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IMPROVING SHEAR STRENGTH OF EXPANSIVE SOIL THROUGH ASPHALT EMULSION AND LOCAL POZZOLANIC ADDITIVES

Khansa Nuansa Oktofani[1], Syahril[1], Indra Noer Hamdhan[2], Victor Firstkiel Feber Naess[1]

[1]) Master of Applied Infrastructure Engineering, Politeknik Negeri Bandung, Bandung, Indonesia*
Corresponding Author's Email : mailto:oktofani.khansa@gmail.com
Nomor HP corresponding Author : 0895412158177
[2]) Civil Engineering Department, ITENAS, Bandung, Indonesia
Email: indranh@itenas.ac.id

ABSTRACT

Expansive clayshale soils pose a significant geotechnical challenge due to their high swell-shrink potential and low shear strength, necessitating urgent development of effective and sustainable stabilization methods. This study explores the stabilization of such problematic soils using a combination of emulsified asphalt (AE) and Bledug Kuwu mud (LBK), a natural pozzolanic byproduct derived from a unique geological phenomenon in Central Java, Indonesia. A total of 51 cylindrical specimens were prepared with a fixed 8% AE content and varying LBK contents (6%, 10%, 14%, and 18%) by dry weight of soil. The mechanical properties were evaluated using Unconsolidated Undrained (UU) triaxial tests, while Scanning Electron Microscopy (SEM) was employed to examine microstructural evolution. The results highlight a marked improvement in shear strength parameters cohesion (c) and internal friction angle (φ)—in tandem with increased LBK content and curing duration. The optimal mixture (18% LBK, 8% AE, and 14 days of curing) showed a significant rise in c from 79.46 kPa to 150.88 kPa and φ from 14.3° to 24.0°, indicating a synergistic interaction between the asphalt binder and pozzolanic compounds. SEM analysis confirmed the formation of a denser and more cohesive matrix, attributed to both the physical encapsulation effect of AE and the pozzolanic reaction products, particularly calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which enhanced interparticle bonding. These findings underscore the effectiveness and urgency of adopting AE–LBK stabilization as a cost-efficient and environmentally friendly alternative for improving expansive soils. The study provides a foundational basis for field-scale implementation and long-term performance assessment in infrastructure development on marginal ground.

Keyword: *Bledug Kuwu Mud, Clayshale Soil, Cohesion, Emulsified Asphalt.*

1. INTRODUCTION

The construction industry has witnessed substantial growth across multiple sectors to meet the increasing demands of a growing population. This expansion is closely linked to advancements in geotechnical engineering, particularly in soil stabilization techniques, which play a critical role in the performance of subgrade layers in infrastructure projects. Within this geotechnical context, clayshale soils are categorized as problematic due to their high sensitivity to environmental exposure, often undergoing significant physical and mechanical alterations when subjected to weathering, air, or water. Their geotechnical behavior poses challenges during site investigation and classification. Clayshale deposits are geographically widespread, occurring with varying prevalence in regions such as Saudi Arabia, Sudan, India, the United States, Indonesia, Australia, the United Kingdom, Syria, and China, with distribution rates ranging from approximately 6% to 37%.[1].

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Soil constitutes a fundamental component in the planning and execution of infrastructure projects, where its strength and stability are critical in ensuring the structural integrity of overlying constructions. Structural failures can arise when the inherent properties of the soil are inadequate to resist imposed loads. To address the limitations associated with natural soil behavior in construction systems, soil stabilization techniques are implemented. These methods involve enhancing the physical and mechanical properties of soil through the incorporation of specific stabilizing agents, thereby improving its load-bearing capacity. Such interventions are particularly vital for soils characterized by low bearing strength, high plasticity index, and poor aggregate gradation that fails to meet technical specifications [2].

Clayshale is classified as a problematic soil type within the field of geotechnical engineering. In its undisturbed state, typically when confined beneath the ground surface, clayshale exhibits considerable structural integrity and high undrained shear strength [3]. Under such conditions, it maintains stability and behaves as a competent material .[4]. However, once exposed to environmental elements such as sunlight, water, or atmospheric air, clayshale undergoes rapid weathering processes. This exposure significantly alters its microstructure, leading to a substantial deterioration in its mechanical properties [5]. Consequently, the material transitions from a high-shear-strength condition to one characterized by severely reduced shear strength, thereby posing serious challenges to construction stability and long-term performance [6].

Clayshale is classified as an expansive soil, characterized by its significant volumetric changes upon interaction with water. One of its defining properties is the tendency to undergo substantial swelling and shrinkage, which can critically impact geotechnical stability. Notably, slope failures and ground movements in clayshale formations have been observed to occur even before full saturation is reached, underscoring the material's high sensitivity to moisture fluctuations. This behavior indicates that even minor variations in water content can substantially compromise the stability of slopes and structures founded on or within clayshale deposits [2].

A notable landslide case associated with clayshale-related soil problems occurred at the Sport Center Facility project in Hambalang, Bogor. The failure in slope stability at this site was primarily triggered by the exposure of clayshale layers during earthwork operations conducted as part of the construction process. The absence of protective measures allowed direct contact with water and air, which accelerated the weathering process of the material. According to findings by I.M. Alatas and P.T. Simatupang, the disintegration ratio of Hambalang clayshale indicated extremely low durability, with the material exhibiting complete structural breakdown after only a single wetting cycle. This case exemplifies the severe geotechnical risks posed by improperly managed clayshale in construction projects, particularly when preventive strategies against environmental exposure are not implemented [7].

Therefore, ground improvement measures are essential for clayshale soils in order to preserve structural integrity and enhance the bearing capacity of the subgrade. Soil stabilization techniques are generally classified into two principal categories: mechanical stabilization and chemical stabilization. Each approach employs distinct methodologies and treatment mechanisms to modify and improve the engineering properties of problematic soils [8]. For clayshale soils, chemical stabilization is generally regarded as a more effective approach due to the material's susceptibility to weathering, which necessitates the use of stabilizing agents to enhance and preserve its strength and structural integrity. Extensive research has been conducted to evaluate the performance of various stabilizing materials applied to problematic soils.

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Previous studies have reviewed and compiled a wide range of chemical stabilizers that have demonstrated potential in improving the mechanical behavior and durability of such soils.[9]. Cement and lime are among the oldest and most commonly employed stabilizing agents in geotechnical engineering, primarily due to their widespread availability and proven effectiveness in enhancing soil strength. In the context of clayshale soil stabilization, one viable approach involves utilizing alternative materials that exhibit similar physicochemical properties to those of cement and lime. This study explores the use of emulsified asphalt and Bledug Kuwu mud waste as stabilizing agents. Bledug Kuwu is an active mud volcano located in Kuwu Village, Kradenan Subdistrict, Grobogan Regency, Central Java, and has been recognized for its potential as a natural resource suitable for soil stabilization applications [10]. At present, the mud eruptions from the Bledug Kuwu mud volcano have not yielded substantial benefits for the surrounding communities. This research seeks to optimize the utilization of Bledug Kuwu mud by exploring its potential application in the construction sector, particularly as a soil stabilization agent [11]. Previous studies have indicated that incorporating Bledug Kuwu mud into soil mixtures can significantly enhance geotechnical performance, with the highest California Bearing Ratio (CBR) values and reduced plasticity index observed at a 15% mixing ratio [12].

According to laboratory testing conducted by the Center for Research and Development of Mineral and Coal Technology (TEKMIRA) in 2020, the chemical composition of Bledug Kuwu mud exhibits significant similarities to that of volcanic ash and fly ash. The material contains key chemical constituents commonly found in fly ash, including calcium oxide (CaO). Given the presence of dominant oxides such as silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), it can be inferred that Bledug Kuwu mud possesses the requisite pozzolanic characteristics, making it a promising candidate for application as a soil stabilization agent [13].

The second mixture incorporates a slow-setting asphalt emulsion, a chemical additive that is relatively uncommon in soil stabilization applications within the construction industry [14]. Previous studies have demonstrated that slow-setting asphalt emulsion can be effectively utilized for soil stabilization [15], with the optimal emulsion content typically ranging between 6% and 8% by weight of the soil mixture [16]. Other research findings further indicate that the inclusion of asphalt emulsion enhances the engineering properties of soils [17], particularly those with soft consistency, by improving their strength and workability [18].

Emulsified asphalt has proven to be an effective material for improving the properties of weak or problematic soils, particularly in tropical and subtropical regions where such soil conditions are prevalent [19]. Emulsified asphalt offers several advantages, including ease of application and relatively low energy consumption during implementation. Moreover, it has been shown to significantly enhance the unconfined compressive strength (UCS) of treated soils, with effective performance typically observed at emulsion contents ranging from 4% to 8% [20].

This study evaluates the effectiveness of Bledug Kuwu mud and emulsified asphalt in enhancing the durability and strength of clayey soil. The mechanical performance of the stabilized soil will be assessed through triaxial testing to observe its behavior under controlled stress conditions for each stabilizing agent. Bledug Kuwu mud is incorporated at varying proportions of 6%, 10%, 14%, and 18%, while the emulsified asphalt is applied at a fixed content of 6%. The ultimate objective of this research is to develop a sustainable, locally sourced, and technically viable soil stabilization method suitable for application in infrastructure projects constructed on expansive clayshale formations.

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2. METHODOLOGY

In addition to evaluating shear strength parameters, index properties of the untreated and treated soils were determined to provide a baseline for comparative analysis. These tests included specific gravity, natural moisture content, Atterberg limits (liquid limit, plastic limit, and plasticity index), dry unit weight, and bulk density. These parameters are essential in understanding the soil's fundamental behavior and its response to stabilization efforts. Sieve analysis and hydrometer tests were also conducted to classify the soil according to grain size distribution, further confirming its fine-grained and low-permeability characteristics.

The preparation of samples followed a strict sequence to ensure consistency across all variations. Initially, the clayshale soil was air-dried, pulverized, and passed through the same No. 40 sieve as the additives. The desired proportions of Bledug Kuwu mud and emulsified asphalt were then blended with the soil in a dry-mix phase, followed by gradual addition of water to achieve the optimum moisture content. The mixture was compacted in cylindrical molds with a height-to-diameter ratio of 2:1 to replicate standard triaxial test conditions.

To examine the evolution of strength with time, the specimens were preserved in sealed plastic wrap to prevent moisture loss during curing. Curing was carried out at room temperature, simulating field conditions where stabilization occurs without artificial heating. The time intervals (0, 3, 7, and 14 days) were selected to monitor the early to intermediate strength development, especially to capture the effects of hydration and pozzolanic reactions initiated by the active compounds in Bledug Kuwu mud.

The SEM analysis was strategically limited to the best-performing sample typically the mixture with 18% Bledug Kuwu mud and 8% emulsified asphalt after 14 days of curing. The micrographs obtained were analyzed for visible changes in particle structure, pore infill, and cementation bridges. These microstructural indicators are critical in confirming the hypothesized mechanisms of strength gain: physical binding by the asphalt emulsion and chemical stabilization through pozzolanic reactions forming C–S–H (calcium silicate hydrate) and C–A–H (calcium aluminate hydrate) compounds.

By integrating macroscopic strength testing with microscopic morphological analysis, this study provides a holistic understanding of how emulsified asphalt and natural volcanic mud can jointly improve problematic soils. The methodology thus combines traditional geotechnical practices with advanced material characterization to validate the stabilization process from multiple dimensions.

All experimental data were analyzed descriptively, and trends were assessed with respect to variations in mixture composition and curing time. The overall research methodology is illustrated in the flowchart presented in Figure 1.

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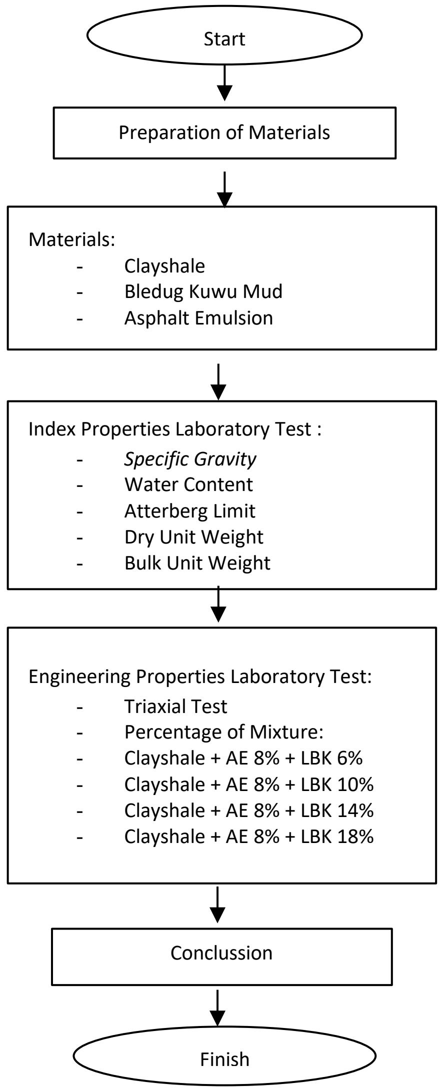

Sources: Processed by Researcher, 2025

Figure 1. Research Flow

The variations in stabilizing agent content and native soil composition for each test specimen are presented in Table 1 below.

Table 1. Weight of Mixture

Sample	Weight of BKM (gram)	Weight of AE (gram)	Weight of Soil (gram)
Clayshale	0	0	4000
Var (1)	240	320	3440
Var (2)	400	320	3280
Var (3)	560	320	3120
Var (4)	700	320	2960

Sources: Processed by Researcher, 2025

This study employed a total of 51 test specimens. The Bledug Kuwu mud was added at incremental proportions of 6%, 10%, 14%, and 18%, while the emulsified asphalt content was maintained at a constant 8%, as outlined in Table 2.

Table 2. Variations of Samples

Sampel	0 Days of Curing	3 Days of Curing	7 Days of Curing	14 Days of Curing
Clayshale	3	-	-	-
Var (1)	3	3	3	3
Var (2)	3	3	3	3
Var (3)	3	3	3	3
Var (4)	3	3	3	3

Sources: Processed by Researcher, 2025

The preparation of specimens involved a systematic procedure comprising material mixing, mechanical compaction, and curing under controlled conditions [21]. As part of the sample preparation process, the Modified Proctor compaction method was employed, a standard procedure widely utilized in large-scale infrastructure developments. The compaction parameters derived from this test play a vital role in the soil stabilization process and serve as a basis for ensuring compliance with the relative compaction criteria outlined in project specifications [22].

Following the molding process, the soil specimens were subjected to a series of tests to determine their index properties and geotechnical behavior. The primary objective of these tests was to evaluate the fundamental characteristics of the soil, with particular emphasis on strength assessment through the Unconfined Compressive Strength (UCS) test. The UCS test measures the maximum axial stress a soil specimen can withstand before failure, thus providing a direct indicator of its compressive strength. This method is particularly well-suited for undrained conditions, where pore water is unable to dissipate during loading.

3. RESULTS AND DISCUSSIONS

3.1. Soil Characteristic

A comprehensive series of index property tests was conducted to accurately classify the soil type used in this study and to gain a deeper understanding of its physical and mechanical characteristics. Various laboratory tests were employed to evaluate the key properties influencing the soil's behavior and performance in geotechnical applications. These tests included specific gravity determination, which provides insights into the particle density and mineral composition of the soil, as well as sieve analysis to assess particle size distribution, which is essential for understanding soil gradation and texture. The testing standards employed in this investigation are summarized in Table 3.

Table 3. Standard of Test

Pengujian	Standar Pengujian
Specific Gravity	(*ASTM D-854-02*) [23]
Dry Weight	(*ASTM D2216*) [24]
Bulk Density	(*ASTM D2216*) [24]
Porosity	(*ASTM D-2435*) [25]
Void Ratio	(*ASTM D-2435*) [25]
Water Content	(*ASTM D2216*) [24]
Atterberg Limits	(*ASTM D4318*) [26]
Compaction	(ASTM D1557-12) [27]
Triaxial	(ASTM D2850)[28]

Sources: Processed by Researcher, 2025

Table 4 presents the outcomes of the index property testing performed on the clayshale soil specimens.

Table 4. Index Properties of Clayshale

No	Pengujian	Simbol	Satuan	Nilai
1.	Berat Jenis	Gs	-	2.686
2.	Batas Atterberg	%		
	-Liquid Limit	LL	%	53.86
	-Plasticity Index	PI	%	32.65
	- Plastic Limit	PL	%	21.21
3.	Berat Isi	γ	gr/cm3	1.706
4.	Nilai Pori	e	-	1.344
5.	Kadar Air	ω	%	48.88
6.	Berat Kering	γd	gr/cm3	1.146
7.	Porositas	n	-	0.573

Source : Test Results, 2025

Based on the laboratory results, the tested material is identified as clayshale, a problematic soil known for its high initial strength in undisturbed conditions and severe degradation upon exposure to environmental elements. The specific gravity (Gs) of 2.686 falls within the normal range for fine-grained soils, indicating typical mineral content. The Atterberg limits liquid limit (LL) of 53.86%, plastic limit (PL) of 21.21%, and plasticity index (PI) of 32.65% classify the material as high-plasticity clay (CH) under the Unified Soil Classification System (USCS). These values indicate significant expansiveness and shrink-swell behavior, which are common in clayshale when weathered or exposed to moisture and air. High PI values also suggest low workability and susceptibility to volume changes, which can negatively affect slope stability and structural foundations.

The measured bulk unit weight (γ) of 1.706 gr/cm³ (17.06 kN/m³) is within the acceptable range, suggesting moderate compaction. However, the void ratio (e) of 1.344 and porosity (n) of 0.573 (57.3%) are relatively high, which indicates a loosely packed structure and high compressibility conditions that can contribute to rapid strength loss once the material is exposed. The water content (ω) of 48.88% is considerably high, showing that the clayshale has absorbed a substantial amount of moisture, consistent with its tendency to deteriorate quickly upon wetting. This condition results in a low dry unit weight (γd) of 1.146 gr/cm³ (11.46 kN/m³), well below the standard range for stable, compacted soils (typically 14–20 kN/m³). Such a low dry density indicates poor mechanical performance and insufficient load-bearing capacity.

3.2. Triaxial Test Results

To evaluate the influence of Bledug Kuwu mud (BKM) and emulsified asphalt (EA) on the mechanical behavior of clayshale soil, unconsolidated undrained (UU) triaxial tests were performed. This testing aimed to determine the shear strength parameters internal friction angle (φ) and cohesion (c) which are critical indicators in slope stability analysis and bearing capacity assessment. The tests were conducted on five mixture variants with varying BKM contents and curing durations to assess the combined effect of stabilizing agents on shear strength improvement under saturated, unconsolidated conditions.

The outcomes of these tests provide insights into the effectiveness of the stabilizing materials in enhancing the mechanical performance of the treated soil. The test procedure involved placing cylindrical soil specimens between two loading plates, followed by the application of axial stress until failure occurred.

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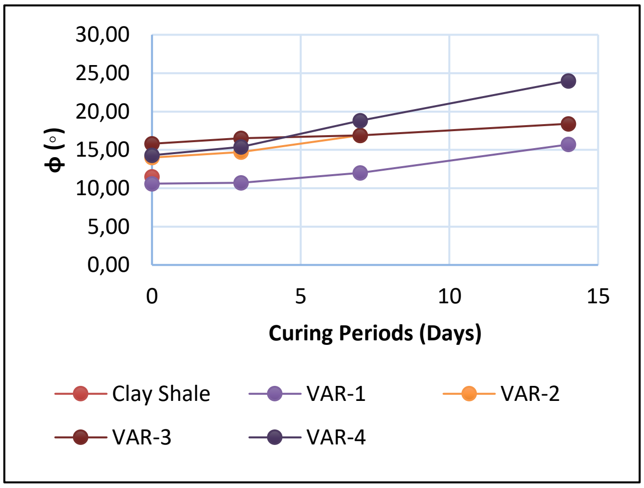
Additionally, Unconfined Compressive Strength (UCS) tests were conducted, yielding key parameters such as the unconfined compressive strength (qu) and the undrained shear strength (cu), where cu is calculated as one-half of qu. The detailed test results are presented in Table 5.

Table 5. Triaxial Test Results

No.	Sample	Curing Period (Days)	φ (◦)	c (Kpa)
1.	Clayshale	0	0,402	53,96
2.	Var (1)	0	0,389	29,53
		3	0,459	35,51
		7	0,573	42,28
		14	0,63	46,50
3.	Var (2)	0	0,627	55,82
		3	0,655	62,78
		7	0,734	73,38
		14	0,843	89,76
4.	Var (3)	0	1,060	66,61
		3	1,043	67,79
		7	1,253	78,87
		14	1,473	99,08
5.	Var (4)	0	1,091	79,46
		3	1,387	90,64
		7	1,555	111,34
		14	1,919	150,88

Source: Test Result, 2025



Source: Test Result, 2025

Figure 2. Shear Strength

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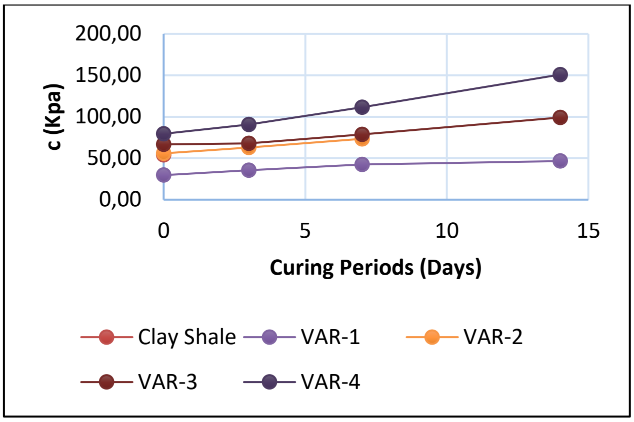


Source: Test Result, 2025

Figure 3. Cohesion

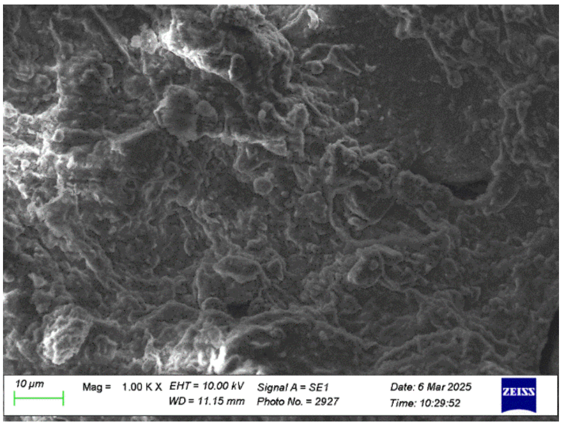
The results of the triaxial tests indicate that the combined addition of emulsified asphalt (EA) and Bledug Kuwu mud (BKM) has a significant effect on enhancing the soil's shear strength parameters, specifically the internal friction angle (φ) and cohesion (c), with these improvements becoming more pronounced as curing time increases.

In the untreated soil (Variant 0), the initial φ and c values were recorded at 11.50° and 53.96 kPa, respectively. Following stabilization with 8% EA and varying BKM contents ranging from 6% to 18%, a progressive increase in both parameters was observed. For instance, in Variant 4 (a mixture of 8% EA and 18% BKM), φ increased from 14.30° to 24.00° after 14 days of curing, while cohesion increased markedly from 79.46 kPa to 150.88 kPa.

These improvements suggest that chemical interactions between the emulsified asphalt and reactive compounds within the BKM promoted stronger interparticle bonding, resulting in a denser and more cohesive soil structure. The upward trend in φ and c further supports the occurrence of cementation and the development of a stabilized matrix within the treated soil mass.

3.3. SEM Laboratory Results

To support the mechanical testing results and elucidate the mechanisms underlying the improvement of soil strength at the microscopic level, a morphological analysis was conducted using Scanning Electron Microscopy (SEM). This examination aimed to observe the microstructural surface features of the stabilized soil samples in order to identify alterations in texture, particle density, and interparticle interactions induced by the addition of stabilizing agents. The SEM observations are expected to provide visual evidence of cementation processes and micro-level densification, both of which contribute to the enhanced shear strength and bearing capacity of the treated soil.



Sources: Processed by Researcher, 2025

Figure 4. SEM of 6% AE + 14% BKM on 14 days of curing

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Based on the Scanning Electron Microscope (SEM) observations of soil samples stabilized with 8% emulsified asphalt (AE) and 18% Bledug Kuwu mud (LBK), the microstructure appeared significantly denser, more homogeneous, and characterized by tightly bonded particle networks. The formation of this structure indicates the occurrence of micro-cementation and pore-filling processes, driven by the chemical interaction between emulsified asphalt and reactive minerals present in the LBK. This structure effectively restricts particle mobility and reduces void spaces, contributing directly to the enhancement of shear strength, as confirmed by the triaxial test results.

From a physical perspective, the incorporation of AE into the clayshale-LBK matrix results in an initial binding effect due to the adhesive and viscoelastic properties of the bitumen emulsion. The emulsified asphalt encapsulates soil and LBK particles, forming a thin film that consolidates individual particles into larger, more stable aggregates. This bonding reduces pore spaces and enhances microstructural density. SEM imagery clearly shows a more compact and uniform texture, suggesting limited particle movement owing to surface bonding from the asphalt film. Moreover, the hydrophobic nature of AE contributes to reduced water infiltration, mitigating swelling potential and improving volumetric stability.

Chemically, LBK serves as a natural pozzolanic agent due to its dominant composition of calcium oxide (CaO), silica (SiO_2), and alumina (Al_2O_3). Under moist conditions, CaO undergoes hydration to form calcium hydroxide ($Ca(OH)_2$), which subsequently reacts with amorphous silica and alumina to form calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), respectively. These hydration products fill the interparticle voids and function as permanent cementing agents. C–S–H, in particular, is recognized as a primary contributor to strength enhancement due to its dense, insoluble nature. SEM imagery exhibits interparticle bonding networks indicative of these hydration phases, reinforcing the assertion that the observed mechanical strength gains are attributable to micro-cementation resulting from AE–LBK chemical reactions.

This correlation is further substantiated by the significant increases in cohesion (c) and internal friction angle (φ) obtained from triaxial testing. The presence of a cohesive matrix layer visible in the SEM micrographs serves as direct evidence that chemical stabilization leads to the formation of strong bonding phases, which enhance the soil's internal resistance to shear deformation. These findings affirm that chemical intervention through stabilization techniques not only improves macroscopic mechanical behavior but also fundamentally alters and strengthens the soil's microstructural framework.

4. CONCLUSION

This study has demonstrated that the combined application of 8% emulsified asphalt (AE) and varying proportions of Bledug Kuwu mud (LBK) significantly enhances the mechanical strength and stability of clayshale soils. Results from unconsolidated undrained (UU) triaxial tests revealed a progressive increase in both cohesion (c) and internal friction angle (φ) with higher LBK content and extended curing durations. At the optimum combination 18% LBK nd 14 days of curing the cohesion value increased from 79.46 kPa to 150.88 kPa, while φ rose from 14.3° to 24°, indicating a substantial improvement in the soil's shear resistance.

Microscopic analysis using Scanning Electron Microscopy (SEM) confirmed the development of a denser, more homogeneous microstructure with tightly bonded particles. The observed strength enhancement is attributable to a dual mechanism: physically, AE forms a cohesive binding film around soil particles that reduces porosity; chemically, pozzolanic reactions between active mineral constituents in LBK produce calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which serve as robust interparticle binding agents. These mechanisms act synergistically to establish a more stable and cohesive soil matrix

The principal contribution of this research lies in the innovative utilization of locally sourced, naturally occurring waste material for the stabilization of expansive soils specifically clayshale, which has historically proven challenging to treat with conventional methods. The findings highlight the potential for developing environmentally sustainable and cost-effective ground improvement techniques, particularly in regions with direct access to LBK such as Central Java, Indonesia. The local availability of Bledug Kuwu mud not only reduces material costs and transportation logistics but also promotes circular use of natural byproducts that otherwise remain unutilized. Moreover, the improved shear strength properties suggest practical suitability for subgrade enhancement in road construction, slope stabilization, and other geotechnical works in expansive soil zones.

Future research is recommended to evaluate long-term durability performance, explore additional variations in AE content, and implement field-scale trials under different drainage conditions to further validate and enhance the practical applicability of this stabilization method.

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LITERATURE STUDY

[1] F. E. Jalal, A. Zahid, M. Iqbal, A. Naseem, and M. Nabil, "Sustainable use of soda lime glass powder (SLGP) in expansive soil stabilization," *Case Stud. Constr. Mater.*, vol. 17, no. November 2023, p. e01559, 2022, doi: 10.1016/j.cscm.2022.e01559.

[2] A. Daraei, B. M. A. Herki, A. F. H. Sherwani, and S. Zare, "Slope Stability in Swelling Soils Using Cement Grout: A Case Study," *Int. J. Geosynth. Gr. Eng.*, vol. 4, no. 1, pp. 1–10, 2018, doi: 10.1007/s40891-018-0127-9.

[3] I. M. Alatas, R. Nazir, M. Irsyam, and P. T. Simatupang, "The effect of weathering process to determination of residual shear strength of clay shale with triaxial multi-stage system," in *International Society for Soil Mechanics andn Geotechnical Enginneering*, 2017, pp. 305–308. [Online]. Available: https://www.issmge.org/publications/online-library

[4] W. Rahayu, "Stabilization of clay shale using propylene glycol and laterite on california bearing ratio," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 620, no. 1, 2019, doi: 10.1088/1757-899X/620/1/012042.

[5] H. Adisurya and C. A. Makarim, "Perilaku Kegagalan Konstruksi Jalan Raya Yang Bertumpu Pada Fondasi Tiang Di Tanah Clay Shale," *JMTS J. Mitra Tek. Sipil*, vol. 5, no. 1, pp. 55–70, 2022, doi: 10.24912/jmts.v5i1.16516.

[6] A. Suryadi, M. Wuldan, and H. Kausarian, "Implications of Clay Minerals in Landslide Disasters : Case Study of the Riau - West Sumatra Highway KM 82 - 89," vol. 8, no. 2, pp. 97–103, 2024, doi: https://doi.org/10.30871/jagi.v8i2.7135.

[7] I. M. Alatas and P. T. Simatupang, "Pengaruh Proses Pelapukan Clay Shale terhadap Perubahan Parameter Rasio Disintegritas (D R)," *J. Tek. Sipil*, vol. 24, no. 1, pp. 77–82, 2017, doi: 10.5614/jts.2017.24.1.9.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

[8] A. Ahmed, M. El-Emam, N. Ahmad, and M. Attom, “Stabilization of Pavement Subgrade Clay Soil Using Sugarcane Ash and Lime,” *Geosci.*, vol. 14, no. 6, 2024, doi: 10.3390/geosciences14060151.

[9] Z. Sabzi and Z. Sabzi, “Environmental Friendly Soil Stabilization Materials Available in Iran,” *J. Environ. Friendly Mater.*, vol. 2, no. 1, pp. 33–39, 2018, [Online]. Available: https://www.researchgate.net/publication/328531948

[10] A. Sabdaningsih, “MITOLOGI DAN SAINS: Bledug Kuwu di Kabupaten Grobogan,” vol. 13, pp. 7–17, 2018, doi: https://doi.org/10.14710/sabda.13.1.7-17.

[11] D. Kumalasari and S. Syahril, “The Effect of Adding Bledug Kuwu Mud and Vermiculite on CBR Values of Expansive Soils,” *Atl. Press*, vol. 207, pp. 220–224, 2021, doi: https://doi.org/10.2991/aer.k.211106.034.

[12] A. B. Winarno and S. Syahril, “Soil Stabilization with Bledug Kuwu Mud and Phosphoric Acid on the Plasticity Index Value,” 2021.

[13] A. B. Winarno, “Stabilisasi Tanah Lunak Menggunakan Lumpur Bledug Kuwu dan Larutan Asam Fosfat Ditinjau dari Nilai Kuat Tekan Bebas,” *J. Teor. dan Terap. Bid. Rekayasa Tek. Sipil*, vol. 31, no. 2, pp. 235–240, 2024, doi: 10.5614/jts.2024.31.2.14.

[14] Sjelly Haniza, Harnedi Maizir, and Danil Jesa Putra, “Analisis Karakteristik Tanah Dasar Lempung Menggunakan Metode Stabilisasi Aspal Emulsi,” *Sainstek (e-Journal)*, vol. 8, no. 1, pp. 37–41, Jun. 2020, doi: 10.35583/js.v8i1.29.

[15] J. K. Thajeel, H. A. Shaia, S. K. Al-Mamoori, and A. D. Almurshedi, “Effect of Emulsified Asphalt on Expansive Soil Strength and Swelling,” *E3S Web Conf.*, vol. 427, pp. 1–9, 2023, doi: 10.1051/e3sconf/202342703009.

[16] M. Zumrawi *et al.*, “A Review Paper on Stability of Soil Block using Bitumen Emulsion,” *Int. Res. J. Eng. Technol.*, pp. 1548–1552, 2017, [Online]. Available: www.irjet.net

[17] A. S. de Medeiros, M. H. S. Cardoso, and M. A. V. da Silva, “Evaluation of the Mechanical Behavior of Soil Stabilized with Asphalt Emulsion Using Multi-Stage Loading,” *Civ. Eng. J.*, vol. 10, no. 1, pp. 20–40, 2024, doi: 10.28991/CEJ-2024-010-01-02.

[18] R. Meysita Pramaesti, “Expansive Soil Stabilization Using Mud (Lapindo) and Asphalt Emulsion,” 2021, doi: https://doi.org/10.35313/potensi.v23i2.2549.

[19] S. Andavan and B. Kumar, “Case study on soil stabilization by using bitumen emulsions – A review,” *Mater. Today Proc.*, vol. 22, Feb. 2020, doi: 10.1016/j.matpr.2019.12.121.

[20] B. D. Oluyemi-Ayibiowu, “Stabilization of lateritic soils with asphalt- emulsion,” *Niger. J. Technol.*, vol. 38, no. 3, p. 603, 2019, doi: 10.4314/njt.v38i3.9.

[21] Faray and W. Rahayu, “Durability and strength improvement of clayshale using various stabilized materials,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 426, no. 1, 2020, doi: 10.1088/1755-1315/426/1/012028.

[22] U. Khalid and Z. ur Rehman, “Evaluation of compaction parameters of fine-grained soils using standard and modified efforts,” *Int. J. Geo-Engineering*, vol. 9, no. 1, pp. 1–17, 2018, doi: 10.1186/s40703-018-0083-1.

[23] “Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer,” ASTM D-854-02, 2002

[24] “Standard Test Methods for Laboratory Determination of Water (Moisture) Content,” ASTM D2216, 2019

[25] “Standard Test Methods for One-Dimensional Consolidation Properties of Soils,” ASTM D-2435, 2011

[26] “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils,” ASTM D4318, 2017

[27] “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort,” ASTM D1557-12, 2012

[28] “Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils,” ASTM D4767, 2011