Vol. 16 No. 2 (2025) 176-185

Jurnal Riset
Teknologi Pencegahan Pencemaran
Industri

Journal homepage: https://www.jrtppi.id

Mechanical Properties Improvement of Peat Soils Stabilized by Palm Oil Fuel Ash (POFA) based Geopolymer

Nurza Purwa Abiyoga[1], Dila Oktarise Dwina[2*], Oki Alfernando[3], Fiona Dehansa Putri[4]
[124]Department of Civil Engineering, Faculty of Science and Technology, Universitas Jambi, Indonesia
[3]Department of Chemical Engineering, Faculty of Science and Technology, Universitas Jambi, Indonesia

ARTICLE INFO

Article history:
Received September 10, 2025
Received in revised form October27, 2025
Accepted Novemeber 22, 2025
Available online Novemeber 19, 2025

Keywords:
Geopolymer
Unconfined Compression Strength
Palm Oil Fuel Ash
Peat

ABSTRACT

Peat soils are generally characterized by high water content, significant organic matter composition, and relatively low shear strength compared to mineral soils. These properties may lead to excessive settlement and reduced load-bearing capacity, which can affect the performance of foundations and embankments constructed on peat deposits. Extensive peatland areas can be found in Jambi, Indonesia and innovative stabilization methods are required to enhance their mechanical properties for sustainable land use. This study develops an alternative method of stabilization by using palm oil fuel ash (POFA) as a base material for geopolymerization. POFA, an industrial by-product, is abundant in Jambi and offers a sustainable alternative to highly polluting Portland cement. The research methodology involved the preparation of geopolymer-stabilized peat samples with 0%, 10%, 15%, and 20% to total dry weight of POFA addition, followed by Unconfined Compressive Strength (UCS) tests to assess the improvement in soil strength. The results indicate a positive trend with increasing compressive strength values as the geopolymer content increases to 15%. The average UCS results for the consecutive amount of POFA geopolymer addition are 15.10 kPa, 30.05 kPa, 37.90 kPa, and 9.71 kPa. In conclusion, using POFA-based geopolymer shows potential as an effective and sustainable solution for improving the strength characteristics of peat soils with a notable maximum amount of addition at 15%. This stabilization technique could provide a viable method for infrastructure development in peatland areas.

1. INTRODUCTION

In recent decades, chemical stabilization has been widely studied as an effective technique for improving peat soils. Many studies have attempted to use pozzolanic materials, especially Palm Oil Fuel Ash (POFA), due to its high silica and alumina content (Anda et al., 2021; Pei, Yang, Gui, Wang, & Zhang, 2022). The inclusion of POFA has shown potential in forming cementitious compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which can improve strength and durability of soil (Andriani, Novasari, & Putra, 2023; Muroby & Anwar Makarim, 2020). However, peat's high organic content and acidic pH significantly inhibit pozzolanic reactions, resulting in poor strength development, especially in early curing stages (Khanday, Hussain, & Das, 2021a). Researchers have also noted that POFA's effectiveness depends heavily on its physical properties, such as fineness and particle size, and on the curing-conditions applied (Dwina, Abiyoga, & Nurdin, 2024).

To overcome these limitations, several recent studies have turned to alkali activation or geopolymer technology as an alternative. Geopolymers are synthesized through the reaction of aluminosilicate

---

*Correspondence author.
E-mail: diladwina@unja.ac.id (Dila Oktarise Dwina)

doi: https://10.21771/jrtppi.2025.v16.no2.p176-185

Accreditation number: (Ristekdikti) 158/E/KPT/2021

materials with alkaline activators, producing amorphous polymeric gels such as sodium aluminosilicate hydrate (N-A-S-H) or calcium-containing gels like (C, N)-A-S-H. These gel products offer greater early strength and long-term performance under harsh chemical environments (Ambily, Ravisankar, Umarani, Dattatreya, & Iyer, 2014; Fu, Ye, Zhu, Fang, & Zhou, 2020). The application of geopolymer technology in peat soil stabilization remains relatively underexplored, particularly in the use of POFA as a geopolymer precursor. Preliminary studies suggest that incorporating POFA into a geopolymer matrix can improve reaction kinetics and binder formation compared to traditional pozzolanic reactions (Khanday, Hussain, & Das, 2021b). However, comprehensive data on the optimal dosage and strength behavior in peat environments is still limited, especially regarding unconfined compressive strength (UCS) as a performance indicator.

Despite growing interest in sustainable binders and agricultural waste utilization, limited attention has been paid to the use of POFA-based geopolymer systems specifically for peat soil stabilization. Most previous studies have focused either on conventional cementitious stabilization of peat or on geopolymer applications in mineral soils such as clay and laterite. As a result, the interaction between alkali-activated POFA binders and peat soils, which are characterized by high organic content and acidic conditions, remains insufficiently understood. In particular, few studies have systematically examined the influence of POFA content and activator composition on strength development in peat environments, especially with respect to early-stage unconfined compressive strength (UCS). Consequently, the optimal mixture design parameters for POFA-based geopolymers in peat stabilization have not been clearly established.

This study addresses this gap by experimentally evaluating the effect of varying POFA content within an alkali-activated geopolymer system on the unconfined compressive strength of stabilized peat soils. Unlike previous studies that primarily assessed conventional pozzolanic reactions, the present research investigates the geopolymerization mechanism within a peat matrix and examines its implications for early strength development, thereby contributing to a clearer understanding of mixture optimization for peat stabilization.

2. METHODS

This study employed a laboratory-based experimental approach to evaluate the effectiveness of alkali-activated POFA geopolymer in stabilizing peat soil. The research was structured into four main stages: material characterization, geopolymer formulation, specimen preparation and curing, and mechanical testing. To identify the optimal stabilization dosage, four POFA contents (0%, 10%, 15%, and 25%) were investigated, expressed as a percentage of the dry soil weight. The mass of the alkaline activator was excluded from this percentage.

The peat soil used in this study was collected from Tanjung Jabung Timur, Jambi Province, Indonesia. Its index properties are presented in Table 1. The soil exhibited a very high natural moisture content (511.70%) and organic matter content (88.54%), together with non-plastic behavior. In accordance with ASTM D2487 (USCS), soils exhibiting highly organic characteristics are classified as peat (*Pt*). The observed properties are consistent with this classification.

Table 1. Index properties of Tanjung Jabung Timur peat soil

No	Parameter	Peat

1	Moisture content (%)	511.70
2	Specific gravity	2.31
3	Sand (%)	28.43
4	Silt (%)	53.07
5	Clay (%)	18.50
6	Optimum moisture content (%)	78.04
7	Maximum dry density (kN/m3)	5.30
8	Liquid limit (%)	151.32
9	Plastic limit	Non-plastic
10	Organic matter (%)	88.54
11	Ash content (%)	11.46

Palm Oil Fuel Ash (POFA), obtained from PT Muara Jambi Lestari, was characterized using X-ray fluorescence (XRF) analysis. As shown in Table 2, POFA contains a high silicon (Si) content (approximately 48.95%), together with calcium (Ca), potassium (K), iron (Fe), and minor oxides. The reported values represent duplicate measurements. The presence of silica and alumina-bearing components indicates potential reactivity under alkaline activation, although the relatively high calcium content suggests that C–A–S–H type reaction products may also contribute to strength development.

Table 2. XRF Results of POFA from PT Muara Jambi Lestari

No	Elements	Sample 1 (%)	Sample 2 (%)
1	Si	48.95	48.37
2	Al	2.14	2.13
3	Ca	19.77	20.32
4	K	12.49	13.10
5	Fe	6.90	7.01
6	P	4.96	4.99
7	Mg	1.39	0.36
8	Cl	0.83	0.55

9	S	0.74	0.83
10	Ti	0.06	0.05
11	Mn	0.44	0.46
12	Cu	0.26	0.28
13	Rb	0.21	0.20
14	Zn	0.16	0.14
15	Sr	0.11	0.13
16	Zr	0.02	0.02
17	Ni	0.02	0.02
18	Cr	0.02	0.02
19	V	0.02	0.01
20	Sc	-	0.01

The alkaline activator was prepared using sodium silicate (Na2SiO3) and 12 M sodium hydroxide (NaOH) at a mass ratio of 1:2 (Na2SiO3:NaOH). The solutions were mixed and allowed to equilibrate for 24 hours prior to application. The activator solution was incorporated as part of the total mixing fluid and adjusted to achieve the target moisture condition corresponding to the soil's Optimum Moisture Content (OMC).

Prior to mixing, peat soil and POFA were oven-dried and sieved to remove oversized particles. The dry constituents were blended thoroughly to ensure homogeneity before gradual addition of the activator solution (Figure 1). The mixture was then immediately compacted into cylindrical specimens measuring 35.2 mm in diameter and 71 mm in height. The compaction was performed in three layers. For each mixture composition, three specimens were prepared. Specimen unit weight was controlled based on the Maximum Dry Density (MDD) and OMC obtained from compaction testing.

(a)

(b)

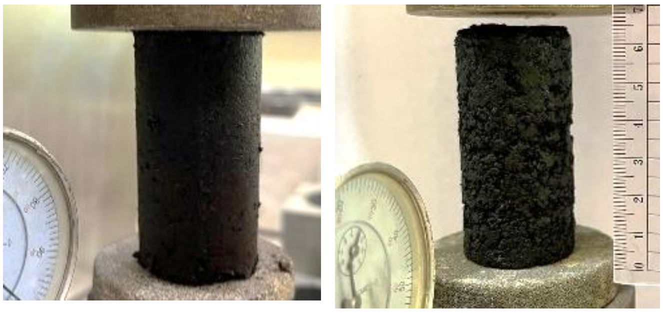
Figure 1 (a) Peat soil and POFA and **(b)** Activator (Na2SiO3 and NaOH)

Following molding, the specimens were sealed to prevent moisture loss and cured at ambient laboratory conditions (room temperature) for seven days. Upon completion of the curing period, Unconfined Compressive Strength (UCS) testing was performed in accordance with ASTM D2166. Strain-controlled axial loading was applied at a strain rate of 2% per minute.

To evaluate the mechanical response of the stabilized specimens, three parameters were derived from the stress–strain curves obtained during UCS testing: unconfined compressive strength (q_u), secant modulus at 50% of peak stress (E_{50}), and brittleness index (I_b). The coefficient of variation (*CV*) was maintained below 15%, indicating acceptable repeatability of the triplicate specimens. The unconfined compressive strength (q_u) was defined as the maximum axial stress sustained by the specimen prior to failure. The secant modulus (E_{50}) was calculated as the slope of the line connecting the origin to the point corresponding to 50% of the peak stress, representing the material stiffness within the pre-peak loading range. The brittleness index (I_b) was determined to quantify the relative reduction in strength after peak stress and to characterize the post-peak deformation behavior of the specimens. These parameters were used to assess the stress–strain characteristics of untreated and geopolymer-stabilized peat soils.

3. RESULT AND DISCUSSION

Figure 2 illustrates the physical appearance of peat specimens after stabilization with POFA-based geopolymer. All stabilized samples exhibited visible surface and internal pores, regardless of the POFA dosage. These pores appeared as small cavities scattered throughout the specimen body, with increasing prevalence observed at higher POFA content. The porous structure suggests that the stabilization process introduced changes not only in the chemical matrix but also in the physical integrity of the material.



(a) (b)

Figure 2 (a) natural condition specimen and **(b)** specimen with 15% addition of POFA-based geopolymer

Several factors may have contributed to this porosity. First, the high organic matter content (88.54%) and fibrous texture of peat soil hinder uniform binder distribution, limiting the interaction between the POFA geopolymer gel and the surrounding soil matrix. Organic compounds are known to interfere with gel bonding and disrupt the formation of a continuous solid phase, resulting in micro voids within the stabilized body (Amaludin, Asrah, & Mohamad, 2023). Second, the geopolymerization reaction itself releases heat and can cause localized drying or expansion during setting, which may lead to entrapped air bubbles or microcracking if the mix is not well-compacted. Additionally, peat's natural water retention capacity may have prevented uniform moisture redistribution during compaction, leading to insufficient densification of the samples during molding.

The presence of these pores has direct implications for the mechanical performance of the stabilized soil. Increased porosity reduces the effective contact area for load transfer, potentially lowering the unconfined compressive strength (q_u) and stiffness (E_{50}) of the specimens. Furthermore, micro voids may act as stress concentration zones, promoting brittle failure and reducing the energy absorption capacity of the material. This is consistent with the UCS results observed in this study, where specimens with higher visible porosity generally exhibited lower strength and stiffness values, especially at early curing stages.

The results of the unconfined compressive strength (UCS) tests are presented in Figure 3, with average UCS values for the 0%, 10%, 15%, and 25% POFA geopolymer mixtures recorded as 15.10 kPa, 30.05 kPa, 37.90 kPa, and 17.33 kPa, respectively. The coefficient of variation (*CV*) ranged from 3.06% to 11.59%, indicating acceptable repeatability of the triplicate specimens. The incorporation of POFA-based geopolymer significantly enhanced the strength of the peat soil, with the 15% mixture yielding the highest UCS, nearly 2.5 times greater than the untreated control. This result suggests that 15% is the optimal dosage for strength development under the given curing conditions (Figure 4).

The 10% mixture also exhibited improved strength, although it remained lower than the 15% dosage. Interestingly, the 25% mixture, while still higher than the untreated sample, showed a noticeable drop in strength compared to both 10% and 15%. This decline indicates that beyond a certain point, additional binder content does not contribute positively to strength and may even reduce it due to poor matrix formation or excessive porosity. Stress–strain curves for the representative samples are shown in Figure 3. The control sample (0%) displayed a brittle response, with a sharp peak followed by immediate loss of strength, characteristic of weak, fibrous peat. As POFA content increased, the curves began to shift, showing smoother ascents and broader peaks, particularly in the 10% and 15% specimens. These curves reflect increased ductility, with the 15% sample showing the widest deformation range before failure, indicating both high strength and moderate flexibility.

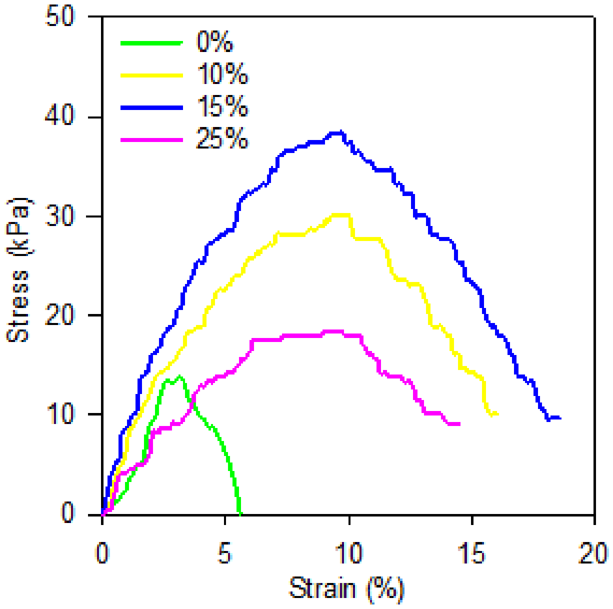


Figure 3 Stress-strain behavior of the test samples

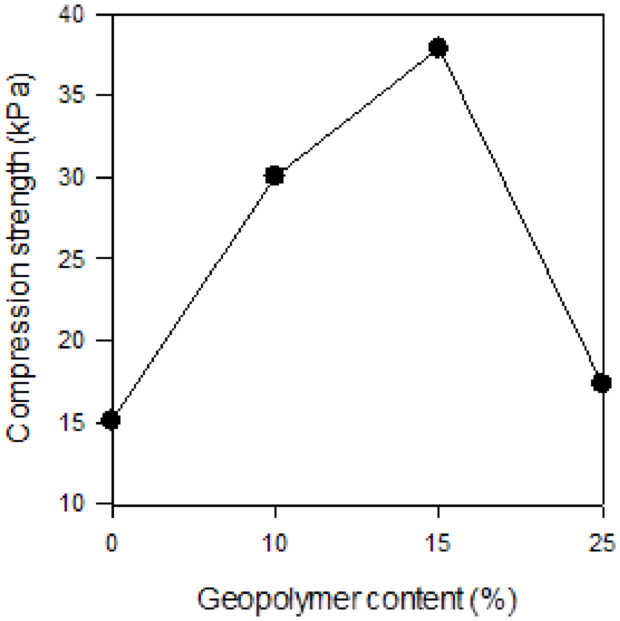


Figure 4 Compression strength development of stabilized peat soil

In contrast, the 25% sample exhibited a softening behavior, with a long, gradual curve and an extended strain at failure. This suggests a more ductile failure mode, likely resulting from the formation of micro voids or interparticle gaps due to excess geopolymer paste. As higher binder content can hinder uniform packing and introduce internal defects, it leads to a more flexible but structurally weaker matrix (Elangbam & Kalita, 2024; Jwaida, Dulaimi, Mashaan, & Othuman Mydin, 2023). Similar trends have been observed in geopolymer-treated soft soils, where increased binder concentrations reduce material brittleness but compromise strength (Khanday, Hussain, & Das, 2023).

Figure 5 illustrates the changes in secant modulus (E_{50}), representing material stiffness. A consistent increase in E_{50} was observed from 400.23 kPa (0%) to 709.37 kPa (15%), confirming that moderate POFA addition enhances the soil's resistance to deformation. However, at 25% POFA content, E_{50} sharply decreased to 164.49 kPa, indicating that excessive geopolymer weakens the structural integrity of the composite. Failure modes observed during UCS testing also varied between mixtures. The 0% and 25% specimens typically exhibited ductile shear failure, where the sample deformed extensively before failure.

The 10% and 15% specimens displayed more brittle or splitting failure, characterized by sudden cracking and limited lateral bulging. These observations reinforce the interpretation that 15% POFA geopolymer yields the best balance between stiffness, strength, and deformability.

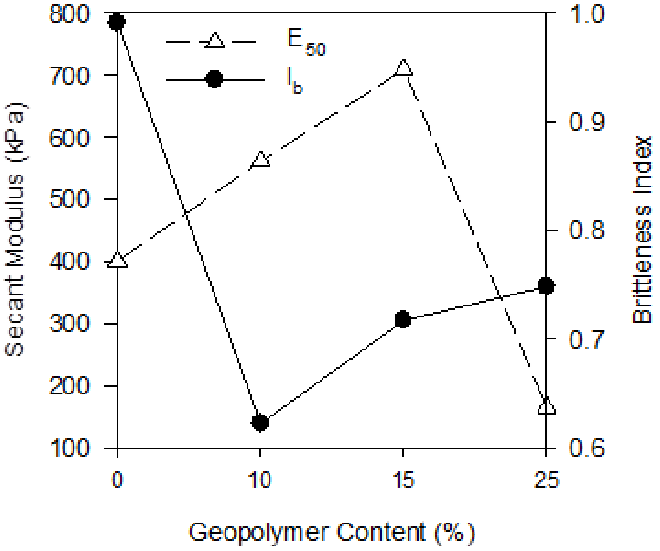


Figure 5 Mechanical behavior of the test samples

The brittleness index (I_b) results revealed distinct patterns in the deformation characteristics of the peat–geopolymer composites. The untreated peat sample (0% POFA) recorded a high I_b value of 0.991, indicating a highly brittle behavior with minimal post-peak deformation. Upon the addition of 10% POFA geopolymer, I_b dropped sharply to 0.622, reflecting a significant improvement in ductility. This change suggests that at moderate geopolymer dosage, the binder enhances internal cohesion and allows for greater strain accommodation before failure. However, as the POFA content increased further, the Ib value rose again to 0.717 at 15% and 0.748 at 25%, indicating a partial return toward brittle behavior. This nonlinear trend implies that while a moderate amount of geopolymer promotes ductile response, excessive binder may reduce this benefit due to changes in the microstructural arrangement of the composite.

The observed behavior can be attributed to several microstructural mechanisms. At 10% POFA, the geopolymer matrix likely fills the voids between peat particles efficiently, forming a cohesive but flexible network. The moderate gel formation may help bridge fibers and particles without over-stiffening the structure, allowing for controlled deformation under stress. At higher dosages (15% and especially 25%), the increased geopolymer content may lead to excessive gel formation and unreacted binder residue, which disrupts the continuity of the soil matrix. This may result in the development of internal microcracks, voids, or weak interfaces due to incomplete bonding or thermal shrinkage during curing. These defects can localize stress and trigger early cracking, thereby increasing the brittleness index. Furthermore, the dense gel matrix might limit the ability of the composite to redistribute stress, reducing its capacity for plastic deformation.

Therefore, the rise in I_b at higher POFA content can be interpreted as a shift from an optimally compacted and flexible matrix to a more rigid and flaw-sensitive structure. This finding aligns with the observed reduction in E_{50} at 25% POFA and supports the conclusion that 15% POFA geopolymer represents an optimal balance, not only in strength but also in post-peak behavior and ductility.

As shown in Table 3, the unit weight of all specimens remained relatively constant, ranging from 0.961 to 0.964 g/cm³ regardless of POFA geopolymer content. This uniformity suggests that geopolymer addition does not significantly influence the bulk density or compaction of the treated soil. Therefore, the observed improvements in mechanical properties are likely due to chemical and microstructural changes rather than variations in physical mass or volume (Ghadir & Ranjbar, 2018).

Table 3. Unit weight and moisture content of tested specimen after curing

No	Geopolymer content (%)	Unit weight (g/cm^3)	Moisture content (%)

1	0	0.964	70.905
2	10	0.961	46.112
3	15	0.962	39.343
4	25	0.961	37.652

In contrast, the moisture content decreased noticeably with increasing POFA geopolymer dosage—from 70.91% (0%) to 37.65% (25%). This reduction can be attributed to the high reactivity and fine particle size of POFA, which increases water demand during geopolymerization. The alkaline activator promotes the dissolution of silica and alumina, consuming free water in the process and forming stable gels such as N-A-S-H and C-S-H, which trap water within their structure. Additionally, the enhanced interparticle bonding from the geopolymer matrix likely reduces the number of free voids and hygroscopic organic bonds, thereby lowering the soil's overall moisture retention (Wassie, Demir, & Köktan, 2023).

These findings imply that moisture reduction is a key mechanism through which POFA-based geopolymers improve peat soil behavior, contributing to both strength gain and reduced deformability. Future microstructural studies (e.g., SEM or XRD) could offer deeper insight into water-binding phases and pore structure evolution during stabilization.

4. CONCLUSION

This study demonstrates that alkali-activated POFA geopolymer substantially improves the early-stage mechanical performance of peat soil. The unconfined compressive strength increased from 15.10 kPa (untreated) to 37.90 kPa at 15% POFA, representing a 151% strength enhancement within 7 days of curing. Stiffness similarly improved, with E_{50} increasing from 400.23 kPa to 709.37 kPa, indicating enhanced resistance to deformation. In addition to strength gain, moderate POFA incorporation reduced brittleness (I_b decreased from 0.991 to 0.622 at 10%), demonstrating improved ductility and more stable post-peak behavior. However, excessive POFA content (25%) led to reduced strength and stiffness, confirming that performance is highly dosage-dependent.

Compared with conventional pozzolanic stabilization approaches reported in previous studies, which often exhibit limited early strength development in high-organic peat, the geopolymer system used in this study promotes faster reaction kinetics through alkali activation, resulting in superior early strength and stiffness enhancement. These findings indicate that optimized POFA-based geopolymer stabilization is a promising approach for road subgrade improvement on soft organic soils, although long-term durability and microstructural validation remain to be investigated.

ACKNOWLEDGMENT

The authors would like to express sincere gratitude to Universitas Jambi for the financial support provided through its research funding program. This support has been instrumental in the successful completion of this research.

REFERENCE

Amaludin, A. E., Asrah, H., & Mohamad, H. M. (2023). A Review of Advances in Peat Soil Stabilisation Technology: Exploring the Potential of Palm Oil Fuel Ash Geopolymer as a Soil Stabiliser Material. *Civil Engineering Journal*, *9*(8), 2085–2104. https://doi.org/10.28991/CEJ-2023-09-08-017

Ambily, P. S., Ravisankar, K., Umarani, C., Dattatreya, J. K., & Iyer, N. R. (2014). Development of ultra-high-performance geopolymer concrete. *Magazine of Concrete Research*, *66*(2), 82–89. https://doi.org/10.1680/macr.13.00057

Anda, M., Ritung, S., Suryani, E., Sukarman, Hikmat, M., Yatno, E., … Husnain. (2021). Revisiting tropical peatlands in Indonesia: Semi-detailed mapping, extent and depth distribution assessment. *Geoderma*, *402*, 115235. https://doi.org/10.1016/j.geoderma.2021.115235

Andriani, Novasari, H., & Putra, H. G. (2023). Improvement of subgrade on peat soil using laterite soil and cement. In *AIP Conference Proceedings* (p. 070021). https://doi.org/10.1063/5.0119156

Dwina, D. O., Abiyoga, N. P., & Nurdin, A. (2024). Palm Oil Fuel Ash Fineness in Modifying CBR Characteristics of Peat Soil. *Bentang : Jurnal Teoritis Dan Terapan Bidang Rekayasa Sipil*, *12*(2), 202–210. https://doi.org/10.33558/bentang.v12i2.9598

Elangbam, T., & Kalita, A. (2024). Comparative Study of Different Stabilizers for Peat Soil Stabilization: A Review (pp. 377–391). https://doi.org/10.1007/978-3-031-39663-2_31

Fu, C., Ye, H., Zhu, K., Fang, D., & Zhou, J. (2020). Alkali cation effects on chloride binding of alkali-activated fly ash and metakaolin geopolymers. *Cement and Concrete Composites*, *114*, 103721. https://doi.org/10.1016/j.cemconcomp.2020.103721

Ghadir, P., & Ranjbar, N. (2018). Clayey soil stabilization using geopolymer and Portland cement. *Construction and Building Materials*, *188*, 361–371. https://doi.org/10.1016/j.conbuildmat.2018.07.207

Jwaida, Z., Dulaimi, A., Mashaan, N., & Othuman Mydin, M. A. (2023). Geopolymers: The Green Alternative to Traditional Materials for Engineering Applications. *Infrastructures*, *8*(6), 98. https://doi.org/10.3390/infrastructures8060098

Khanday, S. A., Hussain, M., & Das, A. K. (2021a). A Review on Chemical Stabilization of Peat. *Geotechnical and Geological Engineering*, *39*(8), 5429–5443. https://doi.org/10.1007/s10706-021-01857-1

Khanday, S. A., Hussain, M., & Das, A. K. (2021b). Rice Husk Ash–Based Geopolymer Stabilization of Indian Peat: Experimental Investigation. *Journal of Materials in Civil Engineering*, *33*(12). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003982

Khanday, S. A., Hussain, M., & Das, A. K. (2023). Ground-Granulated Blast Furnace Slag-Based Geopolymer-Treated Fibrous Peat (pp. 409–418). https://doi.org/10.1007/978-981-19-4055-2_32

Muroby, V., & Anwar Makarim, C. (2020). Design alternative on peat soil. *IOP Conference Series: Materials Science and Engineering*, *1007*(1). https://doi.org/10.1088/1757-899X/1007/1/012178

Pei, L., Yang, X., Gui, Y., Wang, Z. C., & Zhang, Y. (2022). Influence of Organic Matter Content and Ingredient on The Physical and Mechanical Properties of Peat Soils. *Hydrogeology & Engineering Geology*, *49*(2), 77–85.

https://doi.org/http://dx.doi.org/10.16030/j.cnki.issn.1000-3665.202106009

Wassie, T. A., Demir, G., & Köktan, U. (2023). Influence of Curing Time and Initial Moisture Content on Metakaolin-Based Geopolymer-Stabilized Soft Soil. *Advances in Civil Engineering*, *2023*, 1–11. https://doi.org/10.1155/2023/6673716