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# LATERAL SHRINKAGE OF COMPACTED POLYURETHANE-CLAY SUBJECTED TO A SINGLE WET-DRY CYCLE

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**ABSTRACT:** Compacted clay is often used as a sanitary landfill liner due to its impermeable characteristics. However, compacted clay is susceptible to shrinkage as the temperature changes, which may affect the permeability due to the development of shrinkage cracks. Thus, clay was mixed with polyurethane, a stable polymer, once the reaction was completed. The polyurethane-clay mixture was compacted wet of the optimum moisture content and monitored through several moisture contents using direct measurement of the specimen diameter by Vernier caliper. The study inferred that the ratio of the lateral shrinkage of the compacted polyurethane-clay mixture is significantly less than that of the clay specimen with the same initial void ratio. Hence, the changes in the soil structure induced by the addition of polyurethane into the compacted mixture increased the resistance of the soil mass from lateral shrinkage quantified using the free shrinkage ratio. Furthermore, the regression model of the free shrinkage ratio for a wide variety of moisture content was also presented for the compacted polyurethane clay and compacted clay.

*Keywords: Polyurethane, Clay, Shrinkage, Wet-Dry Cycle, Sanitary Landfill*

## 1. INTRODUCTION

Sanitary landfills (SLFs) are designed, constructed, operated, and maintained facilities that prevent the contamination of the surrounding environment [1]. Hence, impermeable materials are utilized as SLF liners to prevent the infiltration of leachate. According to NSWMC and JICA [1], liner facilities are installed to prevent pollution of nearby water bodies and groundwater systems due to leachate leakage. Common materials used as SLF liners include clay, geomembrane, geotextiles, geosynthetic clay liner, and geonet. Clay liners are compacted and remolded into a homogenous mass with high relative compaction to lower permeability. Compacted clay is often preferred among the SLF liners due to the abundance and accessibility of clay. However, compacted clay deteriorates through the presence of cracks due to shrinkage induced by climatic wet-dry cycles [2].

Aside from the climatically induced change in the moisture content of compacted clay, the degradation of waste also produces heat that may affect the liner as moisture decreases. The decrease in moisture content would induce shrinkage cracks wherein leachate could seep through. An increase in leachate volume may also be experienced when the cover liner of SLF cracks due to shrinkage, which would make leachate management more challenging [1].

The deterioration of compacted clay was addressed by different studies that utilized various materials to lessen shrinkage cracks caused by wet-dry cycles. One study incorporated straw fibers in a compacted clay liner that exhibited a decrease in the number of cracks as the amount of fiber increased [3,4]. Other stabilization techniques also include the addition of polymers into the soil matrix, which strengthens the structure between particles [5,6]. Moreover, soil particles that are far away can also be stabilized by polymers through flocculation [6].

One type of polymer widely used in the construction industry is polyurethane (PU), which is used for the ground improvement of expansive soils like clay. Polyurethane is a repeating unit of urethane formed from the reaction of polyol and isocyanate. It was inferred that injecting rigid polyurethane foam into the ground results in improved strength, stiffness, and bearing resistance [7]. In a study conducted by Saleh et al. [7], marine clay, characterized by excessive swelling and shrinkage, was mixed with polyurethane, which increased the shear strength of the mixed specimen.

Thus, the study aims to improve clay soil by mixing it with polyurethane to lessen the shrinkage caused by the variation of moisture content. The study aims to determine the lateral shrinkage of compacted clay and compacted polyurethane clay through a series of different moisture contents from a saturated level to a dry level. Moreover, the study aims to establish a relationship between lateral shrinkage and different moisture content levels. A single wet-dry cycle is utilized in the study to observe the effect of fluctuation in moisture content on the shrinkage behavior of polyurethane-clay samples.

## 2. RESEARCH SIGNIFICANCE

The wet-dry cycle experienced by compacted clay liners due to extreme weather conditions in the Philippines causes their deterioration due to shrinkage. Shrinkage leads to the formation of desiccation cracks, which serve as flow paths for the liquid to pass through. Hence, polyurethane is incorporated into compacted clay to stabilize the bond between particles and resist shrinkage. Exploring the behavior of SLF liner materials that could resist shrinkage would be beneficial for communities that do not have the capacity to use sophisticated materials.

A study conducted by Frianeza and Adajar [8] inferred that polyurethane clay is a suitable SLF liner material due to its low permeability. However, few studies have determined the lateral shrinkage of compacted specimens with polymer measured from a saturated state to a dry state. Thus, monitoring the shrinkage behavior through different levels of saturation to determine the effect of polyurethane in the clay matrix may contribute to the body of knowledge about clay-polymer matrices.

## 3. EXPERIMENTAL PROGRAM

### 3.1 Materials

The clay utilized in the study was excavated at a depth of 2 meters in a proposed SLF site at Kauswagan, Lanao del Norte, which was also the same material used in the study conducted by Frianeza and Adajar [8]. Table 1 shows the index properties of the clay used in the study.

Table 1  Soil properties of clay [8]

| ASTM | 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 [9] |
| D4254 | Minimum void ratio | 1.07 [9] |
| D7928 | $D_{60}$ (mm) | 0.00480 |

The same rigid polyurethane foam used in the study of Frianeza and Adajar [8] was used as a polymer soil-stabilizing agent. The rigid polyurethane foam was also purchased from Polymer Product (Phil.), Inc., wherein the properties and reaction data are tabulated in Table 2.

Table 2  Polyurethane properties [8]

| 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 compaction moisture content of the specimen in the study is 46.5%, which is a wet of the optimum moisture content established in the study of Frianeza and Adajar [8]. The compaction moisture content was established through a series of trial and error, starting at the optimum moisture content to determine the corresponding moisture content that would yield a high relative compaction for the compacted clay. The obtained compaction moisture content, 46.5%, was targeted to be within the varied moisture content in the study of Tiongson and Adajar [9], which ranges from 47.25% to 39.65%. Furthermore, the same compaction moisture content was also used in the study of Frianeza and Adajar [8], which yielded the same mix proportion tabulated in Table 3 to determine the lateral shrinkage. In addition, the ratio of the polyurethane used in the study is 1 part polyol and 1 part isocyanate by weight [8].

Table 3  Sample mix proportion [8]

| 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

Initially, the clay used in both mix proportions was oven-dried to effectively control the amount of water in the mixture. The polyurethane was also synthesized in a single step by directly mixing the polyol and isocyanate within the specified cream time. This method was also exercised by Frianeza and Adajar [8] to prevent the solidification of the polymer before mixing the dried clay and allow further reaction for 20 minutes before the mixing water was added. The mixtures were cured for 24 hours in a sealed plastic bag to ensure the even distribution of mixing water in the soil matrix [8].

### 3.4 Manual Compaction

By utilizing the ASTM test methods and soil properties of clay and polyurethane clay, it was inferred that both are classified as MH or elastic silt through the Unified Soil Classification System [8]. However, polyurethane clay is composed of 16.5% sand, which resulted in a classification of elastic silt with sand; in addition, polyurethane clay has a higher specific gravity of 2.86, as tabulated in Table 4 [8]. The difference in the specific gravity of the two soil types, polyurethane clay and clay, resulted in a difference in the initial void ratio considering that the compaction effort was held constant [8].

Table 4 Soil properties of polyurethane-clay [8]

| 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 |

In the study of Frianeza and Adajar [8], two compaction efforts were applied to the two soil types that resulted in three specimen types, compacted clay liner (CCL), clay liner (CL), and compacted polyurethane-clay liner (CPCL), wherein the same compaction effort was applied to CCL and CPCL as summarized in Table 5. The compaction effort applied on CCL yielded an initial void ratio of 1.06; on the other hand, the same manual compaction effort applied on CPCL yielded an initial void ratio of 1.44 [8]. Thus, to obtain the same initial void ratio of 1.44 as CPCL, less compaction effort was applied to the clay soil type to produce CL, which was also executed by Frianeza and Adajar [8]. The molded specimens, CCL, CL, and CPCL, were cured for 24 hours inside an insulated chest to prevent excessive water loss after compacting and demolding [8].

Table 5 Compaction effort and void ratio [8]

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

### 3.5 Wet-Dry Cycle

Once the cylindrical specimens were demolded, the wet-dry cycle was initiated by ensuring that the specimen was in a very saturated state at the beginning of the cycle. The weight of the specimen was monitored during the air drying process to determine if the weight corresponds to a target weight in a particular moisture content level. Upon compaction, the degree of saturation of CCL is 100%; thus, the wet-dry cycle was initiated upon compaction. On the other hand, the CPCL and CL did not reach a 100% degree of saturation upon compaction; thus, CPCL and CL were both saturated by pouring water over the top of the specimen every 2 minutes until the weight of the specimen corresponds to a fully saturated state. Furthermore, during saturation, the specimens were replaced inside the acrylic mold, which was removed after saturation. At the end of the 7-day air drying process, the specimens were oven-dried to determine their diameter at 0% moisture content level. A single wet-dry cycle was explored in the study since increasing the number of cycles would denote that the specimen would be saturated after the initial drying. The saturation process in the study would produce desiccation cracks as soon as the water is poured, which would affect the data collection by acquiring an erroneous direct measurement through a Vernier caliper. Hence, experimentation was limited to a single wet-dry cycle.

### 3.6 Free Shrinkage Test

The test method used to determine the free shrinkage ratio (FSR) was based on the study of Wan et al. [10]. Initially, each cylindrical specimen has a diameter of 66 mm and a height of 20 mm, which was placed on a smooth surface to ensure that the specimen can freely move as it shrinks. Direct measurement using a digital Vernier caliper was used to monitor the diameter of the compacted specimens at the corresponding target moisture content level. The average of the three diameters obtained in a specimen was used in the computation of the FSR. The shrinkage curve of the specimens in the study was established by plotting the moisture content with the FSR, which was obtained using the equation from Wan et al. [10] expressed in Eq. (1). The shrinkage curve is the graphical representation of the shrinkage behavior of the three specimen types across a wide range of saturation levels.

$$FSR = \frac{A_o - A_w}{A_o} \times 100\% \quad (1)$$

where *FSR* is the free shrinkage ratio in %, $A_o$ is the original area of the specimen in mm$^2$, and $A_w$ is the area of the specimen with moisture content $w$ in mm$^2$.

## 4. TEST RESULTS

### 4.1 XRD Analysis

The X-ray Diffraction (XRD) multiplot of the clay and polyurethane-clay obtained from the study of Frianeza and Adajar [8], shown in Fig. 1 and Fig. 2, has the same trend and spikes, which denotes that there is a strong similarity in composition of both soil types, clay and polyurethane-clay. However, it should be noted that the amount of polyurethane in the soil matrix, which is 3% by weight, may not be significant enough to produce a change in the trend and/or spikes in the XRD multiplot [8].

The XRD analysis of the multiplot shows that aluminum silicate hydroxide, or kaolinite, and silicon oxide, or quartz, are present in both soil types [8]. According to Frianeza and Adajar [8], the presence of kaolinite in both soil types from the XRD analysis agrees with the highly plastic USCS classification of both soil types. In addition, quartz, which is present in both soil types, is a parent material inherited by sand and silt, which also agrees with the USCS classification of both soil types [11].

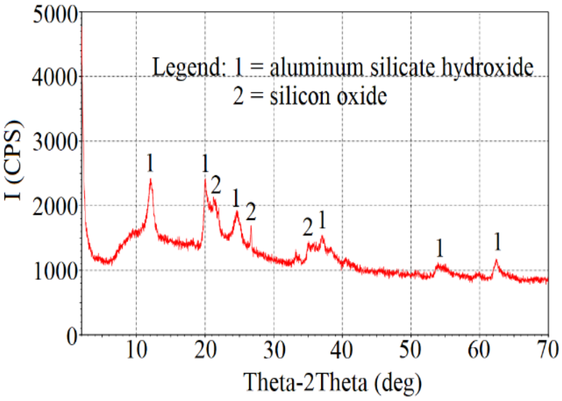


Fig. 1 XRD analysis of clay [8]

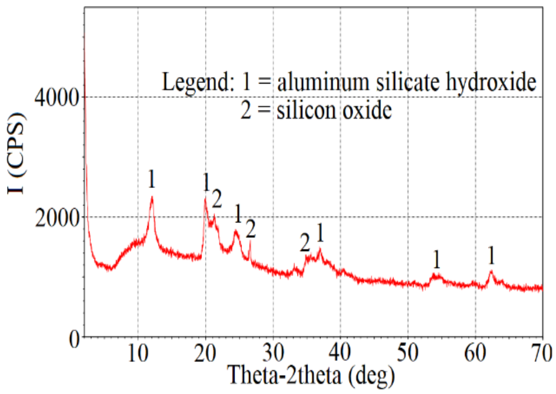


Fig. 2 XRD analysis of polyurethane-clay [8]

### 4.2 EDX Analysis

The Energy Dispersive X-ray (EDX) analysis of the soil types, clay and polyurethane-clay, from the study of Frianeza and Adajar [8] shown in Table 6 exhibits the dominance of oxygen and silicon, which are elements commonly found in soil. However, the EDX analysis also shows the increase in carbon content induced by the incorporation of polyurethane into the clay matrix. The increase in the amount of carbon in soil denotes an increase in soil stability and improvement of the water-holding capacity [12]. Hence, it was inferred that polyurethane-clay is more stable than clay based on the elemental composition from the EDX analysis.

Table 6 EDX analysis of the two soil types [8]

| Element | Weight Percentage | |
|---|---|---|
| | 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 Analysis

The Scanning Electron Microscope (SEM) image of both clay and polyurethane-clay in the study of Frianeza and Adajar [8], shown in Fig. 3 and Fig. 4, exhibits a clustered structure with intergranular and intragranular voids. Furthermore, it was inferred that the spherical particles in the SEM image of the polyurethane-clay are polyurethane particles because pure polyurethane has a spherical shape as denoted by Buzzi et al. [13] and shown in Fig. 5. The SEM images show particles that have the same characteristics as kaolinite and quartz, which were also detected in the XRD analysis [8]. Kaolinite, shown in Fig. 6, has a flaky and plate-like structure similar to the characteristic of some particles from the SEM image of the clay and polyurethane-clay [8]. Moreover, quartz, shown in Fig. 7, has spheroidal particles, which is present in the SEM images of the soil types in the study [8].

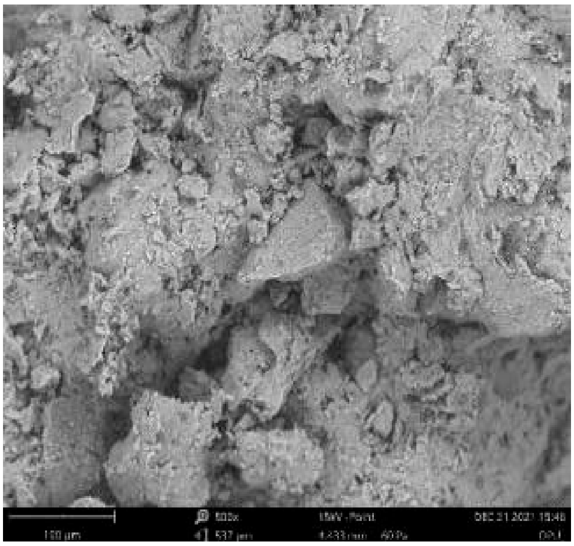

Fig. 3 SEM image of clay [8]

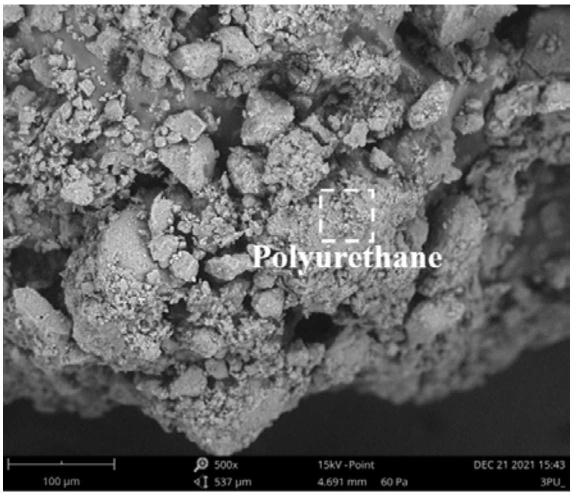


Fig. 4 SEM image of polyurethane-clay [8]

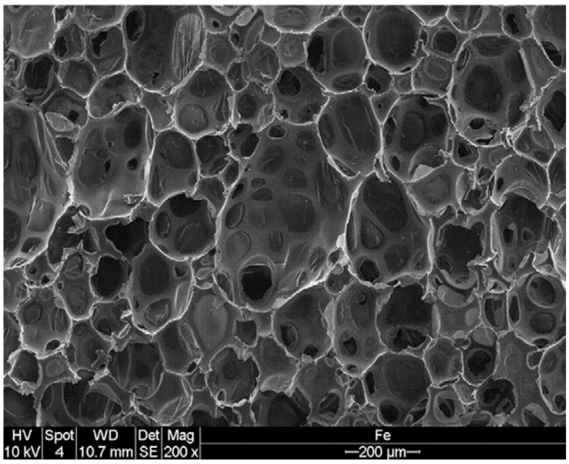


Fig. 5 SEM image of polyurethane foam [8,13]

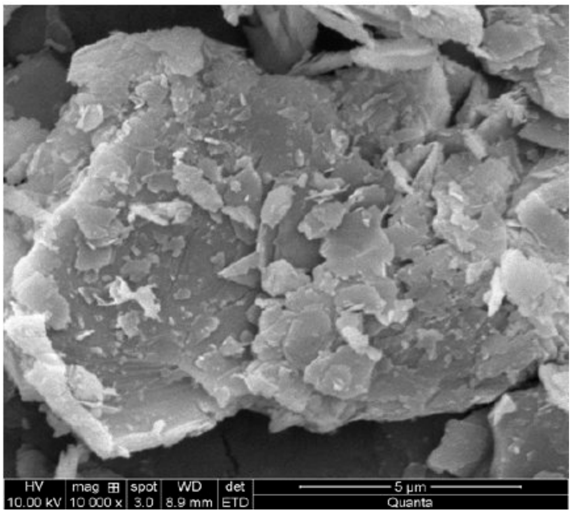


Fig. 7 SEM image of Kaolinite [8,14]

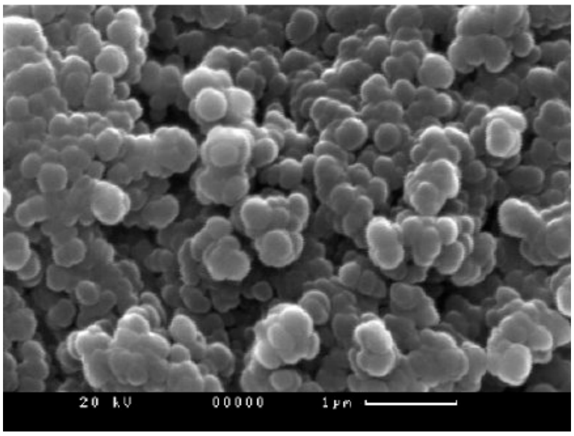


Fig. 8 SEM image of Quartz [8,15]

### 4.4 Shrinkage Curves of Compacted Specimens

The shrinkage curves of the specimens, CCL, CL, and CPCL, are shown in Fig. 9. The shrinkage curves exhibit two stages, normal shrinkage and residual shrinkage. Normal shrinkage is the shrinkage of the specimen as the water in the soil mass evaporates. On the other hand, residual shrinkage is characterized by the negligible change in volume as the soil mass dries. The boundary between the two stages is the shrinkage limit, which is the moisture content required to fill the voids of a soil mass at its minimum void ratio [16]. Moreover, the shrinkage limit is also defined as the point wherein air starts to enter the soil matrix more rapidly, which results in a deviation from the saturation line [17].

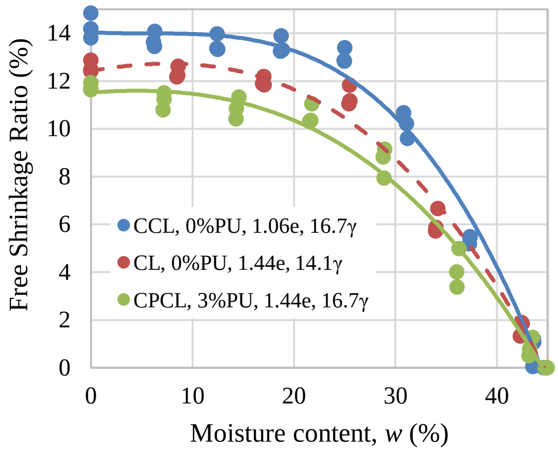


Fig. 9 Shrinkage curve

The shrinkage limits of the clay soil and polyurethane-clay soil types were determined using ASTM D4943 [16], which yielded shrinkage limits of 27.56% and 29.26%, respectively. It is noted from previous studies that specimens with lower shrinkage limits have a higher shrinkage potential, which agrees with the plotted shrinkage curves [18]. It can be observed from Fig. 9 that the compacted polyurethane-clay has a lower amount of shrinkage across various moisture content levels compared to the compacted clay specimens. The liquid limit can also indicate which type of expansive soil is more susceptible to shrinkage. According to Wan et al. [10], soils with higher liquid limit and higher clay content have a greater shrinkage potential. Thus, the liquid limit of the clay soil and polyurethane-clay, which are 73% and 68% respectively, denotes that the clay soil is more susceptible to shrinkage, which agrees with the shrinkage curve in Fig. 9. The increase in carbon content due to the inclusion of polyurethane into the mixture inferred through the EDX analysis, may also have contributed to the resistance to shrinkage of CPCL since an increase in carbon indicates that the soil mass has a structure with improved stability.

#### *4.4.1 Free Shrinkage Ratio of CCL and CPCL*

The free shrinkage ratio, or FSR, of the specimen manually compacted with the same effort, CCL and CPCL, was plotted against various moisture content levels shown in Fig. 10. It can be observed that the shrinkage of CPCL is less than the shrinkage of CCL indicating that the changes induced by including polyurethane into the soil matrix improved the resistance to shrinkage of the material. Rigid polyurethane foam, which was mixed with clay, was considered stable with a closed-form structure by previous studies [13]. Thus, the stability of the polyurethane may have influenced the capability of CPCL to shrink less than the compacted clay as both specimen types move to a drier state. In addition, the grain size distribution of clay and polyurethane-clay shows that the clay soil has smaller particles than the clay mixed with polyurethane, which affected the resistance of the specimens to shrinkage. According to Zhao et al. [19], specimens with smaller particles tend to have larger volume changes, which the specimens exhibited through the lateral shrinkage measured and quantified by the FSR. The amount of water loss as the specimens move to a drier state also significantly affected the FSR obtained at the specific moisture content level as observed in Fig. 10.

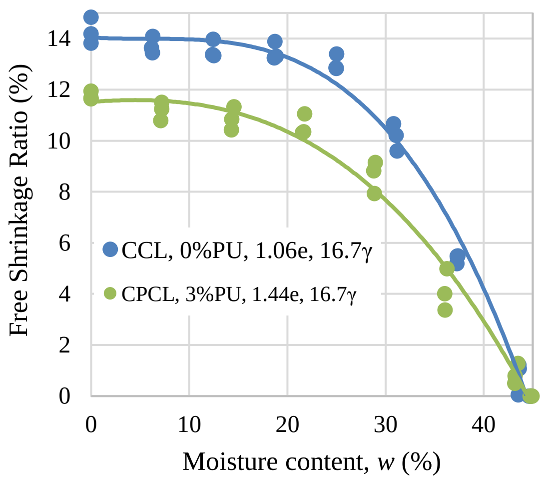


Fig. 10 Shrinkage curve of CCL and CPCL

According to the conducted two-way analysis of variance shown in Table 7, the moisture content and polyurethane content affected the FSR of CCL and CPCL. Thus, statistically, incorporating polyurethane into the soil matrix of the clay resisted shrinkage better compared to the specimen without polyurethane, considering that both CCL and CPCL were compacted with the same effort. The cubic regression model of CCL and CPCL is expressed in Eq. (2) and Eq. (3), respectively.

Table 7 Statistical Analysis of CCL and CPCL

| Source | P-value | |
|---|---|---|
| Model | < 0.0001 | Significant |
| Moisture content | < 0.0001 | Significant |
| Polyurethane content | < 0.0001 | Significant |

$$FSR_{CCL,\gamma} = 13.8285 + 6.12 \times 10^{-2}\mathrm{w} - 9.87 \times 10^{-4}w^2 - 1.66 \times 10^{-4}w^3 \quad (2)$$

$$FSR_{CPCL,\gamma} = 11.7287 - 6.17 \times 10^{-2}\mathrm{w} + 2.77 \times 10^{-4}w^2 - 1.66 \times 10^{-4}w^3 \quad (3)$$

where $FSR_{CCL,\gamma}$ is the FSR of CCL compacted using Standard Proctor compaction effort in %, $FSR_{CPCL,\gamma}$ is the FSR of CPCL compacted using Standard Proctor compaction effort in %, and *w* is the moisture content in %.

#### *4.4.2 Free Shrinkage Ratio of CL and CPCL*

Since water loss is a significant factor that affects the shrinkage characteristic of the specimen as established in the previous discussion and in other literature, the shrinkage of CL and CPCL was also compared and analyzed. CL and CPCL are specimens compacted with different manual efforts; however, the initial void ratio of the two kinds of specimens is equal. The void ratio is a parameter that affects the amount and behavior of water within the void spaces in between soil particles. Thus, holding the initial void ratio constant in the analysis indicates that the volume of voids that the water can occupy in the soil matrix is the same for both specimens. In addition, both specimens were initially saturated with water to reach a fully saturated state that initiated the wet-dry cycle before data collection to quantify the FSR.

It can be observed in Fig. 11 that the FSR of CPCL has a smaller value than the FSR of CL across various moisture content levels. Hence, the compacted polyurethane-clay experienced less shrinkage than the compacted clay considering that both specimens have the same initial void ratio and initial saturation conditions. The improved resistance of CPCL to shrinkage may be attributed to the polyurethane incorporated in the soil matrix and its effect on the grain size distribution of the polyurethane-clay soil type.

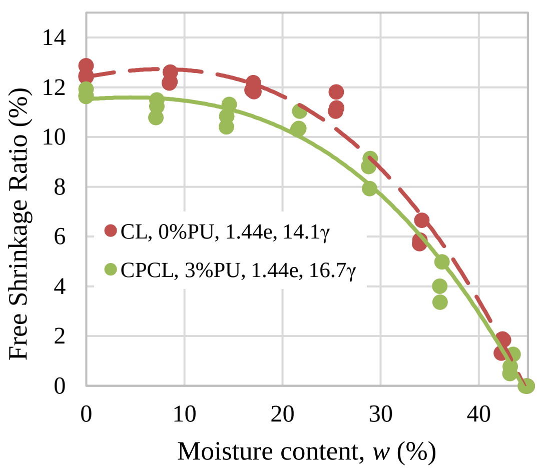


Fig. 11 Shrinkage curve of CL and CPCL

It can be inferred that the rigid polyurethane foam improved the stability of CPCL since polyurethane was inferred to have a stable structure. Furthermore, the increase in grain size induced by the incorporation of polyurethane in the soil matrix also improved the resistance to shrinkage of CPCL as supported by the study of Zhao et al [19], which stated that specimens with larger particles shrink less.

The two-way analysis of variance shown in Table 8 indicates that the moisture content and polyurethane content affected the FSR when the initial void ratio of CPCL and CL are held constant. The quadratic regression model formulated from the relationship of FSR and the various moisture content levels of CPCL and CL, which have the same initial void ratio of 1.44, are expressed in Eq. (4) and Eq. (5), respectively.

Table 8 Statistical analysis of CL and CPCL

| Source | P-value | |
|---|---|---|
| Model | < 0.0001 | Significant |
| Moisture content | < 0.0001 | Significant |
| Polyurethane content | < 0.0001 | Significant |

$$FSR_{CL,1.44e} = 12.4421 + 1.39 \times 10^{-2}\mathrm{w} - 9.19 \times 10^{-3} w^2 \quad (4)$$

$$FSR_{CPCL,1.44e} = 11.0812 + 1.60 \times 10^{-2}\mathrm{w} - 9.19 \times 10^{-3} w^2 \quad (5)$$

where $FSR_{CL,1.44e}$ is the FSR of CL with the initial void ratio of 1.44 in %, $FSR_{CPCL,1.44e}$ is the FSR of CPCL with the initial void ratio of 1.44 in %, and $w$ is the moisture content in %.

## 5. CONCLUSION

Compacted clay is often preferred as a sanitary landfill liner; however, clay is susceptible to deterioration induced by shrinkage. Such deterioration are cracks, which serve as a flow path for leachate to contaminate the surrounding environment. Thus, polyurethane, a stable polymer, was mixed with clay to increase the resistance to shrinkage of the mixture. It was inferred that adding polyurethane into the soil increased the grain sizes and increased the carbon content of the soil mass, which made the compacted mixture of clay and polyurethane less susceptible to shrinkage induced by drying compared to the clay regardless of the initial void ratio or compaction effort.

## 6. RECOMMENDATIONS

Since the specimen in the study was placed on a smooth surface during drying, shrinkage cracks were not present. The absence of the cracks was attributed to the lack of resistance from the contact surface as the specimen dries. Hence, it is recommended to conduct an experiment that would produce shrinkage cracks to observe their development and further explore the behavior throughout different saturation levels. In addition, it is also recommended for future studies to explore volumetric shrinkage instead of lateral shrinkage and use other quantifying methods to monitor the behavior of the specimen throughout different saturation levels in several wet-dry cycles. It is also recommended to explore the mixing methods in actual practice to determine its effect on the reaction of polyurethane and homogeneity of the mixture then consequently on the shrinkage behavior.

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