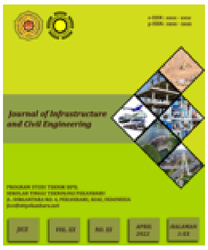
JICE - Journal of Infrastructure and Civil Engineering
Vol. 6, No. 2, (Jul, 2026),
pp. 164-173

Article submitted : 09 06 2026
Review accepted : 18 07 2026
Online Published : 20 07 2026

JICE
JOURNAL OF INFRASTRUCTURE AND CIVIL ENGINEERING
Web: http://jice.sttp-yds.ac.id/index.php/jice/index
ISSN: 2809-5030 (online) 2809-5227 (print)



Modification of Clay Soil Permeability Using Palm Shell Ash for Road Subgrade Improvement

Debby Endriani[1*], Nova Juliana[2], Nor Faizah Bawadi[3]

[1]*Department of Civil Engineering, Universitas Pembinaan Masyarakat Indonesia*
[2]*Department of Civil Engineering, Politeknik Negeri Medan*
[3]*Department of Civil Engineering, Universiti Malaysia Perlis*

*debby@upmi.ac.id

Abstract

The subgrade in Paloh 80, Tanjung Rejo Village, Percut Sei Tuan District, Deli Serdang Regency, is a fine-grained clay with low stability, making it unsuitable for use as a road subgrade without stabilization. Therefore, stabilization efforts are needed to improve its technical properties. This study aims to analyze the effect of adding palm shell ash (ACS) on changes in the permeability coefficient of clay soil. The research method used is a laboratory experiment with variations in ACS mixtures at 0%, 4%, 6%, 8%, 10%, and 12% of the soil's dry weight under optimum water-content conditions. The stabilization process involves mixing clay soil with palm shell ash in varying proportions, followed by testing in accordance with ASTM standards, specifically the falling-head permeability test. The results show that adding palm shell ash significantly reduces the permeability coefficient of clay soil. The original soil permeability value of 8.339 × 10^{-8} cm/s decreased to 4.355 × 10^{-8} cm/s in the 12% mixture. This decrease was caused by the palm shell ash filler, which filled soil pore spaces, thereby inhibiting water flow. The results showed that the addition of ACS significantly reduced the permeability coefficient of clay soil. The original soil permeability value of 8.339 × 10^{-8} cm/s decreased to 4.355 × 10^{-9} cm/s in the 12% mixture. This decrease was caused by the ACS filler, which filled soil pore spaces, thereby inhibiting water flow. Thus, palm shell ash has potential as an environmentally friendly stabilization material to improve the quality of road subgrades.

Keywords: *clay soil, palm shell ash, soil stability, permeability, road subgrade*

1. Introduction

Clay soil is commonly found in Indonesia and is often used as a base for road construction [1]. However, soil conditions at each location vary greatly because soil is a complex, heterogeneous natural material with different mechanical properties, including less favorable technical properties such as high plasticity, low bearing capacity, and permeability that is very sensitive to changes in pore structure [2]. This condition can damage the overlying construction, especially road pavements, which are characterized by cracks, surface waves, and excessive deformation [3].

The clay soil used in this research came from Tanjung Rejo, Percut Sei Tuan District, Deli Serdang Regency. The soil at this location is fine-grained and has a highwater content, resulting in low stability, so it does not qualify as a road subgrade. If used directly as a road subgrade, road construction performance will decline due to low bearing capacity and high potential for water seepage. Therefore, soil improvement or stabilization methods are required to enhance its physical and mechanical properties, making it suitable for use as a road subgrade material [4].

Various stabilization methods have been developed, using cement, lime, and fly ash. Previous research shows that using cement as a stabilizing material can increase the unconfined compressive strength and bearing capacity of soil, while natural pozzolanic materials can improve its hydraulic properties [5]. However, studies on the use of palm kernel shell ash (ACS), one of the most abundant solid wastes from the palm oil industry in North Sumatra, remain relatively limited, particularly regarding its effects on the permeability of clay soil. The use of palm shell ash is expected to improve soil hydraulic properties while supporting the green construction concept [6]. This research focuses on the analysis of changes in the permeability coefficient of clay soil due to the addition of palm shell ash as a road subgrade stabilization material. In addition, previous research generally focuses more on shear strength parameters or CBR values, while soil hydraulic properties, especially the permeability coefficient, have received little attention [7].

Based on these conditions, this study proposes using palm kernel shell ash as a stabilization material for clay soil, with a focus on modifying soil permeability to improve road subgrade performance. This material selection is based not only on local potential and the sustainability of waste utilization, but also on reducing water seepage, which can degrade road pavement performance. Therefore, this research is expected to contribute to soil stabilization technology based on local materials while supporting more sustainable road infrastructure development.

2. Literature Review

2.1. Clay Soil

Clay soil is defined as a group of fine-grained soil particles dominated by clay minerals such as kaolinite, illite, and montmorillonite, which have high plasticity and low permeability. This behavior is due to a chemical process that changes the mineral composition of the original rock, caused by water containing alkali, oxygen, and carbon dioxide. According to Geotechnical Engineering, clay soil behavior is strongly influenced by changes in water content, leading to significant volume changes (shrink-swell behavior), and it is cohesive [8]. Whereas [9] explains that clay soil has low bearing capacity and is very sensitive to changes in environmental conditions, especially water content. This behavior makes clay soil less than ideal for use as a base material for road pavements without improving its technical properties [10]. In the Unified Soil Classification System (USCS), clay soils with medium to high plasticity are generally classified as CL or CH, which exhibit high compressibility and very low permeability.

2.2. Palm Kernel Shell Ash (Palm Shell Ash)

Palm kernel shell ash is a waste product of the palm oil industry's biomass combustion, containing silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). This material has pozzolanic properties. Which, when reacted with free lime or calcium hydroxide ($Ca(OH)_2$) and water, will form cement material, namely calcium silicate hydrate ($C - S - H$), which plays a role in increasing soil strength [11]. According to Construction Materials Engineering research, biomass-based ash, such as palm shell ash, has the potential as a cement substitute material in various geotechnical and concrete applications [12].

Palm shell ash has chemical elements that can be used as a pozzolan, and has the potential to be used as a cement substitute, as shown in Table 1 below:

.

Table 1. Composition of Palm Kernel Shell Ash

Chemical Composition	Palm Shell Ash (%)
Silica (SiO_2)	66.3
Aluminum (AI_2O_3)	18.8
Iron (Fe_2O_3)	4.0
Calcium Oxide (CaO)	3.96
Magnesium Oxide (MgO)	2.8

Source: Physics Lab, State University of Medan (2022)

Several recent studies have shown that palm shell ash has potential as a stabilization material for clay soils, particularly in improving the physical and mechanical properties of the soil. The addition of palm oil waste-based materials has been shown to reduce soil plasticity due to a reduction in the plasticity index through changes in soil structure [13]. In addition, palm shell ash also increases soil density because its fine particles fill the pore spaces (filler effect), so that the soil structure becomes denser and more stable [14]. Thus, the use of palm shell ash not only improves the geotechnical parameters of the soil but also supports the concept of environmentally friendly materials based on a circular economy in civil engineering construction [15].

2.3. Soil Stabilization

Soil stabilization is a geotechnical engineering effort to improve the physical and mechanical properties of soil to meet technical construction requirements. According to Soil Stabilization, stabilization methods can be mechanical, chemical, or a combination of both. Chemical stabilization with cement and lime is the most common method used to increase soil bearing capacity [16]. However, the use of cement has environmental limitations due to its high carbon emissions. In recent years, approaches to soil stabilization have shifted to the concept of "green stabilization," which involves the use of industrial waste materials as a more environmentally friendly alternative stabilization material [17].

Soil stabilization using palm shell ash occurs because fine ash particles fill the soil's pore spaces, reducing the empty spaces between soil particles, which causes a decrease in soil permeability, known as the filler effect. A pozzolanic reaction occurs because silica from palm shell ash reacts with calcium hydroxide to form calcium silicate hydrate, which improves the bond between soil particles. According to the journal Sustainable Construction Materials [18]. This mechanism contributes to increasing soil stability as well as reducing deformation due to loads.

2.4. Soil Permeability

Soil permeability is the soil's ability to transmit water through its pores. According to Darcy's Law, the rate of water flow in soil is directly proportional to the permeability coefficient and the hydraulic gradient. Toyeb, in his research, stated that fine-grained soil, such as clay, has very low permeability because its pores are small and its structure is dense [19]. Changes in soil structure due to stabilization will affect permeability, with increasing soil density generally decreasing the permeability. The permeability coefficient is obtained from a laboratory permeability test to determine the amount of penetration in the soil, and the stabilizer is used as a stabilization material, using two falling-height values and a constant height [20].

3. Research Methodology

This study uses an experimental method in the laboratory with the aim of analyzing changes in the hydraulic properties of clay soil after stabilization using palm kernel shell ash (ACS). All test implementation procedures refer to ASTM (American Society for Testing and Materials) standards.

3.1. Research Location and Materials

The soil samples used were from Tanjung Rejo Village, Percut Sei Tuan District, Deli Serdang Regency, which is known to have clay soil characteristics with high water content and low bearing capacity. The stabilizing material used was palm kernel shell ash (ACS), obtained from solid waste from the PT. Multi Agro Sumatera Palm Oil Processing Factory. Before use, the ACS was tested for its chemical content at the Chemistry Laboratory of Medan State University to ensure the mineral content, such as SiO_2, Al_2O_3, Fe_2O_3, and CaO.

3.2. Mixed Variations

Clay soil was stabilized by adding palm shell ash at the optimum moisture content. The mixtures used varied in concentrations of 0%, 4%, 6%, 8%, 10%, and 12% of the soil's dry weight.

3.3. Soil Characteristics Testing

The physical and mechanical characteristics of the soil were determined through a series of laboratory tests conducted at the Civil Engineering Laboratory of the Medan State Polytechnic. These tests include: soil physical properties tests, including natural water content (ASTM D2216), specific gravity (ASTM D854), Atterberg limits (ASTM D4318), and grain analysis (ASTM D422). While mechanical tests include compaction tests using the Standard Proctor method (ASTM D698) to determine the optimum water content (OMC) and maximum dry unit weight (MDD), permeability tests were conducted using the falling head method (ASTM D5084) to obtain the permeability coefficient (k) value.

4. Results and Discussion

4.1. Physical Properties of Native Soil

Testing of the physical properties of clay soil based on the results of research conducted at the Soil Mechanics Laboratory of the Medan State Polytechnic. The results obtained for water content, specific gravity, sieve analysis, Atterberg, and dry unit weight as in Table 2 below:

With a percentage passing sieve No. 200 of 89.74% (>50%), this soil is classified as fine-grained soil according to the USCS classification, in the CL group, and in the A-7-5 group according to AASHTO. This condition indicates that the soil has medium-high plasticity and low bearing capacity, so it requires improvement for use as a road subgrade.

.

Table 2. Results of Testing the Physical Properties of Native Soil

Native Soil	Value (%)
Water content	75.34
Specific gravity	2.65
Sieve Analysis No. 200	89.74
Liquid Limit (LL)	53.98
Plastic Limit (PL)	35.65
Shrinkage Limit (SL)	32.24
Plastic Index (PI)	18.33
Dry Bulk Weight	1.27

4.2. Mechanical Properties of Native Soil and Palm Shell Ash Mixture

The results of the compaction test on the addition of palm shell ash, which obtained optimum water content and maximum dry unit weight, can be seen in Table 3.

Table 3. Compaction Test Results on Addition of Palm Shell Ash

Mixed Variations	Optimum Water Content (%)	Dry Volume Weight (gr/cm^3)
100% Original Soil	42.00	1.25
Soil 96% + Palm Shell Ash 4%	40.40	1.26
Soil 94% + Palm Shell Ash 6%	37.30	1.28
Soil 92% + Palm Shell Ash 8%	35.60	1.29
Soil 90% + Palm Shell Ash 10%	32.90	1.30
Soil 88% + Palm Shell Ash 12%	29.20	1.32

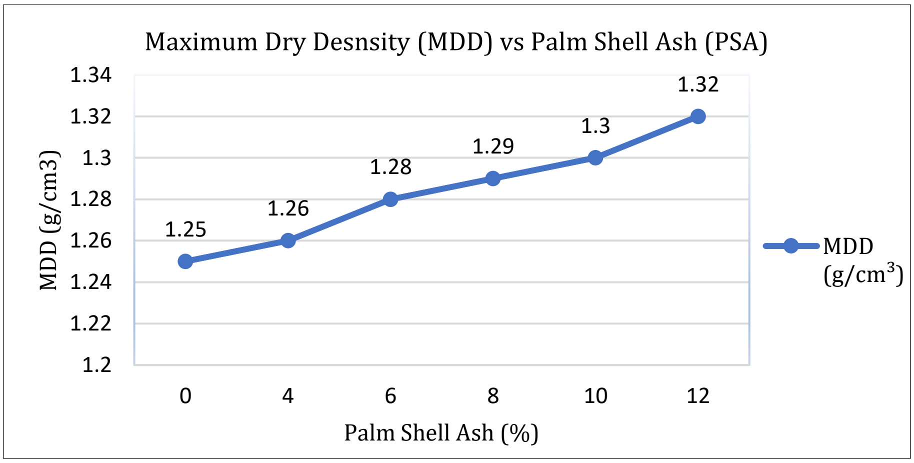


Figure 1. Graph of The Relationship Between Maximum Dry Density (MDD) and Palm Shell Ash (PSA)

The addition of variations in palm shell ash can increase the maximum soil density, as measured by γd max, from 1.25 g/cm3 in the original soil to 1.32 g/cm^3 in the 12% palm shell ash variation. The increase in the maximum dry unit weight value indicates that the mixture of soil and palm shell ash can form a denser and more compact particle arrangement after being stabilized. Geotechnically, denser soils generally have a smaller pore volume.

.

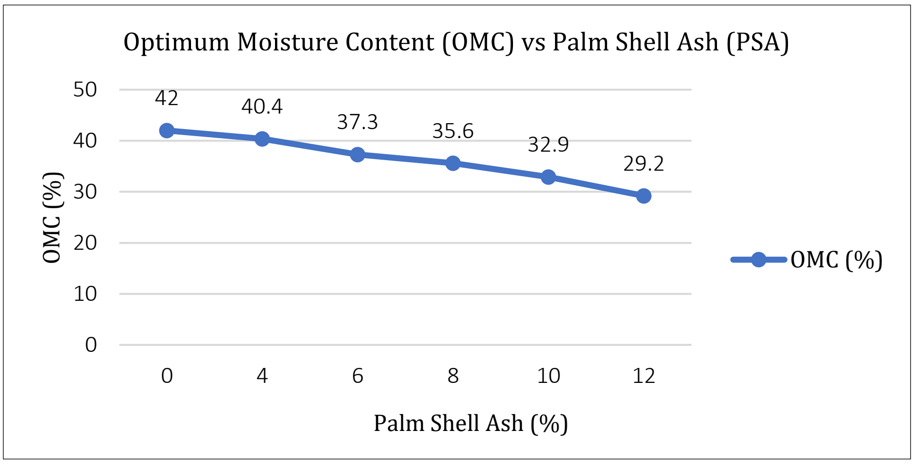


Figure 2. Graph of the relationship between Optimum Moisture Content (OMC) and Palm Shell Ash (PSA)

Furthermore, the optimum moisture content decreased from 42% in the original soil to 29.20% in the 12% palm kernel shell ash variation. This decrease in Optimum Moisture Content (OMC) indicates that the mixture requires less water to achieve maximum compaction. In soil improvement, this condition is beneficial because the soil achieves better density with less water requirement. The decrease in Optimum Moisture Content (OMC) along with the increase in Maximum Dry Density (MDD) strengthens the indication that the clay soil structure becomes more stable after the addition of palm kernel shell ash.

4.3. Effect of Palm Shell Ash on Permeability

The water seepage value in mixed soils is shown in Table 4. The higher the palm shell ash content, the less water seeps in. The processing time for each variation is 24 hours. The results of the permeability test using the seepage method are shown in Table 4:

Table 4. Permeability Test Results on Addition of Palm Shell Ash

Percentage	Time (hours)						Average (ml)	Total Decrease 4-24 hours (ml)	Decline (%)
	4	8	12	16	20	24			
	Seepage Water (ml)								
0%	1930	1779	1591	1407	1221	983	1485	947	49.07%
4%	1857	1724	1565	1370	1152	922	1432	935	50.35%
6%	1761	1641	1487	1310	1097	835	1355	926	52.58%
8%	1551	1433	1295	1117	918	695	1168	856	55.19%
10%	1319	1183	1037	861	649	434	914	885	67.10%
12%	1084	1003	877	740	579	371	776	713	65.77%

Based on the 24-hour test and observation results in the table above, the amount of seepage water in the clay soil showed a significant decrease as the percentage of palm shell ash increased. Throughout the observation period, the original soil sample or a variation of 0% produced the greatest amount of seepage water. Conversely, the soil mixture with the highest percentage of palm shell ash, 12%, produced the lowest amount of seepage water. This percentage indicates that the addition of palm shell ash has an effect on reducing the soil's ability to drain water. The relationship between the addition of palm shell ash and the amount of seepage water can be seen in Figure 3.

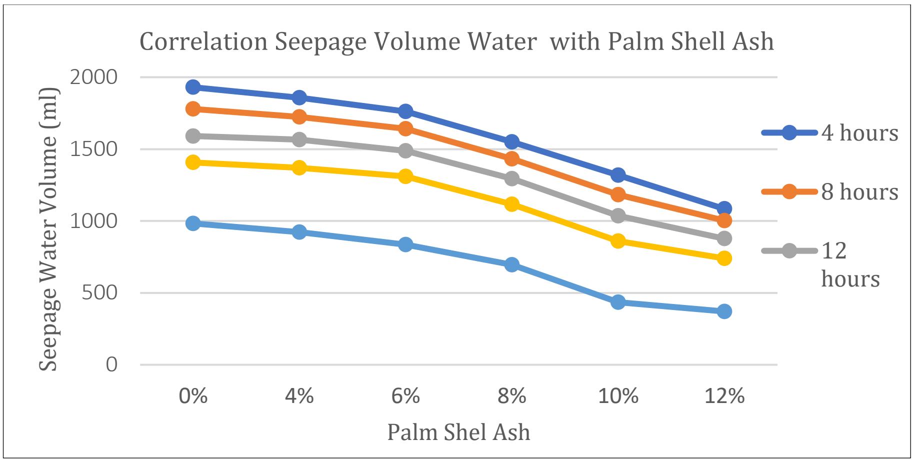


Figure 3. Graph of the relationship between Seepage Water Volume and Palm Shell Ash (PSA)

It can be seen that the higher the percentage of palm shell ash mixture, the lower the volume of water that seeps. During the 24-hour observation period, the original soil produced 983 ml of seepage water, while the 12% palm shell ash mixture only produced 371 ml. Thus, the 12% palm shell ash mixture was able to reduce seepage water by 612 ml compared to the original soil or around 62.26%. These results indicate that palm shell ash plays a role in reducing the water flow path in the soil. Furthermore, the relationship between observation time and permeability testing for seepage water can be seen in Figure 4.

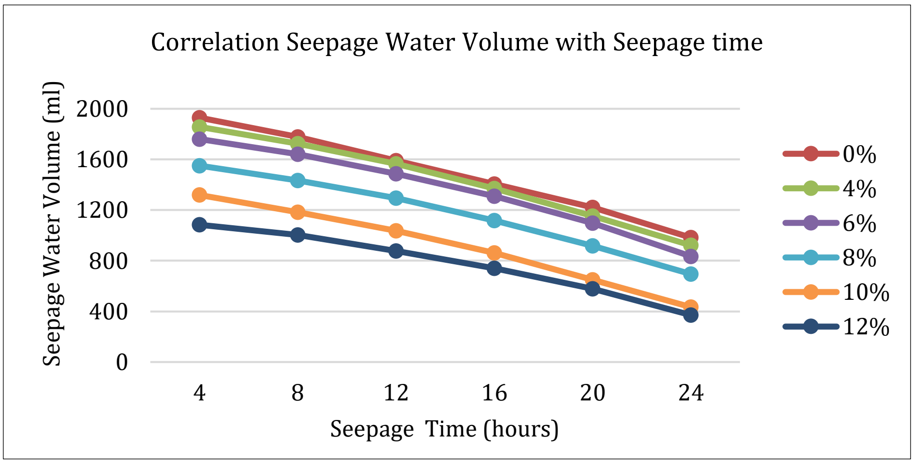


Figure 4. Graph of The Relationship Between Seepage Water Volume and Seepage Time

The image above shows that for each percentage variation in the palm shell ash mixture, the amount of seepage water decreased from 4 hours to 24 hours. This change indicates that the seepage rate is not constant but tends to decrease with increasing observation time. This decrease may occur because water flows through the increasingly saturated soil pore structure, especially in clay soils with very fine pore sizes. Several studies also confirmed that this increase in density contributes to a significant decrease in clay soil permeability because water flow paths become more obstructed [19].

4.4. Addition of Palm Shell Ash to the Permeability Coefficient Value

The results of the permeability coefficient test are shown in Table 5.

Table 5. Results of Permeability Coefficient Against the Addition of Palm Shell Ash

No.	Sample Type	Permeability Coefficient (k) (cm/second)
1	Native Land	8.33×10^{-8}
2	Soil + Palm Kernel Shell Ash 4%	8.03×10^{-8}
3	Soil + Palm Kernel Shell Ash 6%	7.59×10^{-8}
4	Soil + Palm Kernel Shell Ash 8%	6.55×10^{-8}
5	Soil + Palm Shell Ash 10%	5.08×10^{-8}
6	Soil + Palm Shell Ash 12%	4.35×10^{-8}

The table above shows that the permeability coefficient decreases significantly with increasing palm kernel shell ash content. At 12%, the k value decreases by 42,6% compared to the original soil. Of all tested samples, the permeability coefficient of the mixed soil is lower than that of the original soil, as shown in the following figure:

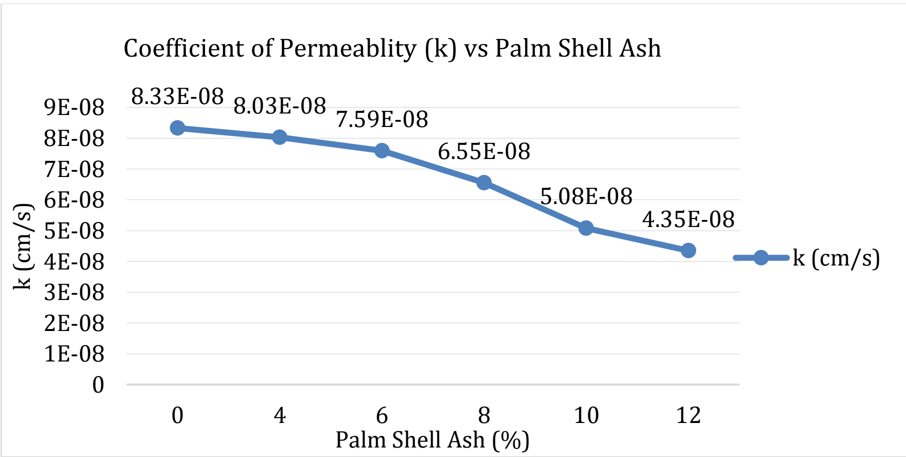


Figure 5. Graph of Coefficient Values in Clay Soil Against Seepage Time

The graph of the permeability coefficient value against seepage time shows that each mixture variation has a different level of permeability. The k value in the graph is displayed as a value that represents each mixture variation during the observation period of 4 to 24 hours. This value indicates that the permeability value of the mixed soil is lower because the palm shell ash can fill the soil cavities, so that the soil's ability to pass water is reduced. According to Darcy's law, flow velocity is directly proportional to the permeability coefficient, so the lower the k value, the better the soil's stability against water seepage.

5. Conclusion

The addition of palm oil shell ash has been shown to reduce the permeability coefficient of the clay soil in the Paloh 80 road subgrade. The permeability of the untreated soil, initially 8.339×10^{-8} cm/s, decreased progressively to 4.355×10^{-9} cm/s upon the addition of a 12% palm oil shell ash mixture. This reduction occurred because the fine palm oil shell ash particles filled the soil voids, thereby impeding water flow. Consequently, the higher the percentage of added palm oil shell ash, the lower the soil permeability. Palm oil shell ash has the potential to serve as an eco-friendly stabilization material for improving the quality of road subgrades.

References

[1] N. R. D. Athifah, "Tingkat Pengembangan Tanah Ekspansif yang Diperkuat dengan Geosintetik." Universitas Hasanuddin Makassar, 2024.

[2] A. Sabilla and C. S. R. Hildayani, "Klasifikasi Tanah Lempung Berdasarkan Sistem Uscs (Unified Soil Classification System) Dan Aashto (American Association of State Highway and Transportation Officials)," *J. Plan. Res. Civ. Eng.*, vol. 4, no. 3, pp. 737–745, 2025.

[3] H.-P. Wang, Y.-X. Guo, M.-Y. Wu, K. Xiang, and S.-R. Sun, "Review on structural damage rehabilitation and performance assessment of asphalt pavements," *Rev. Adv. Mater. Sci.*, vol. 60, no. 1, pp. 438–449, 2021.

[4] D. Barman and S. K. Dash, "Stabilization of expansive soils using chemical additives: A review," *J. Rock Mech. Geotech. Eng.*, vol. 14, no. 4, pp. 1319–1342, 2022.

[5] H.-D. Do, V.-N. Pham, H.-H. Nguyen, P.-N. Huynh, and J. Han, "Prediction of unconfined compressive strength and flexural strength of cement-stabilized sandy soils: a case study in Vietnam," *Geotech. Geol. Eng.*, vol. 39, no. 7, pp. 4947–4962, 2021.

[6] D. Endriani, "XRD, XRF and SEM Test Results," Sumatera Utara, 2022.

[7] Y. Apriyanti and F. Fahriani, "Pengaruh Penambahan Limbah Abu Cangkang sawit (POFA) Terhadap Nilai California Bearing Ratio (CBR) Untuk Stabilisasi Tanah Lempung," in *FROPIL (Forum Profesional Teknik Sipil)*, 2020, vol. 8, no. 2, pp. 102–109.

[8] E. Seyrek, "Engineering Behavior of Clay Soils Stabilized with Class C and Class F Fly Ashes," *IEEE J. Sel. Top. Quantum Electron.*, vol. 25, no. 2, pp. 273–287, 2018, doi: 10.1515/secm-2016-0084.

[9] B. M. Das, *Principles of geotechnical engineering*. Cengage learning, 2021.

[10] P. Lindh and P. Lemenkova, "Geotechnical properties of soil stabilized with blended binders for sustainable road base applications," *Constr. Mater.*, vol. 3, no. 1, pp. 110–126, 2023.

[11] D. Endriani, *Inovasi Limbah Padat Abu Cangkang Sawit Sebagai Material Perkerasan Jalan*, 1st ed. Kota Medan: Deepublish, 2023.

[12] R. Demirboga and K. Z. Farhan, "Palm oil fuel ash (POFA)," in *Sustainable Concrete Made with Ashes and Dust from Different Sources*, Elsevier, 2022, pp. 279–330.

[13] K. A. Rahma, K. Prihatin, and R. Ahmad, "Pengaruh Penambahan Abu Cangkang Kelapa Sawit Terhadap Sifat Fisik dan Mekanik Tanah Lempung," *J. INERSIA*, vol. 15, no. 1, pp. 8–13, 2023.

[14] D. Cakrawisnu, D. O. Dwina, A. Nurdin, and O. Alfernando, "Pengaruh Campuran Palm Oil Fuel Ash (POFA) terhadap Stabilisasi Tanah Gambut Ditinjau dari Nilai CBR Tanah," *J.*

Tek. Sipil Inst. Teknol. Padang, vol. 9, no. 1, pp. 1–7, 2022.

[15] D. Endiani, N. Salsabila, A. Telambanua, and A. P. Hulu, "Subgrade Repair On The Road Pavement In Tanjung Rejo Village Using Palm Kernel Shell Ash As Reviewed From Undrained Consolidated Triaxial Tests," *UPMI Proceeding Ser.*, vol. 2, no. 02, pp. 1–9, 2025.

[16] H. C. Hardiyatmo, "Mekanika Tanah Jilid 1," *Penerbit PT, Gramedia Pustaka Utama, Jakarta*, 2019.

[17] F. A. A. Azam, R. C. Omar, R. Roslan, I. N. Z. Baharudin, and M. Z. Razman, "Mechanical behavior, compressibility, and microstructural analysis of problematic soil through a green soil stabilization approach," *Results Eng.*, vol. 24, p. 103524, 2024.

[18] Y. Hanun and R. N. Sari, "Analisis Dampak Penggunaan Geosintetik Dalam Penguatan Tanah Untuk Infrastruktur Jalan Raya," *J. Syntax Lit.*, vol. 10, no. 3, 2025.

[19] M. Toyeb, "The strength and economic benefit of soil stabilization with Palm Oil Fuel Ash (POFA) as agro-waste," in *E3S web of conferences*, 2022.

[20] M. M. Fauzi, A. M. Indriani, and G. Utomo, "Pengaruh Penambahan Fly Ash Terhadap Nilai Koefisien Permeabilitas Tanah Lempung Organik," *J. Appl. Civ. Eng. Infrastruct. Technol.*, vol. 6, no. 2, pp. 124–128, 2025.