this study, practical insight into improving subgrade conditions for pavement applications can be effectively delivered. However, further evaluation of durability and field performance is still needed before the proposed stabilization approach can be recommended for wider field applications.

3. MATERIALS AND METHODS

3.1. Materials

The sandy Podzol subgrade soil investigated in this study, hereafter referred to as the studied soil, was collected from South Kalimantan, Indonesia. For the soil stabilizers, this study employed by-products and lime from South Kalimantan. FA, RHA, and lime were used, with the Asam-Asam coal-fired power plant (PLTU Asam-Asam) providing the FA. Table 1 tabulates the chemical composition of FA, RHA, and lime. In Table 2, a summary of the moisture contents for all materials is listed.

Table 1. Chemical composition of stabilization materials

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MnO
FA	27.02%	7%	50.84%	10.50%	0.55%	0.68%
RHA	56.03%	13.93%	27.03%	0.20%	0.50%	N/A
Lime	0.20%	8.20%	0.30%	89.83%	N/A	N/A

Table 2. Moisture content of stabilization materials

No	Sample	Moisture Content (%)
1	Fly Ash	1.63
2	Rice Husk Ash (as-used)	66.67
3	Lime	9.65

Table 1 shows that the highest chemical component in the local fly ash is Fe_2O_3 (50.84%), along with moderate amounts of SiO_2. This may be due to the composition of the coal used, especially when coal sources containing pyrite or high sulfur are involved. Therefore, the stabilization response in this study should be interpreted in terms of the specific chemistry of local fly ash rich in Fe_2O_3. The untreated local RHA contains relatively high amounts of SiO_2, Al_2O_3 and, Fe_2O_3 (56.03%, 13.93%, and 27.03%, respectively). In addition, CaO is the major component in lime, with a content of 89.83%. These results indicate that the RHA was silica-rich, while the lime served as the main calcium-rich alkaline material in the FA-RHA-lime stabilization system.

Lime was sourced from a local chemical supplier in Banjarmasin. Rice farmers in Banjarbaru provided the locally sourced RHA. This RHA was generated via conventional open-field burning and was utilized within this study in its original state [without post-processing (calcination, sieving, and grinding)]. Morphologically, the material exhibited a black coloration, along with high residual moisture (66.67%) and unburnt carbon. Concerning construction practices in local and rural areas of South Kalimantan, this study deliberately chose this RHA to accurately reflect the material commonly accessible. For this reason, rather than representing the inherent reactivity of processed laboratory-grade RHA, the findings should be understood as indicative of practical and field-oriented performance. Due to its high moisture content and unburnt carbon, the untreated RHA may behave differently from dry or processed ash materials, which may lead to variable reactivity and limit direct comparison with studies using controlled RHA.

3.2. Methods

3.2.1. Soil Characterization

The physical properties of the untreated soil were assessed. Using ASTM D854 [19] and ASTM D6913/D6913M-17 [20], the specific gravity test and particle-size distribution test were conducted, respectively. Based on the Unified Soil Classification System (USCS), the test results were also utilized to categorize the soil. Likewise, the plasticity characteristics of the soil were analyzed using Atterberg limits testing following ASTM D4318 [21].

3.2.2. Sample Preparation and Curing

Using the dry weight of the untreated soil as a reference point, each stabilization mixture was formulated. Initially, to achieve uniformity, along with eliminating any coarse organic matter, the soil underwent air-drying and was passed through a 2-mm sieve. Based on the standard Proctor compaction method following Indonesian National Standard (SNI) 1742:2008 [22] (comparable to the standard compaction effort outlined in ASTM D698), the optimum moisture content (OMC) of the untreated soil was determined. To ensure consistency, alongside facilitating comparative screening, the moisture content of all other mixtures was adjusted to the OMC of the untreated soil before compaction. Even though the optimal compaction levels might vary for each specific mixture, this approach provided a common basis for comparison among the tested mixtures. Therefore, the results should be interpreted as a comparative screening of mixture performance under a consistent compaction-moisture condition, rather than as the maximum achievable performance of each mixture. This approach may not fully represent the individual optimum compaction condition of each stabilized mixture and may influence mixtures with higher binder contents.

For each mixture, the dry soil was carefully combined with the necessary stabilizing agents (FA, lime, and RHA), along with cement (only for F25LRC). In ensuring a uniform blend, the mixtures were then mixed in a mortar for 5 mins. Subsequently, to ensure uniform moisture distribution, each mixture was adjusted by adding water to reach the selected moisture content, followed by mixing for 3 mins. Following the Standard Proctor compaction method, the prepared mixtures were then compacted into standard CBR molds in three layers. To mitigate the loss of moisture during the curing period, the specimens were placed in sealed containers for 7 days after compaction (ambient laboratory conditions = 25 ± 2°C). The 7-day curing period was selected to evaluate the short-term stabilization response before soaked CBR testing. To mimic the given soaked field conditions seen in humid environments (extensive rainfall and varied levels of groundwater), these specimens were kept immersed in water for a period of four days in accordance with SNI 1744:2012 [23].

Based on the methodology from a previous study [10], a binder framework consisting of 2.5% lime and 5% RHA was deemed effective. However, because the soil type examined in the previous study was different from that used in the present study, three FA contents (15%, 20%, and 25% by dry weight of the soil) were retained to evaluate the effect of FA dosage on the sandy Podzol subgrade soil. Considering this methodological basis, the selected FA dosages were used as a preliminary screening range. Lime and RHA were maintained at constant levels to provide a consistent lime–RHA binder framework, allowing the effect of FA dosage to be assessed more clearly.

Within coarse-grained sandy soils, the response could be influenced significantly by the interplay between cementation at particle contacts, along with the maintenance of packing efficiency. Hence, the potential confusion caused by simultaneous variations in all ternary components could be eliminated when keeping lime and RHA constant, as the correlation between FA content and mechanical performance could be assessed more distinctly.

In this study, one hybrid mixture (F25LRC) was introduced by adding 4.7% cement to the formulation. The dosage was chosen based on practical mixing considerations in the experimental design and is within the estimated range of cement requirements used for Cement Treated Base (CTB), namely 3–5%, as specified in the Indonesian highway specifications [24]. The F25LRC sample served as a practical comparative benchmark representing a cement-assisted stabilization approach, rather than as a rigid compositional standard. This mixture was included to compare the performance of the cement-free FA–RHA–lime ternary system with a widely recognized cement-assisted alternative under the same soil and experimental conditions. Table 3 summarizes the complete mix composition.

Table 3. Stabilization mix design

No	Sample	FA (%)	Lime (%)	RHA (%)	Cement (%)
1	US	0	0	0	0
2	F15LR	15	2.5	5	0
3	F20LR	20	2.5	5	0
4	F25LR	25	2.5	5	0
5	F25LRC	25	2.5	5	4.7

In Fig. 1, the compacted CBR specimens prepared for testing are also depicted. Looking closely at these specimens, a consistent surface texture was observed, along with being free of visible cracks. Therefore, the compaction efforts were uniform, alongside the integrity of the specimens being effectively maintained across all mix designs.

Fig. 1. Compacted specimens prepared for testing

3.2.3. Mechanical and Microstructural Testing

The primary mechanical performance of the stabilized soil was tested using the soaked CBR test in accordance with SNI 1744:2012 (comparable to laboratory-compacted CBR testing principles in ASTM D1883) [23]. For each mixture, three specimens were prepared at different compaction levels to establish the CBR–dry density relationship. For comparative consistency, the reported CBR value was then obtained from this relationship at the fixed target dry density corresponding to the untreated soil MDD of 1.76 g/cm³. Therefore, the reported CBR value should not be interpreted as a replicate-based mean value. Importantly, to offer supportive evidence of chemical interactions associated with stabilization, FTIR analysis was performed. In addition, using SEM imaging, the morphology of selected specimens was qualitatively observed.

4. RESULTS AND DISCUSSION

4.1. Geotechnical Characteristics of the Untreated Soil

The studied soil appeared to be predominantly sandy, along with comprising approximately 95.0% sand, 2.7% gravel, and 2.3% fines (particles that passed the No. 200 sieve). According to USCS, this soil was classified as well-graded sand (SW). From the perspective of engineering, it could also be defined as a clean coarse-grained subgrade soil with little quantity of fines. When analyzing the particle-size distribution curve (see Fig. 2), the coefficient of uniformity (Cu) = 7.43 and coefficient of curvature (Cc) = 1.69 also had its well-graded nature further validated. The fines were found to be non-plastic through the Atterberg limits test.

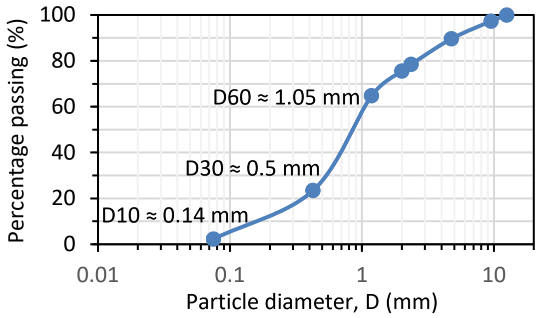


Fig. 2. Particle-size distribution curve of the untreated soil

Because the studied soil is dominated by sand, with low fines content and non-plastic fines, its soaked bearing response is more appropriately interpreted as being governed mainly by frictional particle contact, granular packing, and interparticle load transfer rather than by plasticity-related behavior. Under submerged conditions, reduced contact stability and less effective load transfer within the granular matrix may weaken the soil structure and decrease bearing capacity. Thus, compared to modifying plasticity, enhancing soaked bearing performance is a more pertinent engineering objective [25]. Using the standard

Proctor method, Fig. 3 illustrates the compaction curve of the untreated soil (MDD of 1.76 g/cm³ and OMC of 14.82%). The specific gravity, moisture content, particle-size distribution, and OMC of the untreated soil are listed in Table 4.

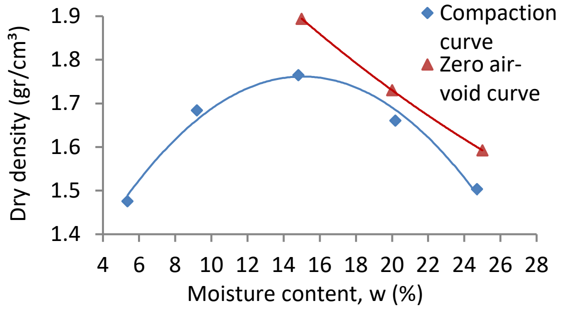


Fig. 3. Compaction curve of the untreated soil

Table 4. Geotechnical properties of the untreated soil

Engineering property	Test results
Specific gravity	2.65
Moisture Content (%)	7.83
Particle size analysis	
Gravel (%)	2.7
Sand (%)	95
Silt (%)	2.3
MDD (g/cm³)	1.76
OMC (%)	14.82

4.2. Soaked CBR Performance and Optimum Binder Dosage

For every mixture, the soaked CBR values are portrayed in Fig. 4. It was then noted that for all stabilized mixtures, they exhibited higher soaked CBR values (F15LR = 7.50%, F20LR = 7.00%, F25LR = 6.40%, and F25LRC = 7.40%) compared to the untreated soil (4.30%). Regarding the corresponding soaked CBR increases, they were recorded to be approximately 74%, 63%, 49%, and 72%, respectively. As such, within moisture-sensitive conditions, the FA-RHA-lime binder system was deemed advantageous. Particularly, the highest soaked CBR was observed in F15LR, although the difference from F25LRC was relatively small and should be interpreted as a numerical trend rather than a statistically significant difference.

From the results, it may be inferred that within the granular matrix, both bonding and load transfer under saturated conditions were improved. The observed increase in soaked CBR may be interpreted in terms of improved interparticle bonding and matrix densification, potentially associated with binder-related reaction products (e.g., C-S-H- and C-A-H-type phases). Similar patterns have also been reported in previous studies on ash- and lime-stabilized soils [26,27].

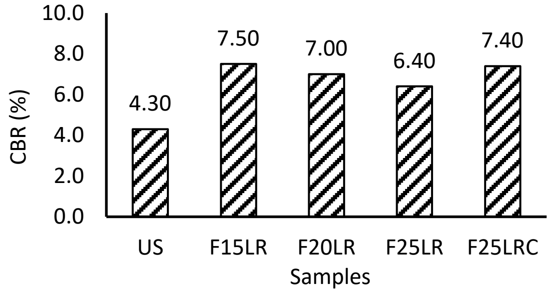


Fig. 4. Soaked CBR values of untreated and stabilized soil specimens after 7 days of curing and 4 days of soaking

From these results, it could be noted that the improvement in soaked CBR was influenced not simply by binder quantity, but by the balance between binder-related chemical interactions and packing efficiency. F15LR appeared to provide the most favorable combination of these factors. Increasing the FA content to 20% and 25% did not yield additional benefit, and the lower performance observed in F25LR indicated that excessive ash content may have reduced matrix uniformity and compaction efficiency. Although the cement-assisted mixture (F25LRC) generated a marked increase in soaked CBR compared to F25LR, its value still fell marginally short of that of F15LR. Overall, these findings suggest that strength development in the present soil was influenced more by dosage efficiency and microstructural balance than by total binder content alone [26–28].

4.3. FTIR Evidence of Stabilization Reactions

The FTIR analysis was conducted to determine the chemical alterations linked to the stabilization by the FA-RHA-lime binder system (see Fig. 5). Accordingly, the spectra of untreated and stabilized specimens produced a similarity in their primary soil-related bands, suggesting that the overall mineral structure of the soil was preserved. Nonetheless, the variations in band intensity, alongside the emergence of new bands in the stabilized specimens, implied that chemical reactions took place during curing and soaking. These spectral changes also aligned with earlier studies utilizing FTIR on stabilized soils and cementitious binders [29,30]. Meanwhile, the lower O-H band near 3600 cm^{-1} was noted in the stabilized specimens, which may reflect moisture consumption throughout hydration and pozzolanic reactions. A band around 1600 cm^{-1} (H-O-H bending vibration of water molecules) was also detected in all specimens. Moreover, a carbonate-related band was observed near 1400 cm^{-1} only in the stabilized specimens (higher intensity at larger FA content and in the cement-assisted mixture). These features may be associated with hydration and pozzolanic reactions, such as C-S-H- and C-A-H-like phase formation, as reported in the literature [31–33].

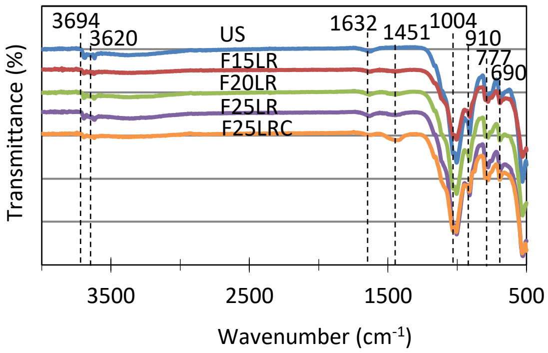


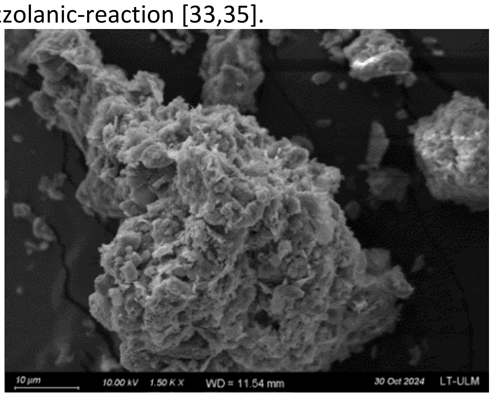
Fig. 5. FTIR spectra of untreated and stabilized soil samples

The stabilized specimens exhibited Si-O-T-related bands near 1000 cm^{-1} and within the 900–700 cm^{-1} range, which may be associated with silicate-based stretching and bending vibrations in the FA-RHA-lime-treated system. However, because these bands may also partly reflect the quartz-rich characteristics of the original sandy Podzol subgrade soil [30,34], the FTIR results are more appropriately interpreted as supportive evidence of stabilization-related chemical interactions rather than as definitive evidence of individual reaction products.

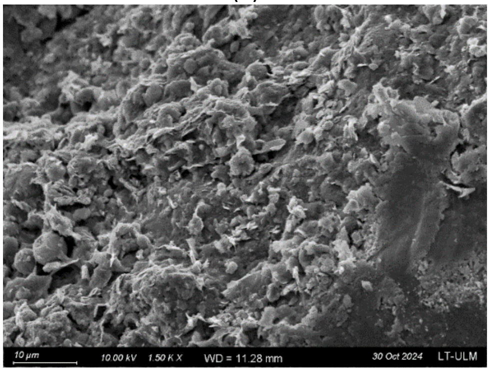
Collectively, these findings suggest that chemical interactions under the ternary binder may have contributed to improved interparticle bonding within the granular matrix. This interpretation was consistent with the soaked CBR results, particularly for F15LR, which exhibited enhanced bearing performance under saturated conditions.

4.4. SEM Evidence of Matrix Densification

The SEM analysis was performed to investigate the changes associated with stabilization by the FA-RHA-lime binder system. For the F15LR and F25LR specimens, Fig. 6 then reveals the SEM images. These micrographs were generally consistent with the FTIR trends observed, indicating that stabilization encouraged the formation of a denser and more bonded granular matrix. Evidence from the F15LR specimen also suggested a more continuous matrix, alongside less evident pore space compared to the F25LR specimen, which related well with its superior soaked CBR. Similar trends were also observed in other studies investigating the microstructural changes due to hydration- and pozzolanic-reaction [33,35].



(a)



(b)

Fig. 6. SEM micrographs of stabilized soil specimens showing (a) F15LR and (b) F25LR, illustrating differences in matrix continuity and bonding morphology

In the F25LR sample, a more heterogeneous, along with a slightly less defined matrix, was observed. Interestingly, the perceived bonding between the regions was weaker than expected, and some particles appeared to be only loosely embedded within their matrix. According to these findings, the saturated performance of the stabilized sandy Podzol subgrade soil was mainly affected by bonding at contact points and densification of a dense matrix (rather than solely by the use of binder).

4.5. Engineering Interpretation and Practical Implications

The combined soaked CBR, FTIR, and SEM results suggested that the stabilization response of this sandy Podzol subgrade soil was influenced by the balance between binder-related chemical interactions and granular packing efficiency. Rather than plasticity modification, the results are more consistent with contact-level bonding, matrix continuity, and packing efficiency. However, this interpretation should consider the chemistry of the Fe_2O_3-rich fly ash used. Moreover, in this mixed FA-RHA-lime system, FA and RHA may supply reactive constituents, while lime acts as the main calcium-rich activator. Nevertheless, without EDS or XRD, their individual contributions could not be directly separated from the SEM observations.

Within the investigated mixtures, F15LR showed the most favorable overall response. Similar interpretations have also been reported in previous studies, where strength improvement was associated more with reaction-related bonding, matrix densification, and dosage efficiency than with binder addition alone [35].

Overall, for clean coarse-grained subgrade soils to remain stable in wet conditions, it was pivotal to attain adequate cementation at the points where grains met, alongside preserving the integrity of the granular structure. Notably, dosage efficiency was more critical than merely increasing the binder content. For both reactivity and packing preservation, their balance could also impact the optimum soaked performance. Within tropical areas, these findings are relevant to enhancing moisture-sensitive sandy Podzol subgrade soils used in flexible pavements. The rise in soaked CBR to 7.50% also suggested enhanced wet-condition subgrade support. Instead of indicating automatic fulfillment of all pavement design requirements, this value should be interpreted as a CBR-based indicator of improved wet-condition subgrade support and as one input for pavement design considerations [36]. Within the Indonesian road-design context, the findings were also pertinent to the existing pavement guidelines. For reference, the treated specimens exceeded the 6% CBR reference level used in Indonesian highway technical specifications for certain subgrade- or foundation-related conditions [24]. Although the increased soaked CBR may indicate potential benefits for pavement design practice, pavement thickness reduction and cost savings were not directly quantified in this study.

In scenarios where performance was influenced by wet conditions, the optimal mixture determined in this study could act as a viable FA-RHA-lime stabilization option for moisture-vulnerable sandy Podzol subgrade soils. This practical implication was in line with earlier pavement works, indicating that enhancing the subgrade could improve pavement support, along with producing a more effective pavement design [37,38], although such design implications were not directly quantified in the present study. Therefore, the outcomes were pertinent to tropical pavement infrastructure, alongside developing-region construction contexts that relied on locally available by-products. In this respect, the proposed stabilization approach could lessen dependence on traditional binders, along with enhancing wet-condition subgrade support within tropical pavement applications.

4.6. Study Limitations

The data should be interpreted in the context of a short-term laboratory study that focused on soaked CBR performance. FTIR and SEM were employed to aid in understanding stabilization-related changes. However, these results should be interpreted as supportive rather than definitive evidence of specific reaction products, because no XRD, EDS, or other phase-identification techniques were employed in the present study.

In addition, the study did not aim to deliver additional mechanical characterization, such as UCS testing, an evaluation of long-term durability, or a quantitative environmental assessment, such as carbon-emission estimation, life-cycle assessment, or cost-benefit evaluation. Accordingly, within the examined ternary binder system, the findings indicated an enhancement in wet-condition bearing performance and dosage efficiency. For future studies, other parameters (curing period, field performance, and material-source variability under real-world service conditions) should be examined.

5. CONCLUSIONS

The soaked bearing performance of moisture-vulnerable sandy Podzol subgrade soil was improved using a ternary binder. Notably, the F15LR specimen (15% FA + 5% RHA + 2.5% lime) produced the maximum CBR improvement within the tested range (4.30% to 7.50%, 74% increase). Further increases in FA dosage did not provide additional benefit. From this observation, it could be noted that the performance of this sandy Podzol subgrade soil was influenced more by dosage efficiency and preservation of granular packing than by binder quantity alone. As supported by the reduced intensity of the O-H band and the emergence of carbonate-related bands, the FTIR results provided supportive evidence of stabilization-related chemical interactions. In addition, the SEM images showed that F15LR exhibited a relatively denser and more continuous bonded matrix than F25LR. As such, the improved soaked performance may be associated with enhanced interparticle bonding and matrix densification at grain contacts.

From a practical pavement engineering standpoint, the rise in soaked CBR signified enhanced wet-condition subgrade support. Within the Indonesian road-design context, the attained value also exceeded the 6% level used for certain pavement applications. Consequently, the optimal mixture may serve as a viable stabilization option for moisture-vulnerable sandy Podzol subgrade soils in tropical regions.

6. ACKNOWLEDGMENTS

The authors would like to express our deepest gratitude to the Universitas Lambung Mangkurat Research Fund for their financial support with the scheme Fundamental Research 2024 No. 961/UN8.2/PG/2024. The authors would also like to thank all students who have contributed to completing this research.

7. REFERENCES

[1] Subardja D.S., Ritung S., Anda M., Sukarman, Suryani E., Subandiono R.E. Petunjuk Teknis Klasifikasi Tanah Nasional [National Land Classification Technical Instructions]. vol. 22. 2014.

[2] Chesworth W. Encyclopedia of Soil Science. Springer Netherlands; 2008. https://doi.org/10.1007/978-1-4020-3995-9_442

[3] BPS Kota Banjarbaru. Kota Banjarbaru dalam Angka 2024 [Banjarbaru Municipality in Figures 2024]. 2024.

[4] Brock O., Kalbitz K., Absalah S., Jansen B. Effects of development stage on organic matter transformation in Podzols. Geoderma 2020;378. https://doi.org/10.1016/j.geoderma.2020.114625

[5] Muir A. The Podzol and Podzolic Soils. Advances in Agronomy 1961;13:1–56. https://doi.org/10.1016/S0065-2113(08)60956-6

[6] Wang C., Diao Y., Guo C., Wu H., Guan H., Qin L., Chu X., Du X. Experimental study on the mechanical behaviour of silty soil stabilized with polyurethane. Constr Build Mater 2024;416:135251. https://doi.org/10.1016/j.conbuildmat.2024.135251

[7] Balreddy M.S., Abilash K.E., Manjunath H.K. Experimental Investigation on Stabilization of Silty Sand Using Fly Ash. In: Satyanarayana Reddy C.N.V., Saride S., Haldar S., editors. Transportation, Water and Environmental Geotechnics, Singapore: Springer Singapore; 2021, p. 281–91. https://doi.org/10.1007/978-981-16-2260-1_27

[8] Ananda M.D.K., Prasetia I., Ma'ruf M.A. Effects of Fly Ash and Rice Husk Ash Mixing with Banjarmasin Soft Clay Soil on CBR, Swelling and Shear Strength Value. International Journal of Civil Engineering and Technology 2024;15(1):36–46.

[9] Alsabhan A.H., Qadri J., Sadique M.R., Alam S., Perveen K., Binyahya A.S. Soil Stabilization Using Silicon Carbide (SiC) Nanoparticles: Confirmation Using XRD, SEM, and FTIR. Journal of Civil Engineering and Management 2022;29:194–201. https://doi.org/10.3846/jcem.2022.18173

[10] Prasetia I., Hutagamissufardal H., Jimmy A., Ananda M.D.K. Experimental investigation on the properties of Borneo soft soil stabilized with industrial waste. International Journal of Engineering and Management Sciences 2024;9(1):25–37. https://doi.org/10.21791/ijems.2023.040

[11] Syahril S., Sagala S.D., Purba D.A., Syahputra K.H. SUSTAINABLE SOFT CLAY STABILIZATION USING RICE HUSK ASH AND WASTE SPENT CATALYST FROM RESIDUAL CATALYTIC CRACKING. International Journal of GEOMATE 2025;29:48–55. https://doi.org/10.21660/2025.131.4842

[12] Muthu Lakshmi S., Geetha S., Selvakumar M., Divya Susanna K. Strength enhancement of Clayey Sand subgrade using lime and rice husk ash. Mater. Today Proc., vol. 46, Elsevier Ltd; 2021, p. 7430–5. https://doi.org/10.1016/j.matpr.2021.01.039

[13] Pushpakumara B.H.J., Mendis W.S.W. Suitability of Rice Husk Ash (RHA) with lime as a soil stabilizer in geotechnical applications. International Journal of Geo-Engineering 2022;13. https://doi.org/10.1186/s40703-021-00169-w

[14] Indiramma P., Sudharani C., Needhidasan S. Utilization of fly ash and lime to stabilize the expansive soil and to sustain pollution free environment - An experimental study. Mater. Today Proc., vol. 22, Elsevier Ltd.; 2020, p. 694–700. https://doi.org/10.1016/j.matpr.2019.09.147

[15] Renjith R., Robert D., Setunge S., Costa S., Mohajerani A. Optimization of fly ash based soil stabilization using secondary admixtures for sustainable road construction. J Clean Prod 2021;294:126264. https://doi.org/10.1016/j.jclepro.2021.126264

[16] Pratiwi A.Y., Prasetia I., Yahya M., Effendi R. Investigation of enhancing industrial waste as a soft soil stabilizer. IOP Conf Ser Earth Environ Sci 2022;999:0–6. https://doi.org/10.1088/1755-1315/999/1/012029

[17] Pratiwi A.Y., Prasetia I., Perina Y.A., Effendi R. Stabilization of soft soil using industrial waste. IOP Conf Ser Earth Environ Sci 2021;758:0–6. https://doi.org/10.1088/1755-1315/758/1/012007

[18] Zaika Y., Suryo E.A. The durability of lime and rice husk ash improved expansive soil. International Journal of GEOMATE 2020;18:171–8. https://doi.org/10.21660/2020.65.5539

[19] ASTM International. ASTM D854: Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method 2023. https://doi.org/10.1520/D0854-23

[20] ASTM International. ASTM D6913/D6913M: Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis 2017.

[21] ASTM International. ASTM D4318: Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International 2017;04:1–14.

[22] Badan Standardisasi Nasional. SNI 1742:2008 Cara uji kepadatan ringan untuk tanah [SNI 1742:2008 Light density test method for soil]. Jakarta, Indonesia: 2008.

[23] Badan Standardisasi Nasional. SNI 1744:2012 Metode uji CBR laboratorium [SNI 1744:2012 Laboratory CBR test method]. Jakarta, Indonesia: 2012.

[24] Direktorat Jenderal Bina Marga. Spesifikasi Umum 2018 untuk Pekerjaan Konstruksi Jalan dan Jembatan, Revisi 2 [General Specifications 2018 for Road and Bridge Construction Works, Revision 2]. Jakarta, Indonesia: 2020.

[25] Bustamante J., Gallardo-Sepúlveda R., Atencio E., Parra P.F. Sensitivity Analysis of the Influence of Heavy-Intensity Rain Duration on the Stability of Granular Soil Slopes Under Unsaturated Conditions. Applied Sciences (Switzerland) 2025;15. https://doi.org/10.3390/app15116074

[26] James J., Pandian P.K. Industrial Wastes as Auxiliary Additives to Cement/Lime Stabilization of Soils. Advances in Civil Engineering 2016;2016. https://doi.org/10.1155/2016/1267391

[27] Simatupang M., Mangalla L.K., Edwin R.S., Putra A.A., Azikin M.T., Aswad N.H., Mustika W. The Mechanical Properties of Fly-Ash-Stabilized Sands. Geosciences (Basel) 2020;10:132. https://doi.org/10.3390/geosciences10040132

[28] Mohanty S., Roy N., Singh S.P., Sihag P. Effect of industrial by-products on the strength of stabilized dispersive soil. International Journal of Geotechnical Engineering 2021;15:405–17. https://doi.org/10.1080/19386362.2019.1654281

[29] Eisazadeh A., Kassim K.A., Nur H. Solid-state NMR and FTIR studies of lime stabilized montmorillonitic and lateritic clays. Appl Clay Sci 2012;67–68:5–10. https://doi.org/10.1016/j.clay.2012.05.006

[30] Yusuf M.O. Bond Characterization in Cementitious Material Binders Using Fourier-Transform Infrared Spectroscopy. Applied Sciences (Switzerland) 2023;13. https://doi.org/10.3390/app13053353

[31] Singhi B., Laskar A.I., Ahmed M.A. Investigation on Soil–Geopolymer with Slag, Fly Ash and Their Blending. Arab J Sci Eng 2016;41:393–400. https://doi.org/10.1007/s13369-015-1677-y

[32] Canakci H., Güllü H., Alhashemy A. Performances of using geopolymers made with various stabilizers for deep mixing. Materials 2019;12. https://doi.org/10.3390/ma12162542

[33] Latifi N., Eisazadeh A., Marto A., Meehan C.L. Tropical residual soil stabilization: A powder form material for increasing soil strength. Constr Build Mater 2017;147:827–36. https://doi.org/10.1016/j.conbuildmat.2017.04.115

[34] Abdila S.R., Abdullah M.M.A.B., Ahmad R., Rahim S.Z.A., Rychta M., Wnuk I., Nabiałek M., Muskalski K., Tahir M.F.M., Syafwandi, Isradi M., Gucwa M. Evaluation on the mechanical properties of ground granulated blast slag (GGBS) and fly ash stabilized soil via geopolymer process. Materials 2021;14:1–19. https://doi.org/10.3390/ma14112833

[35] Joshi A.R., Patel S. Fly ash blended with lime and GGBFS as sustainable subbase material: strength, durability, and microstructure assessment. Innovative Infrastructure Solutions 2023;9:7. https://doi.org/10.1007/s41062-023-01305-4

[36] Federal Highway Administration. Geotechnical Aspects of Pavements Reference Manual. Washington, DC, USA: 2006.

[37] Mostafa A.E.A., Eisa M., Ibrahim M.F. Effect of stabilizing subgrade layer using various additives on the flexible pavement design. Innovative Infrastructure Solutions 2024;9. https://doi.org/10.1007/s41062-024-01430-8

[38] Rohmatun, Suparma L.B., Rifa'i A., Rochmadi. Determination of Optimum Cement Content for Silty Sand Soil Stabilization as the Base Course. International Journal of GEOMATE 2024;26:124–33. https://doi.org/10.21660/2024.115.4215