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Geostability of dewatered sludge as landfill cover material

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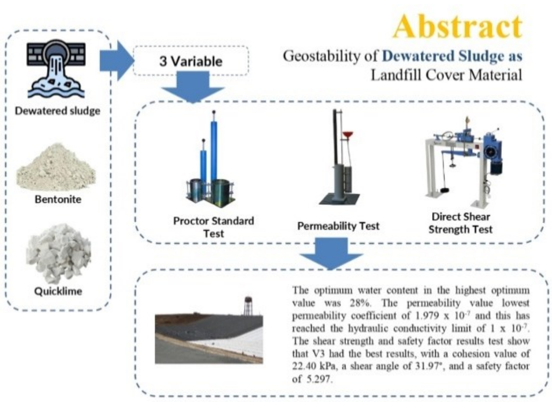
Graphical abstract



Abstract

Dewatered sludge is the main by-product from wastewater treatment and it contains various types of hazardous substances which can cause environmental pollution. The alternative utilization of sludge waste is for covering the landfill or as liner for the landfill. Landfill cover is a critical component to protect the surrounding environment from leachate contamination produced by landfills and it has specific characteristics. This study analyzes the optimum water content, permeability coefficient, and stability of the material consisting of a mixture of dewatered sludge, bentonite, and quicklime. The test results show that the optimum water content in the three composite variables meet the requirements; the highest optimum value was 28%, a mixture with a ratio of 84% sludge, 15% bentonite, and 1% quicklime. The results also show that mixing sewage sludge with bentonite significantly reduces the permeability value with a ratio of 80% sludge, and 20% bentonite produces the lowest permeability coefficient of 1.979×10^{-7} and this has reached the hydraulic conductivity limit of 1×10^{-7}. The shear strength and safety factor results test show that V3 had the best results, with a cohesion value of 22.40 kPa, a shear angle of 31.97°, and a safety factor of 5.297. The addition of bentonite tends to reduce the value of the safety factor. This safety factor can reach a high value because of the ratio of the total shear resistance to the working soil shear stress.

Keywords: dewatered sludge, landfill cover, stabilization, permeability

1. Introduction

Ever-increasing industrial growth has resulted in increasing disposal requirements and increasingly stringent environmental regulations, which cause the problem of sludge disposal from complex wastewater treatment in various cities (Malliou and Katsioti, 2007). One of the disturbing sources of waste from the wastewater and biological treatment plant is the large amount of sludge that is obtained, including microorganisms and harmful inorganic and organic substances (Świerczek *et al.*, 2018). Dewatered sludge is the main by-product from the wastewater treatment process. Mud waste contains various hazardous substances, which can cause secondary environmental pollution (Zhai *et al.*, 2012). Therefore, different utilization methods have been developed to treat dry sludge waste, such as combustion, pyrolysis, and landfill cover (Mphahlele *et al.*, 2021).

One waste sludge management alternative is to cover the landfill. It must be ensured that landfill has low permeability if natural soil is not sufficient to protect the surrounding environment from leachate contamination produced by the landfill (Dąbska, 2019). The presence of heavy metals, relatively high-water content, organic contaminants, and pathogens in dewatered sludge will have potentially harmful effects on soil and groundwater, thus requiring modifications to improve its mechanical properties if used as a cover in landfills (Song *et al.*, 2016; He *et al.*, 2015). A landfill system can safely prevent pollution caused by dry sludge (He *et al.*, 2015). In addition, pyrolysis of sewage sludge can transform the organic matter into clean fuel gases such as H_2, CH_4, and other products, to provide an alternative approach to dewatered sludge management (Zhu *et al.,* 2019).

Some researchers have studied the use of dewatered sludge for landfill cover and its properties and found that it is used because of its strength, hydraulic performance, and leaching toxicity (He *et al.,* 2015). When dewatered sludge is used for landfill cover, the sludge is usually modified with bentonite, cement, lime, and fly ash (He *et al.,* 2015; Kamon *et al.,* 2002). Dewatered sludge usually has high water content and low shear strength, making it difficult for the sludge to be compacted and used as a landfill cover (Li *et al.,*2014). The low shear strength of sewage sludge can cause instability and cell structure in landfills (Lo *et al.,* 2002). Lim, Jeon (Lim *et al.*, 2002) modified it with hydrated lime, loess, and fly ash to increase the shear strength of the sludge Lim. Tang, Li (Tang *et al.*, 2012) used fly ash and lime to stabilize the river silt. Kim, Cho (Kim *et al.*, 2005) modified the sewage sludge with converter slag and quick lime as additives. As well in the research of Rosli, Aziz (Rosli *et al.*, 2020) added red gypsum as a mixed waste sludge material for alternative landfill cover materials. However, many of the studies were repetitive involving the same materials and focused on shear strength and stability as the main criteria for evaluation. There are still few studies that include the standard proctor test in determining the optimum moisture content and soil density in each mixture as a consideration for the composite material for the landfill layer. In addition, in this study bentonite was used as a mixture of leachate retaining layer for landfill which has proven its feasibility and is able to reduce the hydraulic coefficient to 1.0 x 10^{-7} (Budihardjo *et al.*, 2021).

One of the things considered in constructing a landfill layer is hydraulic conductivity (Dąbska *et al.*, 2019). The hydraulic conductivity of landfill cover materials should be tested using at least laboratory and field methods. The results of research by He, Li (He *et al.*, 2015) show that adding dewatered sludge to building materials can increase the compressive strength and hydraulic conductivity to a maximum of 3.1 x 10^{-7} cm/s. According to CJJ 17-2004 (Technical Code For Municipal Solid Waste Sanitary Landfill In China) the upper limit of hydraulic conductivity in landfill covers should be less than 1.0 x 10^{-7}. Li, Liu (Li *et al.*, 2003) suggest that the hydraulic conductivity of the landfill cover be maintained at a value of 10^{-4} cm/s, but this value is quite low for traditional landfills in reducing leachate output. Meanwhile, based on the saturated-unsaturated seepage, it is recommended to range between 1.0 x 10^{-4} cm/s and 1.0 x 10^{-5} cm/s because they are appropriate values for the hydraulic conductivity of daily cover and temporary cover (He *et al.*, 2015). Kamon, Inazumi (Kamon, 2002) suggest that the hydraulic conductivity of modified waste sludge used in landfill cover is less than 1.0 x 10^{-5} cm/s; with this hydraulic conductivity value, the daily cover system can hold rainwater at a satisfactory level. European Union regulations stipulate that landfill covering materials for hazardous and non-hazardous wastes should have a permeability less than or equal to 1.0 x10^{-9} m/s or for final moist disposal less than or equal to 1.0 x 10^{-7} m/s.

According to the results of previous studies, dewatered sludge has high potential as a landfill coating material. Mud and fly ash can be used as additives to build the framework. The hydraulic conductivity of the modified slurry is usually very low, in the range of 1 x 10^{-7} cm/s (He *et al.*, 2015). In this study, the modified materials used to change the properties of the mud, namely bentonite and quicklime, have been used for the combination. Therefore, this study aims to conduct various tests on various mixtures of dewatered sludge, bentonite, and quicklime that are suitable as landfill. coatings in terms of optimum moisture content, permeability, and stability suitable for landfill cover.

Table 1. Dewatered sludge modification composite variation

Variable	Composition
V_1	80% dewatered sludge + 20% Bentonite
V_2	79% dewatered sludge + 20%bentonite + 1%quicklime
V_3	84% dewatered sludge + 15% bentonite + 1% quicklime

2. Methodology

2.1. Materials

In this study, the dewatered sludge was taken from a local water company in the city of Demak. Modification materials are quicklime and bentonite, which are used to modify the mud. The sewage sludge is used to form the skeleton in the modified sludge. Sludge has a relatively high moisture content, relatively high liquid and plastic limits, and low permeability. In addition, the mud usually exhibits low strength, which cannot be measured indefini-tely in the compressive test (He *et al.*, 2015). Therefore, the sludge is not suitable for direct use as a landfill cover material.

Bentonite is clay with high plasticity and colloidal solid properties, and its volume increases several times when in contact with water, forming gelatinous and viscous liquids. The unique properties of bentonite are its capacity to absorb water, its viscosity, hydration, and swelling, and its thixotropy make it a valuable material for various uses and mixtures (Dimirkou *et al.*, 2002). Combining bentonite with coarser aggregates, such as sand, can increase strength and avoid shrinkage cracking problems (Kleppe and Olson, 1985). Based on the research of Deka and Bhattacharjee (Deka and Bhattacharjee, 2017) using bentonite levels of 5%, 7%, 10%, 15%, and 20%, it was found that with the addition of bentonite the permeability coefficient decreased significantly, cohesion increased and the internal friction angle decreased. While research conducted by Akcanca and Aytekin (Akcanca and Aytekin, 2014) with bentonite compositions of 20%, 30%, 40% and 50% of the soil, it was found that the more use of bentonite in the mixture, the lower the value of hydraulic conductivity. As for quicklime, the optimum level is 1% because it can increase the hydraulic conductivity of the mixture. In the study, it was shown that the mixing of bentonite and quicklime more than 1% will cause an increase in the permeability value so that the possibility of leachate escape is greater. Therefore, the composition used to modify the sewage sludge consists of sewage sludge, bentonite, and quicklime which is divided into three variations which can be seen in Table 1.

Mixing quicklime in bentonite for the leachate retaining layer of a landfill can increase the optimum water content, reduce the dry density, and increase the material's compressive strength (Firoozfar and Khosroshiri, 2017). However, adding excess lime will potentially increase the permeability, affecting the performance as a leachate retaining layer (Bozbey and Guler, 2006).

2.2. Analytical methods

Preliminary tests were carried out first, consisting of standard Proctor tests and Atterberg limit tests. Meanwhile, direct shear strength and permeability tests were carried out to determine the stability and hydraulic conductivity of the composite variation as a landfill coating. The Atterberg limit test was carried out to determine the shrinkage limit, plastic limit, and liquid limit according to ASTM D-4318. Tests and percentage calculations were carried out using the shadow method based on ASTM D 422-63 (ASTM, D., *422-63 (2007), 2011*). The calculation formula can be seen in formula (1).

$$\textit{Retained Percentage} = \frac{\text{Weight Hold}}{\text{Total weight}} \text{x100\%} \qquad (1)$$

The modified sludge material with various compositions of bentonite and quicklime mixture was tested for water content to determine the optimum water content in the modified waste sludge with the standard Proctor test method based on ASTM D-698. The standard Proctor test used a press tool to compact the soil. The standard Proctor test compacted the ground in a cylindrical mold. During the experiment, the mold was glued to a base plate, and it was given a cylindrical extension. Modified variations of sewage sludge are given water and then compacted using a special pounder.

In addition, a permeability test was carried out using the falling head method from AS 1289.6.7.2-2001. The falling head permeability test uses water dripping through a soil sample attached to a standpipe filled with water. The vertical pipe is equipped with a height unit to calculate how much water moves through the model. The test is carried out by passing water through the soil sample to the water level in the vertical pipe. The soil used must be wet, and the vertical line must be filled with water to a certain height before measurements are made. In most cases, the falling head test has been carried out for the permeability test to obtain the average value.

A direct shear test was also carried out to determine the stability of the composite, which displays the value of the safety factor. GeoSlope/W software was used to analyze the results of the importance of the aspect of soil safety and slopes using the equilibrium limit. Direct shear testing was carried out following the ASTM D3080 test standard, which confirmed the parameters of the shear strength of the cohesive soil (c) and the shear angle of the earth (Ø) (Chen *et al.*, 2011). The value of shear strength can be obtained from the formula obtained from Mohr-Coulomb, which is shown in formula (2) (Budihardjo *et al.*, 2021).

$$\tau = c' + \sigma'n. \text{ Tan } \text{Ø}' \qquad (2)$$

Where is the shear strength of the soil, c' is the cohesion of the ground, σ' is the effective soil stress on the soil plane, and Ø' is the internal shear angle. Direct shear strength testing is done manually with a direct shear tool. This test was carried out on composite variations preserved with distilled water for 24 hours. The same treatment was carried out on combined variations that had been soaked in leachate for 24 hours.

3. Results and discussion

3.1. Proctor standard test

The use of sewage sludge as a landfill cover material is modified with a variety of different compositions. Water content is one aspect that affects permeability, where the permeability will affect the hydraulic conductivity of the landfill cover (Liu *et al.*, 2022). Compaction is carried out to reduce soil volume, a reduced pore volume, but not reduced grain volume. According to Meer and Benson (Meer and Benson, 2007), water content is a crucial factor controlling hydraulic conductivity. In this water content test, the proctor test determines the optimum water content (OMC) and maximum dry weight (MDD) of the modified waste sludge used for landfill cover. The composite variation of 79% sewage sludge, 20% bentonite, and 1% quicklime produced the highest optimum water content. In contrast, the composite variable with the composition of 84% sewage sludge, 15% bentonite, and 1% quicklime had the lowest optimum water content value.

Table 2. Proctor standard test results

No. Sample	Composition	OMC (%)	MDD (gr/cm^3)
V_1	80% dewatered sludge + 20% bentonite	30.5	1.32
V_2	79% dewatered sludge + 20% bentonite + 1% quicklime	33.8	1.3
V_3	84% dewatered sludge + 15% bentonite + 1% quicklime	28	1.345

It can be seen from Table 2 that, for composite variable three, the sewage sludge significantly reached the optimum water content with a value of 28%. The optimum moisture content decreased substantially from 33.8% to 28%, along with the addition of sewage sludge from 79% to 84% sewage sludge and a reduction in bentonite content from 20% to 15%. This shows that the higher the addition of bentonite, the more it causes an increase in OMC and a decrease in MDD. This is in line with the research of Rout and Singh (Rout and Singh, 2017), which stated that adding bentonite could increase the OMC value until the bentonite content reaches the optimal value. The results of the standard Proctor test can be seen in Figures 1(a)-(c), which shows the relationship between MDD and OMC. According to He, Li (He *et al.*, 2015) (Chen *et al.*, 2013), it is crucial to maintain the solid content at a level greater than 60%; in other words, the optimum moisture content required to meet the landfill cover moisture content requirements is less than 40%. Therefore, it is crucial to control the water content of the modified waste sludge, because the compressive strength value will be relatively high, and the conductivity value will increase with the increase in water content (He *et al.*, 2015). The three composite variables have met the OMC requirements for landfill cover.

The addition of lime to the composite also causes changes in the OMC and MDD values. This is due to the reaction between water and one material with other materials (Sahu *et al.*, 2017). The nature of lime is very reactive with water and can produce pores in the particles (Dhandapani and Santhanam, 2017). The addition of lime showed an increase in the value of OMC and MDD, as happened in V2, where the OMC value increased after adding lime, and V3 increased MDD after adding lime. However, adding excessive lime will reduce the OMC and MDD values drastically (Budihardjo *et al.*, 2021). A small percentage of lime will cause hardening without producing too many pores. At the same time, a large portion of lime will cause so many pores that the density decreases (Martínez-García *et al.*, 2019).

3.2. Permeability test

The permeability coefficient is influenced by several factors, namely the viscosity of the liquid, the grain size distribution, the number of pores, the grain surface roughness, and the degree of soil saturation. In addition, other factors that affect the seepage of clay are the concentration of ions and the thickness of the water layer attached to the clay grains (Budihardjo *et al.*, 2021). The hydraulic conductivity of modified sewage sludge is usually very low, in the range of 1 x 10^{-7} cm/s (Ng and Lo, 2007). According to McBean (McBean, 1995), the permeability coefficient of municipal solid waste usually ranges from 1.0 x 10^{-5} to 1.0 x 10^{-2}. In this study, all composite variables had a lower coefficient value (~10^{-7}cm/s) than the stabilized sludge from previous studies. This follows the research by Li, Liu (Li *et al.*, 2014), which found a permeability coefficient value (~10^{-6} cm/s) so the risk of heavy metals and organic matter entering the leachate is low because it has a lower permeability coefficient.

Table 3. Permeability test results

Variable	Composition	Permeability (%)	Plastic Index (%)
V_1	80% dewatered sludge + 20% bentonite	1.979 x 10^{-7}	44.19
V_2	79% dewatered sludge + 20% bentonite + 1% quicklime	3.965 x 10^{-7}	46.93
V_3	84% dewatered sludge + 15% bentonite + 1% quicklime	3.969 x 10^{-7}	42.45

Table 4. Direct shear test results

Variable	Normal Stress	Shear Stress (σ)	Cohesion (c')	Internal Friction Angle(Ø)	Safety Factor
	KPa	kg.cm^{-2}	kPa		
V_1	15.78	31.5	20.80	32.87	4.74
	31.56	40.2			
	47.34	51.9			
V_2	15.78	32	21.33	33.13	4.517
	31.56	41.2			
	47.34	52.6			
V_3	15.78	31.8	22.4	31.97	5.297
	31.56	43			
	47.34	51.5			

The first variable in the composite used a composition of 80% sludge and 20% bentonite, which had the lowest coefficient of permeability compared to other composite variables. This is due to the specific content of each material. In addition, the results of previous research by Pandey and Jain (Pandey and Jain, 2017) show that the optimal value of the bentonite content used for the mixture was 20%. The composite variable with the maximum permeability coefficient value is variable 3, with a composition of 84% sludge, 15% bentonites, and 1% quicklime. Katsioti, Katsiotis (Katsioti at al., 2008) suggest that mixing 50% wet sewage sludge with 20% bentonite and 30% cement was sufficient to stabilize and produce a material that could be applied as an additive in landfill liners. The three composite variables meet the coefficient of permeability of the landfill cover. Adding bentonite to the sewage sludge mixture can reduce leachate seepage into the soil (Katsioti at al., 2008).

From the results of the permeability test in Table 3, it can be seen that mixing sewage sludge with bentonite significantly reduces the permeability value. The test results show that adding bentonite in the composite variation decreases the permeability coefficient value and affects the plasticity index value (Budihardjo *et al.*, 2021). The permeability value decreases with the addition of bentonite (Daniels *et al.*, 2017). The decrease in the permeability coefficient value in the composite variation consisting of dry mud and bentonite is caused by the bentonite development process, which causes the pores between particles to become narrow. The lower the value of the permeability coefficient, the more the value of the plasticity index will increase (Roy and Bhalla, 2017). The composite plasticity index is an indicator that shows whether water can seep and make it plastic. The addition of lime also causes a decrease in the permeability value because lime has properties as a binding material, such as plasticity, ease of hardening, and good bonding power

(Nugroho *et al.*, 2019). However, higher lime content causes clumping between lime and mud, which causes enlargement of the pores, and the permeability value increases (Budihardjo *et al.*, 2021).

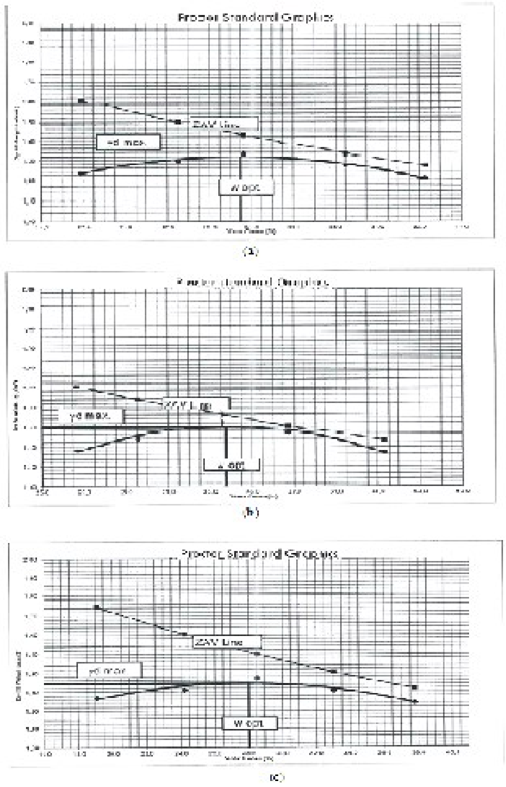


Figure 1. Relationship between OMC and MDD (a) composite variation V1 (b) composite variation V2 (c) composite variation V3. Source: author's analysis, 2022

3.3. Soil shear strength and stability analysis

An important factor in selecting materials for a landfill containment system is the strength of the material to withstand loads vertically and horizontally (Weerasinghe *et al.*, 2020). The direct shear strength test is used to determine the stability of the material used in the leachate retaining layer on the landfill slope (Lin *et al.*, 2018). The shear strength of the sewage sludge is required to assess slope stability in the landfill (Zhan *et al.*, 2008). When testing the shear strength of modified sewage sludge, bentonite and lime were stored for seven days in a humidity control chamber at a constant temperature of 20 ºC and relative humidity greater than 95%, which contributed to the stability of the composite for the landfill coating during the shear strength test. The use of manual direct shear test equipment also causes lever rotation speed instability, which can affect the reading of the shear observation. In addition, fluctuating results were also obtained due to differences in the homogeneity of each composite and differences in the characteristics of the waste sludge that was used from the start.

Table 4 shows that the addition of bentonite affects the effect of shear stress. This is because adding bentonite will fill the space between the aggregates, thereby reducing the amount of friction (Taheri *et al.*, 2018). The highest value of shear strength is found in the V_3 composite variation with the addition of 15% bentonite. The internal shear angle and cohesion are parameters of the shear strength of the composite (Wei *et al.*, 2018). The inner shear angle shows the stability, which is converted in the form of an angle. Cohesion offers adhesion between composite particles to maintain their strength. The direct shear strength test results show that the use of bentonite in the composite causes an increase in the cohesion value. The decrease in internal shear angle is caused by the addition of bentonite, which causes the aggregate friction to decrease (Ozhan, 2021). The compositional differences in the composite variables also affect the addition and subtraction of cohesive values and internal shear angles (Yang *et al.*, 2021).

Table 4 in V_1 and V_2, it was found that quicklime affects the increase in the effect of shear stress. Composite cohesiveness changes after adding lime. The cohesiveness value of V_1, which contains 80% sludge and 20% bentonite, has the lowest value, while in V_2, which includes 79% sludge, 20% bentonite, and 1% quicklime, the cohesiveness value increases. The contact between clay minerals and lime is caused by the reaction of lime with aggregates (sludge and bentonite) (Liu *et al.*, 2018). This reaction results in ion exchange which produces calcium silica gel that does not decompose in water, resulting in clumping, which causes the closing of the pores of the aggregate, thereby increasing the stability of the aggregate (Muente *et al.*, 2022). The addition of shear angle also occurs in V_1 and V_2 due to the role of lime in the composite, which increases the bonding power between particles and causes the internal shear angle to increase. In addition, other factors that cause a decrease in the internal shear angle can be the composite's homogeneity and the sewage sludge's shape (Korol *et al.*, 2020).

Based on Table 4, the safety factor value of composite V_1, which consists of 80% sludge and 20% bentonite, has the lowest safety factor value. At the same time, the V_3 composite variation, which contains 84% sludge, 15% bentonite, and 1% quicklime, has the highest, value. From the analysis results using the Geoslope/W, the safety factor value ranges from 4 to 5. The increase in safety factor was highest when it was given 15% bentonite content and 1% lime addition. The decrease in a safety factor and the reduction in shear strength are represented by the value of cohesion and the internal shear angle of the composite (Arvin *et al.*, 2021). The value of the safety factor can reach a high value because it is the ratio of the total shear resistance to the shear stress of the working soil, so the composite shear resistance is more excellent than the shear stress (Kererat, 2019).

4. Conclusion

This study used bentonite and quicklime as admixtures to stabilize the sewage sludge. The geotechnical properties in this study can meet the requirements for landfill cover. Based on the standard proctor test, it can see that the optimum water content in each variable meets the requirement that it is less than 40%. The optimum water content decreased significantly from 33.8% to 28%, along with the addition of sewage sludge from 79% to 84% sewage sludge.

The falling head permeability test found that the three composite variables met the landfill layer's permeability coefficient, ranging from 10-6 cm/s. The addition of bentonite causes a decrease in the value of the permeability coefficient. As a result, the permeability coefficient of dewatered sludge is lower (~10-7 cm/s) than the stability of the waste sludge in previous studies (~10-5 cm/s and ~10-6 cm/s). This results in a lower risk of heavy metals and organic matter entering the leachate because it has a lower permeability coefficient.

The shear strength and safety factor test results showed that V_3 had the best results, with a cohesion value of 22.40 kPa, a shear angle of 31.97°, and a safety factor of 5.297. The addition of bentonite tends to decrease the value of the safety factor. The safety factor can reach a high value because it is the ratio of the total shear resistance to the shear stress of the working soil so that the composite shear resistance is much better than the shear stress.

Based on the research, it has been found that of the three composites, V3 has the best results with a low optimum moisture content value of 28%, a permeability value lower than 10^{-6}, and the highest safety factor value of 5,297. It is recommended in further research, the use of sewage sludge to be taken at the same time in all tests so that the characteristics of the sludge obtained are uniform. This is intended to avoid the possibility of significant differences in the characteristics of the sewage sludge which will affect the test results.

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References

Akcanca F., and Aytekin M. (2014). Impact of wetting–drying cycles on the hydraulic conductivity of liners made of lime-stabilized sand–bentonite mixtures for sanitary landfills. *Environmental Earth Sciences*, **72**(1), 59–66.

Arvin M.R., Abbasi M., and Fahliani H.K. (2021). Shear behavior of geocell-geofoam composite. *Geotextiles and Geomembranes*, **49**(1), 188–195.

ASTM, D., *422-63 (2007).* (2011). Standard test method for particle-size analysis of soils.

Bozbey I., and Guler E. (2006). Laboratory and field testing for utilization of an excavated soil as landfill liner material. *Waste Management*, **26**(11), 1277–1286.

Budihardjo M A., Syafrudin., Bagus P.I., and Surya R.B. (2021). Hydraulic Stability of Fly Ash-Bentonite Mixtures in Landfill Containment System. *Journal of Ecological Engineering*, **22**(7), 132–141.

Budihardjo M., Hadiwidodo M., Wardhana I.W., Praptomo E.G., Samadikun B.P., Puspita A.S., and Ramadan B. S. (2021). Stability performance of demolition waste composite as landfill liner. in IOP Conference Series. *Earth and Environmental Science,* IOP Publishing.

Budihardjo M.A. *et al.* (2021). Hydraulic Stability of Fly Ash-Bentonite Mixtures in Landfill Containment System. *Journal of Ecological Engineering*, **22**(7).

Chen A., Cu Y., Zheng X., Yang J., and Chen P., Research on advanced dewatered sewage sludge as intermediate cover soil at refuse landfill site. *China Water Wastewater*, **27**(19), 85–87.

Chen P., Lin W.A., Zhan X.J., and Jiang Y.Y. (2013). Influence of leachate soaking on strength and permeability of deeply dewatered sewage sludge. *Rock and Soil Mechanics*, **34**(2), 337–341.

Dąbska A. (2019). Hydraulic conductivity of compacted lime-softening sludge used as landfill liners. *Water, Air, & Soil Pollution*, **230**(12), 1–16.

Daniels K.A., Harrington J.F., and Zihms S.G. (2017). Wiseall A. C., Bentonite permeability at elevated temperature. *Geosciences*, **7**(1), 3.

Deka K., and Bhattacharjee A. (2017). Improvement of Brahmaputra silt for embankment construction. *In Indian Geotechnical Conference*.

Dhandapani Y., and Santhanam M. (2017). Assessment of pore structure evolution in the limestone calcined clay cementitious system and its implications for performance. *Cement and Concrete Composites*, **84**, 36–47.

Dimirkou A., Ioannou A., and Doula M. (2002). Preparation, characterization and sorption properties for phosphates of hematite, bentonite and bentonite–hematite systems. *Advances in Colloid and Interface Science*, **97**(1–3), 37–61.

Firoozfar A., and Khosroshiri N. (2017). Kerman clay improvement by lime and bentonite to be used as materials of landfill liner. *Geotechnical and Geological Engineering*, **35**(2), 559–571.

He J., Li F., Li Y., and Cui X. (2015). Modified sewage sludge as temporary landfill cover material. *Water Science and Engineering*, **8**(3), 257–262.

Kamon M. (2002). Evaluation of waste sludge compatibility for landfill cover application. *Soils and Foundations*, **42**(4), 13–27.

Kamon M., Inazumi S., and Katsumi T. (2002). Performance evaluations of landfill cover systems with sludge barriers. *Geotechnical Engineering*, **33**(3), 113–132.

Katsioti M., Katsiotis N., Rouni G., Bakirtzis D., and Loizidou M. (2008). The effect of bentonite/cement mortar for the stabilization/solidification of sewage sludge containing heavy metals. *Cement and Concrete Composites*, **30**(10), 1013–1019.

Kererat C. (2019). Effect of oil-contamination and water saturation on the bearing capacity and shear strength parameters of silty sandy soil. *Engineering Geology*, **257**, 105138.

Kim E.-H., Cho J.-K., and Yim S. (2005). Digested sewage sludge solidification by converter slag for landfill cover. *Chemosphere*, **59**(3), 387–395.

Kleppe J.H., and Olson R.E. (2017). Desiccation cracking of soil barriers, **263**, 1985: ASTM International.

Korol J., Glodniok M., Hejna A., Pawlik T., Chmielnicki B., and Bondaruk J. (2020). Manufacturing of lightweight aggregates as an auspicious method of sewage sludge utilization. *Materials*, **13**(24), 5635.

Li Q., Liu D., and Yang L. (2003). Selection of temporary cover materials for bioreactor landfills. *Environmental Science & Technology*, **26**, 29–30.

Li Y., Liu W., Chen YJ.Y., Shi Y.F., Mao W., Liu H., Li Y., He S., and Yang J.K. (2014). Reuse of dewatered sewage sludge conditioned with skeleton builders as landfill cover material. *International Journal of Environmental Science and Technology*, **11**(1), 233–240.

Lim S., Jeon W., Lee J., Lee K., and Kim N., Engineering properties of water/wastewater-treatment sludge modified by hydrated lime, fly ash and loess. *Water research*, **36**(17), 4177–4184.

Lin H., Zhang L., and Xiong Y. (2018). Research on shear strength of needle-punched GCL by simple-shear of composite liner. *Engineering Geology*, **244**, 86–95.

Liu D., Edraki M., and Berry L. (2018). Investigating the settling behaviour of saline tailing suspensions using kaolinite, bentonite, and illite clay minerals. *Powder Technology*, **326**, 228–236.

Liu M., Lu H., Deng Q., Ji S., Qin L., and Wan Y. (2022). Shear strength, water permeability and microstructure of modified municipal sludge based on industrial solid waste containing calcium used as landfill cover materials. *Waste Management*, **145**, 20–28.

Lo I.M., Zhou W., and Lee K.M. (2002). Geotechnical characterization of dewatered sewage sludge for landfill disposal. *Canadian Geotechnical Journal*, **39**(5), 1139–1149.

Malliou O., and Katsioti M. (2007). *Properties of stabilized/solidified admixtures of cement and sewage sludge. Cement and Concrete Composites*, **29**(1), 55–61.

Martínez-García C., González-Fonteboa B., Carro-López D., and Martínez-Abella F. (2019). Impact of mussel shell aggregates on air lime mortars. Pore structure and carbonation. *Journal of cleaner production*, **215**, 650–668.

McBean E.A. (1995). *Solid waste landfill engineering and design*.

Meer S.R., and Benson C.H. (2007). Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers. *Journal of Geotechnical and Geoenvironmental Engineering*, **133**(5), 550–563.

Mphahlele K., Matjie R.H., and Osifo P.O. (2021). Thermodynamics, kinetics and thermal decomposition characteristics of sewage sludge during slow pyrolysis. *Journal of Environmental Management*, **284**, 112006.

Muente A., Cipriani-Avila I., Garcia-Villacis K., Pinos-Velez V., Hidalgo-Lasso D., Ruiz P., and Luna V. (2022). Evaluation of the Use of Lime and Nanosilica for the Improvement of Clay Soil Structure and Degradation of Hydrocarbons. *Pollutants*, **2**(4), 422–434.

Ng K.T., and Lo I.M. (2007). Mechanical behaviors of a synthetic paste of tire chips and paper sludge in MSW landfill daily cover applications. *Canadian geotechnical journal*, **44**(8), 928–941.

Nugroho S.A., Zulnasari A., Fatnanta F., and Putra A.D. (2019). Mechanical Behavior of Clay Soil Stabilized with Fly Ash and Bottom Ash. *Makara Journal of Technology*, **26**(1), 1.

Ozhan H.O. (2021). Determination of mechanical and hydraulic properties of polyacrylamide-added bentonite-sand mixtures. *Bulletin of Engineering Geology and the Environment*, **80**(3), 2557–2571.

Pandey M., and Jain P. (2017). Compaction and seepage characteristics of fly ash mixed with bentonite. *International Research Journal of Engineering and Technology*, **4**(3), 2277–2280.

Rosli N.A., Aziz H A., Selamat M.R., and Lim L.L.P. (2020). A mixture of sewage sludge and red gypsum as an alternative material for temporary landfill cover. *Journal of environmental management*, **263**, 110420.

Rout S., and Singh S.P. (2017). Effects of Molding Moisture Content on Strength and Hydraulic Properties of Pond Ash-Bentonite Mixes. In *Indian Geotechnical Conference*.

Roy S., and Bhalla S.K. (2017). Role of geotechnical properties of soil on civil engineering structures. *Resources and Environment*, **7**(4), 103–109.

Sahu V., Srivastava A., Misra A.K., and Sharma A. K. (2017). Stabilization of fly ash and lime sludge composites: Assessment of its performance as base course material. *Archives of civil and mechanical engineering*, **17**(3), 475–485.

Song J., Yang J., Liang S., Shi Y., Yu W., Li C., Xu X., Xiao J., Guan R., Ye N., Wu X., Hou H., Hu J., and Xiao B. (2016). Red mud enhanced hydrogen production from pyrolysis of deep-dewatered sludge cakes conditioned with Fenton's reagent and red mud. *International Journal of Hydrogen Energy*, **41**(38), 16762–16771.

Świerczek L., Cieślik B.M., and Konieczka P. (2018). *The* potential of raw sewage sludge in construction industry–a review. *Journal of cleaner production*, **200**, 342–356.

Taheri S., Ebadi T., Maknoon R., and Amiri M. (2018). Predicting variations in the permeability and strength parameters of a sand-bentonite mixture (SBM) contaminated simultaneously with lead (II) and diesel. *Applied Clay Science*, **157**, 102–110.

Tang H., Li X., Li M., Song L., Wu Z., and Xu H. (2012). Properties and mechanism of CFBC fly ash-cement based stabilizers for lake sludge. *Journal of Wuhan University of Technology-Mater. Science. Edition*.,**27**(4), 750–753.

Weerasinghe I., Gallage, C., Dawes L., and Kendall P. (2020). Factors affecting the hydraulic performance of a geosynthetic clay liner overlap. *Journal of Environmental Management*, **271**, 110978.

Wei J., Binglin S., Jinlin L., Shasha L., and Xiubin H. (2018). Shear strength of purple soil bunds under different soil water contents and dry densities: A case study in the Three Gorges Reservoir Area, China. *Catena*, **166**, 124–133.

Yang J., Bunchatheeravate P., Thakur S. C., Bullard J. W., and Curtis J.S. (2021). Experimental and numerical investigations of the shear behavior of binary particle blends. *AIChE Journal*, **67**(1), e17090.

Zhai Y., Peng W., Zeng G., Fu Z., Lan Y., Chen H., Wang C., and Fan, X. (2012). Pyrolysis characteristics and kinetics of sewage sludge for different sizes and heating rates. *Journal of thermal analysis and calorimetry*, **107**(3), 1015–1022.

Zhan T.L., Chen Y., and Ling W. (2008). Shear strength characterization of municipal solid waste at the Suzhou landfill, China. *Engineering Geology*, **97**(3–4), 97–111.

Zhu X., Zhao L., Fu F., Yang Z., Li F., Yuan W., Zhou M., Fang W., Zhen G., Lu X., and Zhang X. (2019). Pyrolysis of pre-dried dewatered sewage sludge under different heating rates: Characteristics and kinetics study. *Fuel*, **255**, 115591.