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EFFECTIVENESS OF COMPACTED POLYURETHANE-CLAY AS A SANITARY LANDFILL LINER

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ABSTRACT: Sanitary landfill is a waste disposal facility that has control over the potential impact of solid waste by using impermeable liners to prevent contamination of the environment. Several studies improved the impermeability of compacted clay liners by adding bentonite. However, bentonite is an expansive soil susceptible to volume change that would cause the deterioration of the sanitary landfill liner. Hence, the study aimed to investigate the effectiveness of compacted clay mixed with polyurethane as a sanitary landfill liner since polyurethane is a polymer known for its stability and impermeability. Through experimentation using a rigid wall permeameter, it was inferred that the hydraulic conductivity of the compacted polyurethane-clay is acceptable as a sanitary landfill liner. On the other hand, the compacted clay with the same initial void ratio as the compacted polyurethane-clay is not an acceptable landfill liner. Thus, the changes in the soil structure induced by adding polyurethane to the clay has a significant effect on the permeability characteristics.

Keywords: Polyurethane, Clay, Sanitary Landfill Liner, Permeability

1. INTRODUCTION

It was believed that the leachate produced from the degradation of waste was filtered by the soil; however, several studies showed that leachate contaminates the surrounding soil and eventually will contaminate the groundwater system [1]. Thus, sanitary landfill (SLF), a waste disposal facility, was developed to have an impermeable layer that prevents the infiltration of leachate and the contamination of the surrounding environment [1].

There are different kinds of impermeable materials that may be used as an SLF liner, such as clay, geomembrane, geotextiles, geosynthetic clay liner, geonet, or a combination of these materials [1]. Among these materials, compacted clay liner is preferred due to the abundance and availability of native clay. A layer of clay used as an SLF liner is compacted to lower the hydraulic conductivity, a measure of permeability, and to remold the soil aggregates into a homogenous soil mass. Different factors such as moisture content of the clay, method of compaction, and compactive effort influence the hydraulic conductivity of the compacted clay liner [2]. In actual practice, the hydraulic conductivity of clay is further reduced by incorporating bentonite. It was inferred that the addition of bentonite in the native clay mixture is effective in reducing the permeability of bentonite-modified clay [3]. However, bentonite, which consists of montmorillonite minerals, increases the shrinkage capability of the soil mixture when subjected to a decrease in moisture content [3]. Thus, the study aims to incorporate an impermeable and stable material into the soil matrix of a local clay, which would yield a hydraulic conductivity that is acceptable as an SLF liner based on the standard design criteria. Such material that may be incorporated into the soil matrix are polymers.

Polymers stabilize soil through the reduction of the rate of water invasion into the soil structure [4]. The effectiveness of polymers in increasing the water-stable aggregation is related to the strength of interparticle bonding induced by the material [4]. Polyurethane (PU) is a polymer formed from the chemical reaction between polyol and isocyanate that produce the repeating unit in the polymer, urethane [5]. Polyurethane is widely used in the construction industry for ground improvement of expansive soils. Inclusion of polyurethane foam in the soil mass through mixing successfully increased the shear strength of marine clay, a soil characterized by excessive volume change [5]. Application of polyurethane also includes decreasing soil settlement when used as a grout; moreover, polyurethane grout micro piles improve the response of the ground to dynamic forces [5]. A study has also shown that polyurethane foam, when injected into the ground, is found to improve strength, stiffness, and bearing resistance [5]. Aside from the ground improvement in terms of strength, polyurethane injection was also inferred to lower permeability of cracked expansive soils. A study about the effects of polyurethane resin injection in desiccated expansive soil mass showed that the veins of the injected polyurethane resin acted as a moisture barrier better that intact clay; in addition, the injected polyurethane resin did not increase the swelling of the soil mass [6].

2. RESEARCH SIGNIFICANCE

In a developing country like the Philippines, the sudden growth in population and shift in living conditions yield a growth in solid wastes, which are not properly disposed of. Hence, safe waste disposal facilities, such as SLFs lined with impermeable and accessible materials, could help in alleviating the problem in disposing of the growing amount of solid waste. The stability and improved impermeability of the clay mixed with polyurethane could help small communities that do not have the capacity to construct a state-of-the-art disposal facility. Moreover, there are only few studies regarding the properties of clay mixed with polyurethane and there are none regarding the hydraulic conductivity of such mixture. Thus, the findings in the research may contribute to the overall body of knowledge about the behavior of the soil matrix of polyurethane-clay.

3. EXPERIMENTAL PROGRAM

3.1 Materials

The two components of the compacted polyurethane-clay include the local clay and the rigid polyurethane foam. The expansive soil used in the study was from a proposed SLF site in Kauswagan, Lanao del Norte and was excavated at least 2 meters below the ground to ensure that no organic matter is present in the soil mass. ASTM standards were used to determine the different soil properties necessary for computational purposes and to analyze the control specimen, the compacted local clay. The soil properties of the excavated soil from Kauswagan, Lanao del Norte is tabulated in Table 1.

Table 1 Soil properties of local clay

Standard	Soil property	
D698	Optimum moisture content (%)	31.15
D854	Specific gravity	2.41
D4318	Liquid limit (%)	73
D4318	Plastic limit (%)	47
D4318	Plasticity index (%)	26
D4943	Shrinkage limit (%)	28
D4253	Maximum void ratio	1.55 [7, 8]
D4254	Minimum void ratio	1.07 [7, 8]
D2487	Soil classification	MH
D7928	D_{60} (mm)	0.00480

The rigid polyurethane foam used in the study was purchased from Polymer Product (Phil.), Inc. The rigid polyurethane foam is produced from the two components, polyol and isocyanate. The properties and reaction data of the rigid polyurethane foam is shown in Table 2.

Table 2 Polyurethane properties

Property	Value
Specific gravity	1.1 to 1.2
Viscosity at 25°C	100 cps to 400 cps
Cream time	19 seconds to 27 seconds
Gel time	117 seconds to 130 seconds
Tack free time	230 seconds to 262 seconds

3.2 Mix Proportion

The obtained optimum moisture content of the local clay was 31.15%, which served as a basis to determine the moisture content upon compaction that would yield the desirable hydraulic conductivity of the compacted local clay. According to previous studies, compacting the specimen at a higher moisture content would yield a lower hydraulic conductivity [9]. Thus, five trials were conducted to approximate the compaction moisture content that would yield an acceptable hydraulic conductivity of the compacted local clay. In which, the trial specimen for this study was targeted to have a similar hydraulic conductivity with the specimen from the study of Tiongson and Adajar [7, 8] that used the same type of expansive soil from the same site in Kauswagan, Lanao del Norte. The compaction moisture content established from the trial tests was 46.5%, which was used in the mix proportion of the specimens used in the experimentation to obtain the hydraulic conductivity of the compacted polyurethane-clay. The mix proportion of the two kinds of specimen, local clay and polyurethane-clay, is tabulated in Table 3 wherein the weight of the rigid polyurethane foam (PU) is 0% and 3% of the dry weight of the specimen. In addition, the mixing ratio for the rigid polyurethane foam is 1-part polyol and 1-part isocyanate by weight.

Table 3 Sample mix proportion

PU content	Dried clay (kg)	PU (kg)	Dried clay and PU (kg)	Water (kg)
0%	68.26	0.00	68.26	31.74
3%	66.22	2.04	68.26	31.74

3.3 Mixing and Curing

The local clay used to produce the specimen was oven-dried to ensure that the water in the mixture is controlled. The rigid polyurethane foam was synthesized in a single step by directly mixing the polyol and isocyanate. Mixing of the polyurethane components was conducted within the cream time before the dried local clay was added. The dry mixing of the rigid polyurethane foam and the dried local clay was done as fast as possible to prevent the solidification of the polyurethane before it is evenly integrated into the local clay matrix. The polyurethane-clay mixture was placed in an airtight container for 20 minutes before adding the amount of water required to meet the compaction moisture content so that further reaction between components may occur. The mixture of polyurethane, clay, and water was cured for at least 24 hours in a sealed plastic bag before it was compacted to ensure that the water is evenly distributed in the mixture. The same methodology was applied to produce the compacted local clay specimen without incorporating the rigid polyurethane foam.

3.4 Manual Compaction

The soil properties of the polyurethane-clay mixture are tabulated in Table 4. Based on the tabulated soil properties of local clay and polyurethane-clay, it can be observed that the liquid limit of the local clay is higher than the liquid limit of the polyurethane-clay. In addition, the liquid limit and plasticity index of both local clay and polyurethane-clay intersect below the "A" line of the plasticity chart in ASTM D2487. Thus, both soils are classified as MH or elastic silt; however, the polyurethane-clay consists of 16.5% sand, which denotes that its classification is elastic silt with sand.

Table 4 Soil properties of polyurethane-clay

ASTM	Soil property	
D854	Specific gravity	2.86
D4318	Liquid limit (%)	68
D4318	Plastic limit (%)	48
D4318	Plasticity index (%)	20
D4943	Shrinkage limit (%)	29
D2487	Soil classification	MH with Sand
D7928	D_{60} (mm)	0.02025

Furthermore, it can be observed that the specific gravity of the local clay and polyurethane-clay differs, which are 2.41 and 2.86, respectively. The difference denotes that there will also be a difference in the void ratio of the local clay and polyurethane-clay specimen when compacted with the same effort. Hence, two compaction efforts were applied that yielded three kinds of compacted specimen labeled as compacted clay liner (CCL), clay liner (CL), and compacted polyurethane-clay liner (CPCL). The summary of the initial void ratio and the description of the manual compactive effort applied for the three kinds of compacted specimen are tabulated in Table 5. The compactive effort that produced the CCL, with an initial void ratio of 1.06, compaction moisture content of 46.5%, and an acceptable hydraulic conductivity based on the study of Tiongson and Adajar [7, 8] that used the same type of soil, was applied to polyurethane-clay that produced the CPCL. CPCL had the same compactive effort as CCL, but a higher initial void ratio of 1.44. Less compactive effort was applied to the third type of compacted specimen, CL, to obtain the same initial void ratio as CPCL, which is 1.44. All test specimens were cured for 24 hours after compaction in the airtight permeameter mold. After curing, all specimens were saturated for 14 days to initiate the permeability test.

Table 5 Compaction effort and initial void ratio

Specimen	PU	Initial void ratio	Compaction
CCL	0%	1.06	Standard
CPCL	3%	1.44	Standard
CL	0%	1.44	Less

3.5 Permeability Test

The ASTM standard test method used in the study to determine the hydraulic conductivity is ASTM D5856 [10], or the standard test method for measurement of hydraulic conductivity of porous material using a rigid wall, compaction-mold permeameter. The components used to conduct the test included the flow measurement system and a rigid wall permeameter as shown in Fig. 1. In addition, the falling head method was used with a hydraulic gradient of 1.07. Since the expected hydraulic conductivity is low, it was anticipated that a single run of the experiment would take approximately 60 days; thus, each run was conducted simultaneously. The diameter of each specimen is 63.5 mm, and the height is 110 mm.

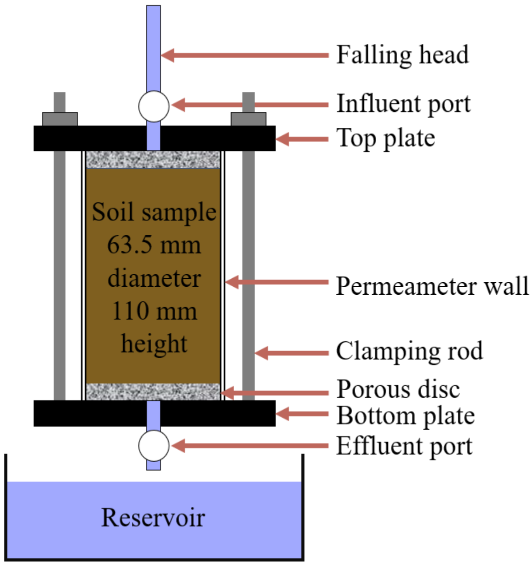

Fig. 1 Rigid wall permeameter setup

The hydraulic conductivity of each specimen tested in a rigid wall permeameter under the falling head system was calculated using Eq. (1).

$$k = \frac{aL}{At} ln \left(\frac{h_1}{h_2}\right) \quad (1)$$

Where k is the hydraulic conductivity in m/s, a is the cross-sectional area of the standpipe in m^2, L is the length of the specimen in m, A is the cross-sectional area of the specimen in m^2, t is the time between determination of h_1 and h_2 in seconds, h_1 is the head loss across the specimen at time t_1 in m, and h_2 is the head loss across the specimen at time t_2 in m.

4. TEST RESULTS

4.1 XRD Analysis

The x-ray diffraction (XRD) analysis of the local clay and polyurethane-clay are shown in Fig. 2 and Fig. 3, respectively. The XRD analysis determined that aluminum silicate hydroxide and silicon oxide, which are also known as Kaolinite and Quartz, are present in both local clay and polyurethane-clay. Furthermore, the multiplot of both soil types have the same trend and spikes, denoting that the soil types are similar in composition. However, it should be noted that the amount of polyurethane in the polyurethane-clay mixture is only 3% of the dry weight of the specimen, which may not be a significant amount to produce a change in the spikes plotted.

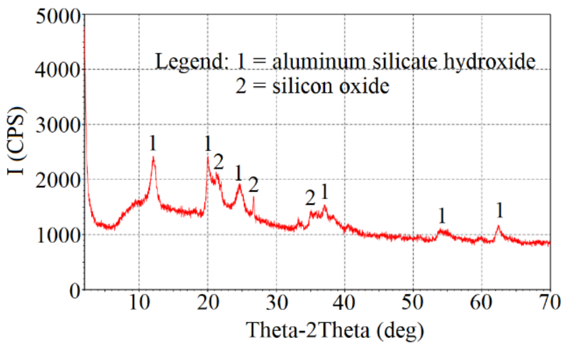

Fig. 2 XRD analysis of local clay

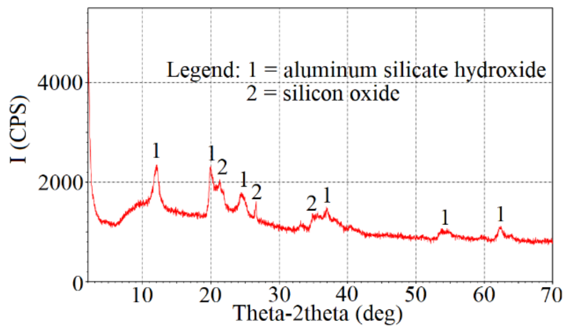

Fig. 3 XRD analysis of polyurethane-clay

One of the minerals found in both soil types is Kaolinite, which is a non-swelling, soft clay mineral that is plastic in nature; moreover, Kaolinite is assumed to be the least reactive among the clay minerals [11]. It can also be noted that the obtained plasticity index of local clay and polyurethane-clay when tested using the ASTM standard reflected a highly plastic property, which agrees with the highly plastic characteristic of Kaolinite [11]. The other mineral detected through XRD analysis is Quartz, which is a mineral present in almost all parent materials and inherited by silt and sand [12]. Considering the classification of the local clay and polyurethane-clay, which is elastic silt and elastic silt with sand, it can be inferred that the presence of Quartz agrees with the soil classification.

4.2 EDX Analysis

The energy dispersive x-ray (EDX) analysis of the local clay and polyurethane-clay detected traces of oxygen, silicon, bromine, carbon, and iron, tabulated in Table 6. The dominant elements in the analysis are oxygen and silicon, which are commonly found in soils. Moreover, it can be observed that polyurethane-clay has more carbon than local clay; thus, it can be inferred that incorporating polyurethane into the soil matrix of the local clay increases the carbon content of the mixture. An increase in carbon content denotes that the soil mass has a more stable structure and a better water holding capacity [13]. Thus, a higher carbon content in the soil mass also results in reduced soil erosion because of the improved capability of the soil mass to hold particles together [14]. Therefore, based on the elemental distribution established through the EDX analysis that exhibited an increase in carbon content, it can be inferred that polyurethane-clay is more stable than local clay.

Table 6 EDX analysis of uncompacted specimen

Element	Weight Percentage	
	Local Clay	Polyurethane-clay
Oxygen	44.69	41.26
Silicon	14.69	14.29
Bromine	28.73	27.29
Carbon	2.99	9.96
Iron	8.90	7.20

4.3 SEM Image Analysis

The scanning electron microscope (SEM) image of the local clay and polyurethane-clay are shown in Fig. 4 and Fig. 5, respectively. It can be observed that the particles of both soil types are clustered and the microstructures both have intergranular and intragranular voids. However, it can be observed that the SEM image of polyurethane-clay exhibits spherical particles on the surface of the clay particle, which is inferred to be polyurethane foam based on the existing SEM image of polyurethane foam. The SEM image of pure polyurethane foam is shown in Fig. 6, in which spherical particles are predominant. SEM images shown in Fig. 4 and Fig. 5 also exhibit characteristics of Kaolinite and Quartz, which were the elements detected on the local clay and polyurethane-clay through XRD analysis.

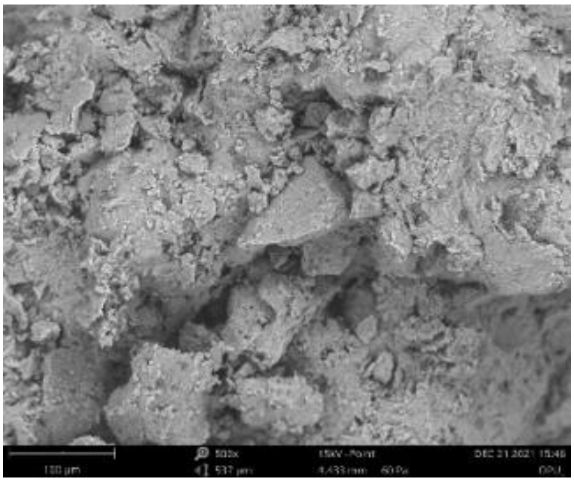

Fig. 4 SEM image of local clay

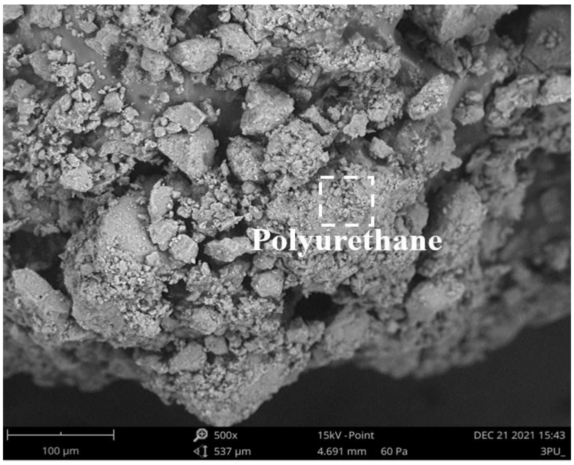

Fig. 5 SEM image of polyurethane-clay

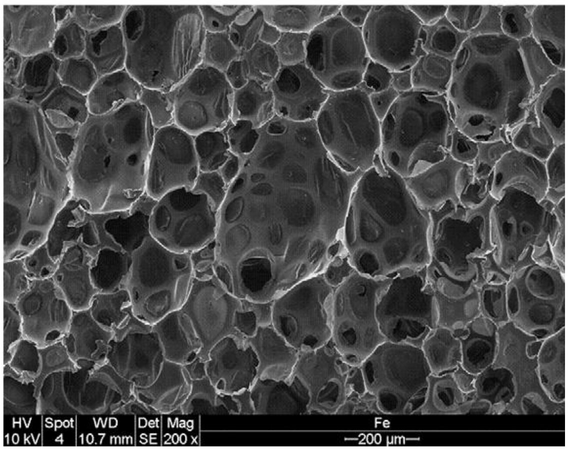

Fig. 6 SEM image of polyurethane foam [15]

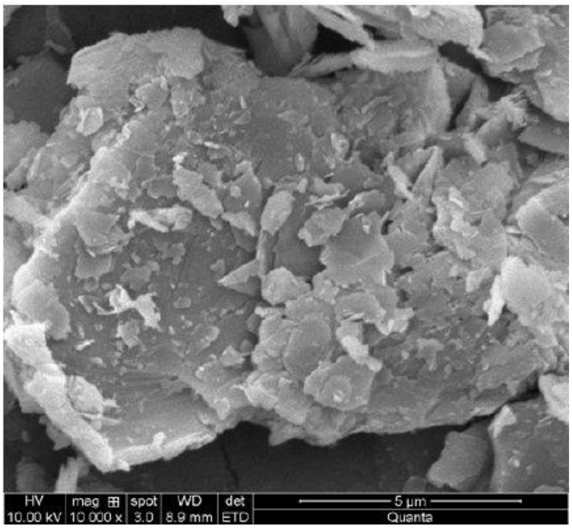

Fig. 7 SEM image of Kaolinite [16]

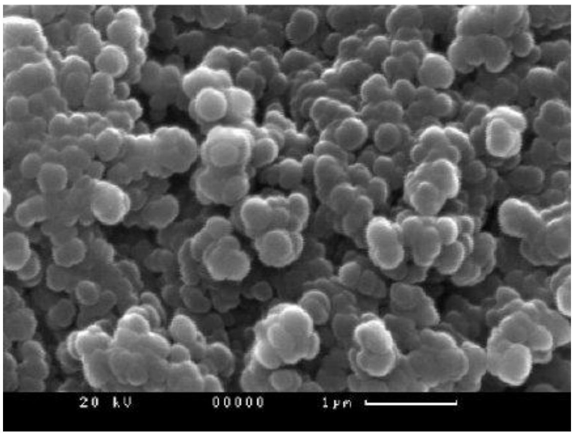

Fig. 8 SEM image of Quartz [17]

Kaolinite, which is described as thick, rigid, and plate-like with a hexagonal shape [16, 18], appears flaky and plate-like on Fig. 4 and Fig. 5. On the other hand, the spheroidal particles observed in Fig. 4 and Fig. 5 are inferred as Quartz based on the similarity of the particle shape shown in Fig. 8. It can be observed in Fig. 5 that more spheroidal-shaped particles are found in polyurethane-clay, which agree with the grain size distribution established for the polyurethane-clay that shows more sand particles as compared to the composition of the local clay.

4.4 Hydraulic Conductivity

The hydraulic conductivity obtained from the experimentation for the three kinds of compacted specimen are tabulated in Table 7. Hydraulic conductivity is one of the major parameters considered to determine if a material is a suitable SLF liner; thus, CL and CPCL, were compared considering that the two specimen types have relatively the same initial void ratio. It was opted that the initial void ratio would be held constant instead of the compactive effort because a constant void ratio denotes that the volume of voids that water could occupy between soil particles are also constant for both specimen types, CL and CPCL.

Table 7 Hydraulic conductivity

Specimen	PU	Void ratio	Hydraulic conductivity, *k*
CCL	0%	1.09	2.27×10^{-8} cm/s
CL	0%	1.38	6.47×10^{-5} cm/s
CL	0%	1.42	8.08×10^{-5} cm/s
CPCL	3%	1.50	2.36×10^{-8} cm/s
CPCL	3%	1.53	3.44×10^{-8} cm/s

The decrease in hydraulic conductivity as polyurethane was incorporated into the soil matrix of the local clay may be due to the impermeable nature of polyurethane. A previous study inferred that polyurethane, in its pure form, is relatively water resistant due to the closed porosity of its microstructure; in addition, polyurethane injected into cracked clays are observed to have a low permeability of 10^{-8} cm/s [15]. Therefore, the polyurethane improved the impermeability of the polyurethane-clay mixture based on the comparison between the hydraulic conductivity of CPCL and CL, which are specimens with the same initial void ratio. However, the difference in hydraulic conductivity of CL and CPCL may also be attributed to the difference in compactive effort applied. The compactive effort applied on CPCL and CCL is greater compared to the compactive effort applied to CL, since the compactive effort used on CL had an objective to attain the high initial void ratio of CPCL.

4.5 Estimated Compactive Effort

By utilizing the model proposed by Tiongson and Adajar [7, 8] to predict the hydraulic conductivity for the same local clay, the compactive effort of the manually compacted specimen in the study may be determined. The actual hydraulic conductivity of CCL is similar to the predicted value for specimen in which the Standard Proctor effort of 600 kN-m/m^3 was applied as the compactive effort. On the other hand, the predicted hydraulic conductivity of CL is two orders of magnitude lower than the actual hydraulic conductivity of CL as shown in Table 8.

Table 8 Predicted hydraulic conductivity

	Void ratio	Actual *k* (cm/s)	Predicted *k* (cm/s)	
			Reduced Proctor	Standard Proctor
CCL	1.09	2.27×10^{-8}	2.07×10^{-8}	2.29×10^{-8}
CL	1.42	6.47×10^{-5}	1.50×10^{-7}	2.39×10^{-7}
CL	1.38	8.08×10^{-5}	1.17×10^{-7}	1.78×10^{-7}

Thus, this indicates that the compactive effort of CL is considerably smaller than the compactive effort of CCL. Moreover, it should be noted that the manual compactive effort applied on CCL is relatively the same as the manual compactive effort applied on CPCL. Therefore, it can be inferred that the manual compactive effort applied on CPCL may also be the Standard Proctor effort.

4.6 Effectiveness of CPCL as SLF Liner

Most of the related literature that discussed the suitability of landfill liner material utilized a maximum hydraulic conductivity of 10^{-7} cm/s. Furthermore, the said hydraulic conductivity was utilized by most studies to ensure that the landfill liner material is less permeable to avoid the contamination of the surrounding environment. The lowest permeability required for a compacted SLF liner in the Philippines is 10^{-7} cm/s or 10^{-9} m/s [19]. Thus, for a material to be considered as a suitable SLF liner for all SLF categories, the obtained hydraulic conductivity should be equal to or lower than 10^{-9} m/s. Based on the design standards, it can be inferred that the compacted polyurethane-clay liner is a suitable SLF liner for all SLF categories with regards to its permeability. On the other hand, the clay specimen compacted to have the same initial void ratio as CPCL is not a suitable SLF liner for any SLF category.

One-way analysis of variance was used to statistically compare the hydraulic conductivity of CPCL and CL. The result of the analysis of variance, tabulated in Table 9, indicates that the model and the polyurethane content are significant since the P-values are less than 0.05. Thus, incorporating polyurethane into the soil mixture, statistically, has an effect on the hydraulic conductivity. It can be inferred that the polyurethane in the soil mixture decreased the hydraulic conductivity of the specimen, which can be considered as a suitable SLF liner as opposed to the compacted clay without polyurethane that have the same initial void ratio as CPCL.

Table 9 Statistical analysis of hydraulic conductivity

Source	P-value	
Model	0.0120	Significant
Polyurethane content	0.0120	Significant

5. CONCLUSION

Bentonite-modified clay is often used as sanitary landfill liners; however, the characteristic of bentonite makes the clay susceptible to deterioration due to shrinkage. Thus, the local clay was mixed with polyurethane, a polymer often used to stabilize soil. Changes in the soil structure induced by incorporating polyurethane into the clay matrix, such as an increase in carbon content, improved the water holding capacity of the compacted specimen when compared to the compacted local clay with the same initial void ratio. The impermeable nature of polyurethane was inferred to have contributed to the decrease in hydraulic conductivity. Thus, the compacted polyurethane-clay was classified as a suitable landfill liner in accordance with the Philippine design standard for all sanitary landfill categories.

6. RECOMMENDATION

Since excessive volume change could deteriorate the impermeability of clay SLF liners, it is recommended that future studies explore the shrinkage resistance of polyurethane-clay. It is also recommended that future studies explore the unsaturated hydraulic conductivity of polyurethane-clay since SLF liners are not always saturated.

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