

Original Research

The Effect of Different Mixtures on Desiccation Crack Behaviour and Hydraulic Stability of a Compacted Liner

Mochamad Arief Budihardjo^{1†}, Nita Citrasari², Muhammad Altin Massinai³, Bimastyaji Surya
Ramadan¹ and Annisa Sila Puspita⁴

¹Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, 50275, Indonesia

²Department of Biology, Faculty of Science and Technology, Universitas Airlangga, 60115, Indonesia

³Department of Geophysics, Faculty of Mathematics and Natural Sciences, Universitas Hasanuddin, 90245, Indonesia

⁴Environmental Sustainability Research Group, Department of Environmental Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang, 50275, Indonesia

† Corresponding author: Mochamad Arief Budihardjo; m.budihardjo@ft.undip.ac.id

ORCID IDs 0000-0002-1256-3076

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Abstract: Landfills are equipped with leachate containment systems that include a compacted liner layer with low hydraulic conductivity. In general, the required hydraulic conductivity is $\leq 1 \times 10^{-5}$ cm/s for final cover liners and $\leq 1 \times 10^{-6}$ cm/s for bottom liner applications to prevent leachate migration into surrounding soil and groundwater. In this study, composites made from textile-industry sludge amended with bentonite, lime, and rice husk ash were tested to evaluate their suitability as landfill liner materials. The results showed that composites containing 40% or more bentonite (by mass) mixed with dewatered sludge could meet landfill permeability standards. However, adding 1% lime and 8% rice husk ash further reduced permeability. The addition of bentonite tends to increase cohesion and decrease the internal friction angle. Meanwhile, the addition of lime and rice husk ash tended to increase the internal friction angle and produced fluctuating cohesion values.

1. INTRODUCTION

Leachate is a liquid that seeps through a waste pile, carrying dissolved and suspended materials (Singh & Hendry, 2013). Landfills must be equipped with a semi-impermeable liner to retain leachate and prevent environmental pollution (Mokhahlane, 2013). Many landfills are generally equipped with clay liners. Clay swells under humid conditions and shrinks under dry conditions (Staub et al., 2011). This swelling–shrinkage behavior can reduce the liner’s effectiveness by triggering cracks (Chegenizadeh et al.; Vaverková et al., 2018). To avoid significant cracking, the shrinkage limit for liner construction should be less than or equal to 4% (Maritsa et al., 2016). Therefore, identifying a robust alternative landfill liner material is essential.

Many studies have investigated alternative materials, such as coal ash (Nurdin et al., 2016), bentonite (Chaduvula et al., 2017), red mud (Vipulanandan & Leung, 1995), and others, to reduce reliance on excessive use of indigenous soil (Puspita et al., 2024). Bentonite is commonly used as an additive for landfill leachate barriers due to its favorable properties and low permeability (Kumar & Yong, 2002). Other materials are often blended with bentonite to reduce costs while meeting landfill liner performance requirements. In this study, dewatered sludge from textile industrial waste is used as the primary material, mixed with bentonite, lime, and rice husk ash to form a composite leachate-retaining layer. Hazardous waste from the textile industry commonly includes sludge or sand that cannot be reprocessed by the producer (Uddin, 2021). This waste is typically stored temporarily after incineration before being transferred to a third party. The use of dewatered sludge as a landfill liner material, therefore, requires the addition of supporting materials to improve performance. Stability is a critical consideration in landfill design, both for the internal waste mass and for the leachate barrier layer (Jones & Dixon, 2005; Omididi et al., 1996). The stability of the leachate-retaining layer is inversely related to permeability (Koerner & Soong, 2000). According to common landfill design standards, the hydraulic conductivity requirement for a compacted final cover liner is typically $\leq 1 \times 10^{-5}$ cm/s, whereas bottom liner systems generally require a more stringent criterion of $\leq 1 \times 10^{-6}$ cm/s to ensure effective long-term containment (Witt & Zeh, 2005).

Bentonite exhibits a very low permeability coefficient (approximately 1.8×10^{-9} cm/s), making it highly effective in resisting leachate infiltration. However, bentonite is highly expansive, shrinking under dry conditions and swelling when exposed to moisture (Holtz, 1959). The incorporation of lime has been reported to improve the physical and mechanical properties of the base material, reduce moisture content, and enhance long-term impermeability (Little, 1998). When lime is blended with bentonite for leachate barrier applications, it may increase optimum moisture content, decrease maximum dry density, and improve compressive strength (Jain, 2024). In addition, rice husk ash can enhance the adsorption of key contaminants, including heavy metals, while reducing permeability and maximum dry density, increasing optimum moisture content, and significantly improving compressive strength, reaching values up to 200 kN/m² (Cokca & Yilmaz, 2004). This study aims to identify the optimum composition of landfill liner composites based on dewatered sludge amended with

bentonite, lime, and rice husk ash. The resulting composites are expected to serve as an alternative material for landfill leachate containment systems.

2. MATERIALS AND METHODS

The samples consisted of dewatered textile-industry sludge waste, bentonite, lime, and rice husk ash. The dewatered textile-industry sludge waste was obtained from one textile industry in Indonesia. Bentonite clay was obtained from mineral mining facilities. Lime and rice husk ash were purchased commercially. Each characteristic test was performed by mixing the materials at specific compositions. The dewatered textile-industry sludge waste, bentonite, lime, and rice husk ash were mixed using the cone-and-quartering method to ensure homogeneous mixtures. This study conducted characteristic tests, including sludge grain size distribution, bentonite swelling, initial moisture content, Atterberg limits, specific gravity, Standard Proctor compaction, and morphological analysis using SEM–EDX.

Table 1

Sample Variations

No	Sample Variation	Variable Code
1	100% S	V1
2	79% S + 20% B + 1% K	V2
3	69% S + 30% B + 1% K	V3
4	59% S + 40% B + 1% K	V4
5	49% S + 50% B + 1% K	V5
6	39% S + 60% B + 1% K	V6
7	71% S + 20% B + 1% K + 8% ASP	V7
8	61% S + 30% B + 1% K + 8% ASP	V8
9	51% S + 40% B + 1% K + 8% ASP	V9
10	41% S + 40% B + 1% K + 8% ASP	V10
11	31% S + 40% B + 1% K + 8% ASP	V11

2.1 Permeability Test

The permeability test was performed in accordance with the falling-head method specified in AS 1289.6.7.2-2001 (Standards Australia, 2001). This method involves allowing water to flow through a soil specimen connected to a vertical standpipe filled with water. The standpipe is marked with height graduations, enabling measurement of changes in water level and calculation of the volume of water passing through the soil

sample over time. Prior to testing, the soil specimen was fully saturated to ensure consistent flow conditions, and the standpipe was filled with water to a predetermined initial height. The test commenced by allowing water to permeate through the soil, during which the decrease in water level within the standpipe was carefully observed and recorded. To ensure reliability and reproducibility, each permeability test was conducted in triplicate ($n = 3$) for every composite variation. The hydraulic conductivity values reported in this study represent the mean of three independent tests, and measurement variability is expressed as the standard deviation (\pm SD). The low variation among replicate tests indicates good consistency of the falling-head method for evaluating the hydraulic performance of the composite materials.

2.2 Desiccation Test

The drying behavior of desiccation cracking was observed for different composite materials under two temperature conditions: the minimum temperature (25.7°C) and the maximum temperature (40°C). A desiccation test was performed to identify cracks in the sample caused by the drying process and to estimate the hydraulic conductivity of the cracked soil specimen (Puspita et al., 2023). The plate containing dewatered sludge composites with bentonite, lime, and rice husk ash was left to rest, and changes during drying were observed, including the occurrence of cracking. Photographs of the cracks were taken in both black-and-white and color. The photographs were then analyzed using MATLAB software to determine the percentage of crack area, from which the crack area width in the composite layer was determined.

2.3 Direct Shear Test

This test was conducted to determine the soil shear strength parameters, namely cohesion and the internal friction angle. The shear force applied by pushing the upper section caused shear failure in the soil. Calculations were carried out to convert normal loads to normal stresses and to compute shear force and shear stress. These parameters provided the basis for evaluating the shear strength of the composite. A graph of shear stress versus normal stress was used to obtain the cohesion value and the internal friction angle of the composite material. Composite stability was then evaluated based on safety factors. The analysis was carried out using GeoSlope/W with the Morgenstern–Price method, assuming a 30% slope and a layer thickness of $30\text{ cm} \times 2$.

3. RESULTS AND DISCUSSION

3.1. Characteristic Test

The sieve analysis results showed that 99.62% of the dewatered sludge was classified as sand, while the remaining 0.38% was classified as clay and silt. The swelling test for pure bentonite showed a free swell index (FSI) of 390%. Bentonite typically expands in distilled water. This swelling ability is expected to fill the voids between dewatered sludge particles and improve soil density (Masihi & Gholikandi, 2020; Qin et al., 2023). An FSI of 390% indicates that the bentonite expanded by approximately 39 times. A higher clay content increases

cohesion and reduces the shear angle (Bozbey & Guler, 2006). These phenomena occur because sand is a non-cohesive soil type, particularly under dry conditions. Non-cohesive soils do not exhibit well-defined plasticity boundaries (Nhan et al., 1996; Rubey, 1933). In terms of permeability, a higher sand percentage generally increases permeability (Churchman et al., 2006; Revil & Cathles Iii, 1999). The Atterberg limit test results showed that not all composite variations exhibited plastic behavior. Composites containing 30% bentonite or more exhibited plasticity, as indicated by the plasticity index. Based on the material composition, the composite with 30% bentonite had a plasticity index of 0.48–1.1%, whereas composites with 40%, 50%, and 60% bentonite had plasticity indices of 16.21%, 11.5%, and 14.01%, respectively.

The initial moisture content ranged from 19.24% to 36.56% across all composites. Bentonite addition increased the initial moisture content in a non-linear manner. Lime application also increased the moisture content substantially. In contrast, rice husk ash reduced the moisture content compared with the composite containing dewatered sludge, bentonite, and lime. Bentonite addition tended to increase specific gravity because its swelling fills pores within the dewatered sludge matrix. However, lime and rice husk ash reduced bentonite performance, resulting in a subsequent decrease in specific gravity. The Standard Proctor test produced different optimum moisture content (OMC) and maximum dry density (MDD) values across the composites. Composite VI, which did not contain bentonite, showed the highest OMC and the lowest MDD. This reflects the behavior of dewatered sludge, which interacts poorly with water and therefore requires higher moisture to achieve maximum density. Lime addition increased both OMC and MDD. When rice husk ash was added, OMC decreased, and MDD increased, likely because rice husk ash promotes hardening, making the material stiffer and denser. When lime is added, it can also accelerate hardening before the composite absorbs a large amount of water.

3.2 Permeability Behavior of the Composites

The first set of experiments compared MgCl_2 and MgO as magnesium sources across a pH range of 6–11. The results demonstrated that MgCl_2 consistently outperformed MgO in nutrient removal. For ammonium, the greatest reduction was achieved at pH 9, whereas phosphate removal peaked at pH 10. At these points, more than 70% of the phosphate and nearly 60% of the ammonium could be removed from the solution. The lower performance of MgO can be attributed to its limited solubility, which releases Mg^{2+} ions at a slower rate, thereby delaying nucleation and crystal growth. In contrast, MgCl_2 provided an immediate and high concentration of soluble magnesium, enabling rapid supersaturation and precipitation. The pH dependence observed here is consistent with established findings that struvite crystallization is strongly influenced by solution chemistry (Petal Battistoni et al., 1997). At near-neutral pH (6–7), little precipitation occurred because the availability of PO_4^{3-} ions was restricted. Under highly alkaline conditions (>10.5), competing precipitation of calcium phosphate and

amorphous phosphate species may explain the decline in removal efficiency. Thus, pH 9–10 can be considered the optimal window for struvite precipitation in composting leachate, which is consistent with previous studies on wastewater and digestates (Kabdaslı et al., 2000; Yetilmezsoy & Sapci-Zengin, 2009).

The permeability (hydraulic conductivity) test was conducted to determine the composite material's ability to transmit water through the soil horizontally and laterally, in order to select a suitable composite for use as a landfill layer (Ng et al., 2016; Scalia IV & Benson, 2011). The test was performed using specimens prepared at the remaining soil density from the Proctor test and evaluated using the falling-head method. The permeability test results are presented in Table 2.

Table 2.

PERMEABILITY TEST RESULTS

No	Sample Variation	Hydraulic Conductivity (cm/s)
1	100% S	$(1.36 \pm 0.05) \times 10^{-2}$
2	79% S + 20% B + 1% L	$(6.42 \pm 0.21) \times 10^{-5}$
3	69% S + 30% B + 1% L	$(6.42 \pm 0.18) \times 10^{-5}$
4	59% S + 40% B + 1% L	$(9.79 \pm 0.32) \times 10^{-7}$
5	49% S + 50% B + 1% L	$(1.83 \pm 0.07) \times 10^{-7}$
6	39% S + 60% B + 1% L	$(8.16 \pm 0.29) \times 10^{-7}$
7	71% S + 20% B + 1% L + 8% RHA	$(3.03 \pm 0.11) \times 10^{-5}$
8	61% S + 30% B + 1% L + 8% RHA	$(3.55 \pm 0.13) \times 10^{-5}$
9	51% S + 40% B + 1% L + 8% RHA	$(1.17 \pm 0.04) \times 10^{-6}$
10	41% S + 40% B + 1% L + 8% RHA	$(2.34 \pm 0.08) \times 10^{-6}$
11	31% S + 40% B + 1% L + 8% RHA	$(1.02 \pm 0.03) \times 10^{-6}$

The observed reduction in hydraulic conductivity across the composite variations can be attributed primarily to microstructural changes within the pore network. The incorporation of bentonite plays a dominant role due to its swelling capacity. Upon hydration, bentonite particles expand and occupy void spaces between dewatered sludge particles, resulting in reduced pore size and decreased pore connectivity. This swelling mechanism significantly restricts water-flow pathways and consequently lowers the permeability of the composite materials (Horpibulsuk et al., 2011; Qiang et al., 2014). In addition, the increase in plasticity index observed in composites containing $\geq 30\%$ bentonite contributes to reduced permeability. Higher plasticity reflects greater water retention and enhanced interparticle bonding, which limits the formation of continuous flow channels within the compacted matrix. As a result, hydraulic conductivity decreases as bentonite content

increases. The incorporation of lime and rice husk ash further modifies the pore structure through physicochemical reactions. Lime induces flocculation and promotes pozzolanic reactions, forming cementitious compounds such as calcium silicate hydrate (C–S–H), which enhance interparticle bonding and reduce pore connectivity. Rice husk ash, which is rich in amorphous silica, reacts with calcium derived from lime to strengthen the composite matrix. These reactions contribute to improved structural integrity and an additional reduction in hydraulic conductivity. However, partial replacement of bentonite with rice husk ash may reduce the swelling contribution, which may explain the variability in permeability observed among certain compositions.

3.3 Desiccation Crack Analysis

Crack testing was conducted using MATLAB software by converting the original RGB image into a binary image. The crack area was then identified using the crack intensity factor (CIF) formula. The CIF value is used to quantify the crack area across the entire image. Composite V1, with a composition of 100% dewatered sludge, could not be evaluated in the desiccation test because cracks could not be detected using the MATLAB software. This occurred because pure dewatered sludge contains granular particles (commonly referred to as aggregates) that are dispersed and non-plastic (see Figure 1). This finding is supported by preliminary grain size testing. The dewatered sludge consists of 99.62% sand; sand is classified as a non-cohesive (easily loosened) soil under dry conditions. Therefore, sand does not exhibit plasticity.



Fig 1. Composite V1 from Day 0 to Day 9 (cracks cannot be detected)

For composites other than V1, the addition of bentonite, lime, and rice husk ash from day 0 to day 9 reduced the water content and triggered desiccation, which caused cracks to form on the sample surface at the minimum temperature (25.7°C). The addition of bentonite, 1% lime, and 8% rice husk ash decreased the CIF value, as shown in Figure 2.

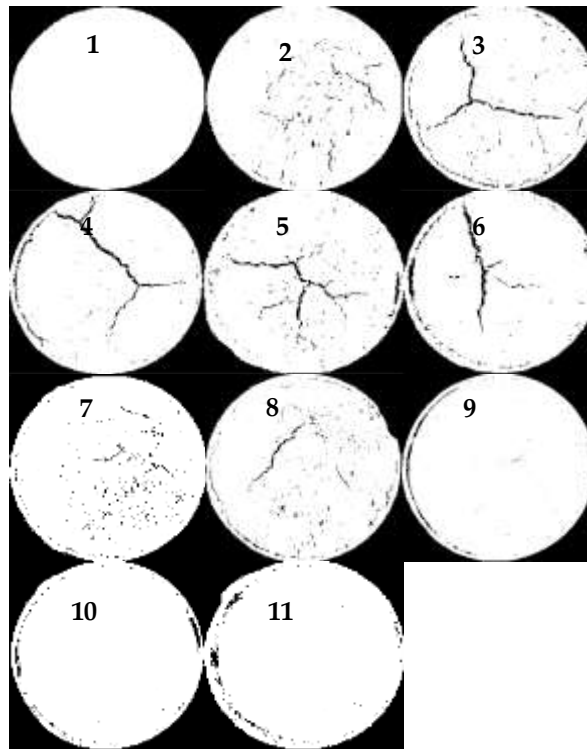


Fig 2. Binary image of cracks at the minimum temperature on Day 9

The images were taken on the 9th day at the minimum temperature. The CIF values were undefined for V1 and were 0.72% (V2), 2.58% (V3), 2.37% (V4), 2.67% (V5), and 2.78% (V6). For the remaining composites, the CIF values were 0.64% (V7), 2.37% (V8), 1.10% (V9), 1.16% (V10), and 1.20% (V11). The largest CIF value occurred in V6, which consisted of 39% dewatered sludge, 60% bentonite, and 1% lime, while the smallest CIF value occurred in V7, which consisted of 71% dewatered sludge, 20% bentonite, and 1% lime.

The incorporation of 8% rice husk ash was found to reduce the CIF value. The use of rice husk ash in composites containing expansive soils contributes to lowering the soil's swelling potential. When combined with lime, rice husk ash functions as a binding agent within the aggregate structure (Çoruh & Ergun, 2010; Sua-Iam & Makul, 2013). This behavior is attributed to the pozzolanic characteristics of rice husk ash, which reacts with expansive soil to form a stiffer, more rigid composite matrix. The silica content in the pozzolanic material reacts with quicklime, enhancing interparticle bonding and overall material strength. In addition, the presence of rice husk ash helps minimize shrinkage, thereby reducing crack formation within the composite (Amran et al., 2021; Kaya & Durukan, 2004). Shrinkage mitigation occurs because rice husk ash lowers the maximum dry density while increasing the OMC, resulting in more plastic composite behavior. At an elevated temperature of 40°C, testing was conducted on all V2–V11 composite variations containing bentonite, lime, and rice husk ash

over a curing period from day 0 to day 6. The results indicate a continuous decrease in moisture content across the V2–V11 samples, leading to desiccation and the subsequent formation of surface cracks, as illustrated in Figure 3.

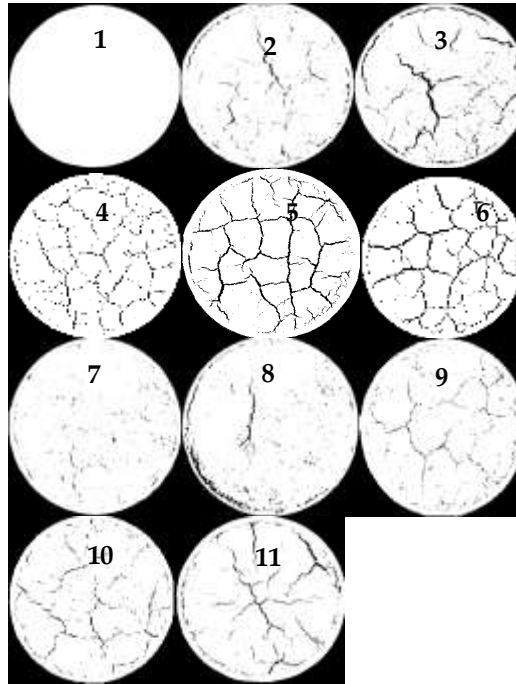


Fig 3. Binary image of cracks at the maximum temperature on Day 6

Images taken on the 6th day produced CIF values that were undefined for V1 and were 2.25% (V2), 4.96% (V3), 4.00% (V4), 5.70% (V5), 6.21% (V6), 1.51% (V7), 3.10% (V8), 2.31% (V9), 2.71% (V10), and 3.41% (V11). The results of the desiccation crack analysis are presented in Table 3.

Table 3. Desiccation Crack Test Results

Variation	CIF (%)	
	27°C	40°C
V1	-	-
V2	2.55	2.25
V3	2.58	4.96
V4	2.38	4.00
V5	2.68	5.70
V6	2.78	6.21
V7	0.64	1.51
V8	2.37	3.10
V9	1.10	2.31
V10	1.16	2.71

V11

1.21

3.41

At both temperature conditions, composites V2, V8, V9, V10, and V11 showed CIF values below 4%. The remaining composites exhibited CIF values above 4%. The lowest crack intensity was observed in composite V7, with a CIF value of 0.64% at the minimum temperature and 1.51% at the maximum temperature.

3.4 Shear Strength and Stability Analysis

The findings show that, as the bentonite content increased, the internal friction angle tended to decrease, while cohesion increased. These two parameters describe the shear strength of the composite materials (Budihardjo et al.). The internal friction angle indicates the stability of the composite in terms of angular resistance, whereas cohesion indicates the bonding force between particles that contributes to the material's strength. The reduction in internal friction angle and the increase in cohesion were neither linear nor uniform. The decrease in the friction angle can be ascribed to the fact that bentonite occupies the spaces between aggregates and consequently reduces interparticle friction. On the other hand, cohesion was higher at higher bentonite contents because bentonite acted as a binding material within the composite structure.

The addition of lime to the composite materials caused changes in the internal shear angle and a decrease in cohesion. Lime-aggregate interaction promotes contact between lime and clay minerals, precipitating an ion-exchange reaction that creates calcium-silicate gel. This gel is insoluble in water and causes flocculation of particles, which decreases pore spaces in the aggregates and increases overall structural stability (Rubinos et al., 2015). In lime and rice husk ash composites, the internal shear angle increased, whereas cohesion showed sporadic changes. It is possible that these variations in cohesion were caused by a non-uniform rate of shear displacement, but the overall variations were not significant. The low and irregular cohesion response could be explained by an insufficient balance in the rice husk ash-to-lime ratio and, therefore, a non-optimal and non-uniform reaction between the two substances across the composite samples.

It was observed that curing behaviour significantly affected the shear strength parameters, namely the internal shear angle and cohesion, across all composite variations. Progressive enhancement of both parameters over a four-hour period was achieved when the composites were cured using leachate. This indicates an increase in mechanical stability and resistance to shear deformation in the composite materials. Concurrent changes in internal shear angle and cohesion imply stronger bonding between particles and enhanced frictional resistance within the composite matrix. The measured increases in shear strength parameters indicate the potential for

these composites to be used as leachate-retaining layers. The fact that the composites can retain, and even enhance, their stability under leachate-curing conditions means that exposure to leachate does not compromise their structural integrity. It follows that leachate intrusion into the composite will not eliminate its mechanical strength, confirming the suitability of these composite materials for waste management systems as long-term containment and barrier elements.

The GeoSlope/W analysis was conducted to evaluate the factor of safety of the composite material when applied as a leachate barrier layer. The stability assessment was performed using the Morgenstern–Price method with a 30% slope inclination and a liner thickness of 30 cm (two layers). The model assumed homogeneous material properties derived from laboratory direct shear parameters (cohesion and internal friction angle), with no external surcharge loading or waste overburden pressure. Pore water pressure conditions were simulated under steady-state assumptions without additional hydraulic head. A slope is classified as stable when the factor of safety exceeds 1.25 (Herrmann et al., 2009). The factor of safety of composites composed of dewatered sludge and bentonite generally exhibited a declining trend. For instance, the V1 composite, consisting solely of 100% dewatered sludge, recorded a factor of safety of 14. The relatively high factor of safety values obtained in this study were primarily influenced by the shallow slope geometry, limited liner thickness, and the relatively high cohesion values measured under laboratory-controlled conditions. These modeling assumptions tend to produce conservative stability outcomes in the absence of external loading. The observed reduction in the factor of safety with increasing bentonite content is attributed to decreased shear resistance, as reflected by lower cohesion and internal friction angle values of the composite. High factor of safety values are primarily governed by elevated internal friction angles and cohesion parameters. In contrast, composites incorporating lime and rice husk ash displayed a different trend in the factor of safety behavior. The addition of lime, both individually and in combination with rice husk ash, resulted in an increase in the factor of safety, with the maximum value reaching 21.67. It should be noted that this maximum value reflects idealized boundary conditions and does not account for long-term field factors such as waste settlement, dynamic loading, or full saturation conditions, which would likely reduce the overall factor of safety in practical applications. Furthermore, leachate curing treatment also contributed to higher factor of safety values, accompanied by improvements in cohesion and internal friction angle across all composite variations. All tested composite configurations, under the defined

modeling assumptions, satisfied the stability criteria, indicating a low potential for slope failure under controlled analytical conditions.

3.5 Microstructural Analysis (SEM–EDX)

SEM observations revealed the presence of surface cracks within the composite materials. At higher magnification, the micrographs showed that bentonite particles progressively filled and bridged the crack spaces, resulting in a denser and more compact microstructure. This infilling behavior reduced crack continuity and limited the formation of interconnected pore channels, which supports the observed decrease in hydraulic conductivity. However, the incorporation of lime and rice husk ash altered the swelling behavior of bentonite. The interaction between calcium derived from lime and silica-rich rice husk ash promoted pozzolanic reactions, leading to the formation of cementitious compounds. EDX analysis confirmed the presence of silica (Si), calcium (Ca), and aluminum (Al), corresponding to oxides such as SiO_2 , Al_2O_3 , and CaO . These components contribute to the development of secondary bonding phases that enhance matrix stiffness and structural integrity. While this reaction improves mechanical strength, it may partially restrict excessive bentonite swelling, explaining the variation in crack closure among composite formulations. It should be noted that the SEM analysis conducted in this study was primarily qualitative. Quantitative measurements of pore size distribution or crack width were not performed. Therefore, the SEM–EDX findings serve as microstructural support for the macroscopic permeability and shear strength results rather than as direct quantitative evidence. Future studies incorporating image-based pore analysis or advanced porosimetry techniques are recommended to further quantify the evolution of the pore network.

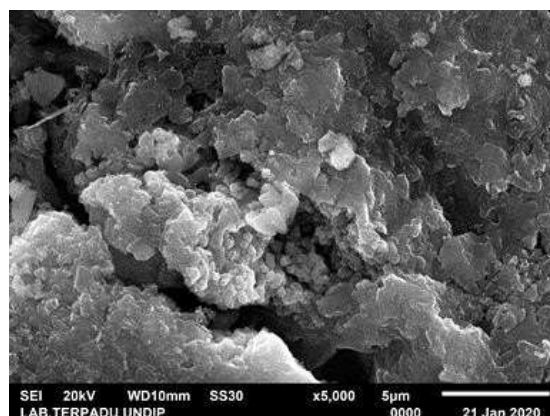


Fig 4. Composite SEM Results

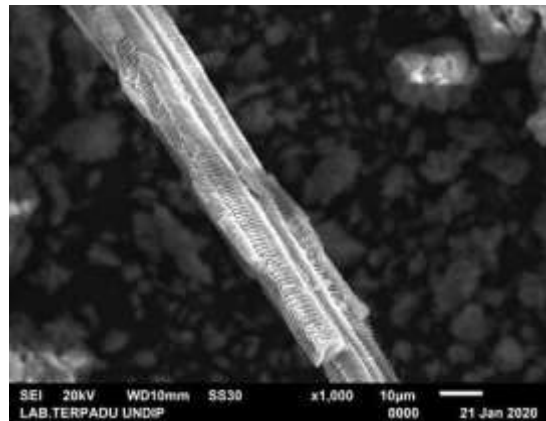


Fig 5. SEM Results of Rice Husk Ash

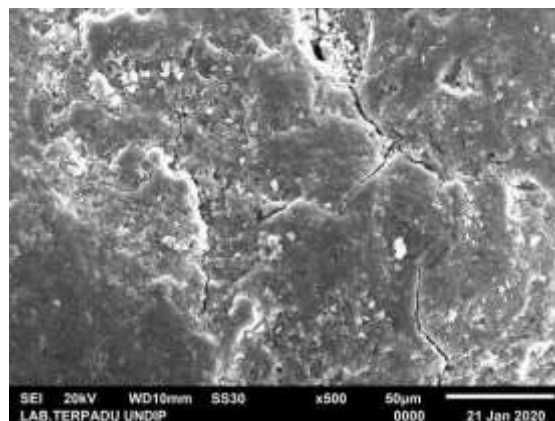


Fig 6. Composite Surface SEM Results

3.6. Environmental Risk Considerations

The utilization of dewatered textile sludge as a component of landfill liner materials requires careful consideration of potential environmental risks. Textile sludge may contain residual contaminants, such as heavy metals, dye compounds, and other industrial by-products, depending on the characteristics of the wastewater treatment process at the source facility. These contaminants may pose a risk if mobilized under long-term field conditions. In the present study, leachability testing, such as the Toxicity Characteristic Leaching Procedure (TCLP) or other standardized extraction methods, was not conducted. Therefore, the potential release of heavy metals or other contaminants from the composite liner material was not quantitatively evaluated. This represents a limitation of the current investigation and should be considered when interpreting the applicability of the material for large-scale implementation. Nevertheless, the incorporation of bentonite, lime, and rice husk ash may contribute to contaminant immobilization through several mechanisms. Bentonite possesses a high cation exchange capacity and adsorption potential, which can retain metal ions within its interlayer structure. Lime addition can increase pH and

promote the precipitation of metal hydroxides, thereby reducing metal solubility. Furthermore, pozzolanic reactions between calcium compounds and silica-rich rice husk ash can encapsulate contaminants within a denser cementitious matrix, limiting their mobility. These stabilization mechanisms are commonly reported in solidification–stabilization processes for contaminated materials. Future studies should include comprehensive leachability assessments, such as TCLP or long-term column leaching tests, to evaluate the environmental safety and regulatory compliance of the composite liner material. Such investigations are essential to confirm that the improved mechanical and hydraulic performance observed in this study is accompanied by adequate environmental protection under field conditions.

4. CONCLUSIONS

Pure dewatered sludge has the lowest initial moisture content and the lowest specific gravity, and it exhibits no plasticity. The characteristics of the composites vary with changes in the composition and percentage of dewatered textile-industry sludge. The addition of bentonite, lime, and rice husk ash decreased permeability, increased plasticity, and increased shrinkage strength, which led to cracking. Adding bentonite to dewatered sludge tends to decrease the internal friction angle and increase cohesion. Meanwhile, the addition of lime and rice husk ash caused fluctuations in cohesion and increased the internal friction angle. The safety factor of composites with added bentonite also decreased. The desiccation behavior of the composites was characterized by moisture reduction during drying, which induced surface cracking. Composites incorporating rice husk ash demonstrated lower crack intensity factors, indicating improved resistance to desiccation cracking under both minimum and maximum temperature conditions. Composite variations that may be used as an alternative cover liner, meeting the shrinkage limit criterion of less than 4% (to avoid cracking) and a permeability value less than or equal to 1×10^{-5} , include V10 (41% dewatered sludge, 50% bentonite, 1% lime, and 8% rice husk ash). The bottom-liner alternative is V4 (59% dewatered sludge, 40% bentonite, and 1% lime). Although the mechanical and hydraulic performance of the developed composites is promising, further investigation into the leaching behavior and environmental safety of dewatered textile sludge is necessary to ensure long-term compliance with environmental regulations. Comprehensive leachability testing is recommended before field-scale application.

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