The Effect of the Matric Suction of Compacted Polyurethane-Clay Liner on the Development of Desiccation Cracks

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The Effect of the Matric Suction of Compacted Polyurethane-Clay Liner on the Development of Desiccation Cracks

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Abstract: *Sanitary landfills utilize impermeable liners to prevent leachate leakage, and the incorporation of polymer in clay layers have been studied to reduce the permeability. Studies that incorporated the polymer, polyurethane, with clay showed decreased permeability and shrinkage potential. Thus, the study investigates the crack propagation in a compacted clay layer drying on a grooved acrylic plate, which simulates friction during drying. The matric suction from the wet to dry condition was evaluated to determine its effect on the development of cracks. The findings indicate that the clay compacted with lower effort exhibited a lower suction, which reduced the cracks due to the reduction of internal stresses. Moreover, the increase in particle size induced by incorporating polyurethane affected the development of cracks.*

Keywords: Desiccation Cracks; Matric Suction; Shrinkage; Polyurethane-clay; Sanitary Landfill Liner.

1. INTRODUCTION

Sanitary landfills (SLFs) are disposal facilities with control over the potential environmental impacts from its development and operation. SLFs are lined with impermeable layers to prevent infiltration of waste substances, such as leachate, to the environment. SLF liners may be composed of clay, geomembranes, geotextiles, geosynthetic clay liners, geonets, or a combination of these materials. Among these materials, clay liners are the most accessible and abundant in the Philippines. Hence, to ensure the effectiveness of clay liners as SLF liners, they are compacted to lower the hydraulic conductivity and remold the soil into a homogenous mass free of voids [2].

To ensure that the compacted clay would prevent the seepage of leachate, several studies have utilized techniques to lower the permeability or hydraulic conductivity of compacted clay, one of which includes the incorporation of polymer to stabilize the soil mixture and prevent volumetric changes as the soil dries. The study of Frianeza and Adajar incorporated a polymer, polyurethane (PU), into an expansive soil matrix, which reduced the permeability and improved the water holding capacity of the compacted soil due to the increase in carbon content. In the study of Frianeza and Adajar, the compacted clay mixed with polyurethane in a saturated state had an average hydraulic conductivity of 2.9×10^{-8} cm/s, which makes the compacted specimen a suitable landfill liner. According to DAO No. 10 [0], the minimum required hydraulic conductivity for a compacted SLF liner in the Philippines is 10^{-7} cm/s or lower to qualify as a liner in all SLF categories.

As the environmental conditions experienced by the clay liner changes from wet to dry, the compacted layer experiences shrinkage, which induces shrinkage cracks. The shrinkage cracks or desiccation cracks formed from the variation of moisture content within the soil matrix would serve as preferential flow paths for leachate to seep through that would cause environmental damage. The deterioration of the compacted layer of clay was addressed by various studies that utilized techniques such as the addition of fibers as added reinforcement and flocculation of soil particles through the addition of polymers, such as polyurethane [4-8]. In another study of Frianeza and Adajar [8], it was inferred that adding polyurethane in the soil mixture, which was predominantly composed of kaolinite and quartz, before compaction increased the grain size of the mixture and the carbon content of the soil mass. In addition, it was also inferred that the increase in grain size and carbon content made the compacted mixture of clay and polyurethane less susceptible to shrinkage induced by drying compared to the clay without polyurethane regardless of the initial void ratio or compaction effort [8]. According to Ramanathan et al. [9], the rate of the swell-shrink of a clay mineral group, like kaolinite, is dependent on the arrangement of the mineral layers, which affects the moisture absorption of water. Thus, Frianeza and Adajar [8] quantified the rate of shrinkage by determining the change in the surface area of the cylindrical specimen on a smooth desiccation surface at various moisture content levels. The shrinkage of the compacted specimen on the smooth surface ensured that no cracks would develop.

Aside from volumetric changes such as swelling or shrinkage, the suction experienced by the compacted clay also changes as the environmental condition changes from wet to dry. In an unsaturated soil, water is subjected to matric suction, which is equivalent to a negative pressure potential [10]. This suction is due to the physical affinity between the soil particle surfaces, capillary pores, and water. When a suction gradient exists, water will flow from where the matric suction is lower to where it is higher to equilibrate the potential. The transition of the soil condition from saturated to unsaturated induces an increase in suction. The matric suction may be analyzed with the corresponding moisture content of the soil specimens through the determination of the water retention curve (WRC). Thus, the study aims to observe the desiccation cracks of polyurethane-clay and clay with varying initial void ratio and to evaluate how its corresponding matric suction affects the formation of cracks in the compacted soil layer. The study aims to observe the desiccation cracks through a series of varying moisture content from the saturated level to the dry level. In addition, the desiccation of the compacted soil is conducted on a grooved plate to simulate friction in between layers of compacted soil through a single wet-dry cycle.

2. MATERIALS

The clay utilized in the study was the same clay utilized in the study of Frianeza and Adajar [2,8], which was excavated at a depth of 2 meters in a proposed SLF site at Kauswagan, Lanao del Norte. In addition, the same rigid polyurethane foam used in the study of Frianeza and Adajar was also used as a polymer soil-stabilizing agent. Table 1 shows the index properties of the clay while Table 2 shows the properties of the rigid polyurethane foam from Polymer Product (Phil.).

Table 1. Index properties of clay

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 Error! Reference source not found.
D4254	Minimum void ratio	1.07 Error! Reference source not found.
D7928	D_{60} (mm)	0.00480

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. METHODOLOGY

The methodology consists of the sample preparation, which includes the mixing, compaction, and curing of the specimens. In addition, the methodology also includes the implementation of the wet-dry cycle, measurement of the matric suction using the filter paper method, and the procedure of the desiccator plate test to observe the crack propagation at varying moisture content levels.

3.1 Sample Preparation

The compaction moisture content and mix proportion of the specimen prepared in the study was also based on the study of Frianeza and Adajar [2,8], which is 46.5%, while the mix proportion is tabulated in Table 3. In addition, the ratio of the polyurethane used in the study 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

The clay excavated from the proposed SLF liner was initially oven-dried to control the amount of water within the mixture and to ensure that the compaction moisture content is 46.5%. On the other hand, the rigid polyurethane foam was synthesized in a single step through the direct mixing of the polyol and isocyanate within the duration of the cream time. This method was implemented to prevent the solidification of the polyurethane before mixing the oven-dried clay, which was also implemented in the study of Frianeza and Adajar [2,8]. Further reaction was permitted for 20 minutes after mixing the polyurethane and clay before the water was added. The mixture was allowed to cure for 24 hours in a sealed plastic bag to ensure the homogenous distribution of water in the mixture [2,8].

By utilizing the ASTM test methods and soil properties of clay and polyurethane-clay, it was determined that polyurethane-clay, or the mixture of polyurethane and clay, has a higher specific gravity of 2.86, as tabulated in Table 4. The difference in the specific gravity of the two soil types, polyurethane-clay and clay, resulted in various sets of specimens that had a different initial void ratio even though the compaction effort was held constant. Thus, in the study of Frianeza and Adajar, two compaction efforts were applied to the two soil types, which resulted in three specimen types tabulated in Table 5 with the corresponding initial void ratio and compaction effort. The specimen types were labeled as compacted clay liner (CCL), clay liner (CL), and compacted polyurethane-clay liner (CPCL). The compaction effort applied on CCL produced a specimen with an initial void ratio of 1.06 while the same compaction effort applied on CPCL produced a specimen with an initial void ratio of 1.44. Thus, to obtain the same initial void ratio of 1.44 as CPCL, less compaction effort was applied to clay to produce CL. The compacted specimens were cured for 24 hours inside an insulated chest to prevent excessive water loss after compacting and demolding, as necessary.

Table 4. Index 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

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

3.2 Wet-Dry Cycle

The wet-dry cycle was initiated by ensuring that the compacted specimen is in a very saturated state at the start of the cycle. The compacted specimens were air dried until the target moisture content was achieved at which the necessary data were gathered. To determine if the target moisture content was achieved, the compacted specimens were repeatedly weighed until the weight that corresponds to the target weight of the specimen for a certain target moisture content was obtained. Table 6 shows the target moisture content for various saturation levels of the three types of compacted specimen.

Table 6. Target moisture content

Saturation levels	Target moisture content (%)		
	CCL	CL	CPCL
Level 1	43.98	59.75	50.35
Level 2	37.69	51.21	43.15
Level 3	31.45	42.72	36.00
Level 4	25.16	34.18	28.80
Level 5	18.87	25.63	21.60
Level 6	12.58	17.09	14.40
Level 7	6.29	8.54	7.20
Level 8	0.00	0.00	0.00

3.3 Measurement of Matric Suction using the Filter Paper Method

ASTM D5298 [12], or the standard test method for measurement of soil potential, or suction, using filter paper, was used to determine the matric suction in the study. To determine the matric suction at a specific moisture content, a 55-millimeter circular Whatman No. 42 filter paper together with two 60-millimeter circular ashless quantitative filter paper were oven-dried and placed in a desiccant jar. Once the filter papers were cooled in the desiccant jar, a single ashless quantitative filter paper was placed on top of a 66-millimeter cylindrical compacted specimen at a specific moisture content. The height of the compacted specimen is 20 millimeters. On top of the ashless quantitative filter paper, a Whatman No. 42 filter paper was placed, followed by another ashless quantitative filter paper before another cylindrical compacted specimen with the same moisture content as the first one was placed as shown in Fig. 1.

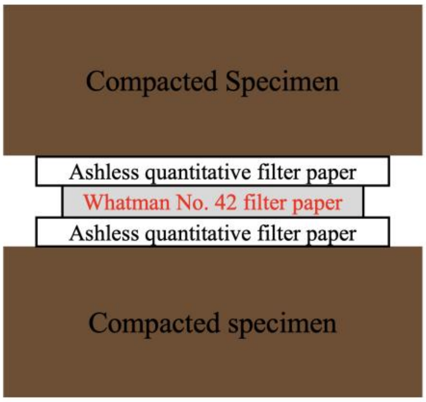

Fig. 1. Filter papers in between compacted specimens.

The set of Whatman No. 42 filter paper in between the two ashless quantitative filter papers, which were in between the two cylindrical specimens in Fig. 1. was placed in a glass jar and sealed with vinyl tape. The sealed glass jars were placed in an insulated chest to regulate the temperature of the glass jars because extreme heat or variation in temperature would affect the data obtained in the study. After 7 days, the used Whatman No. 42 filter paper was weighed to determine its water content. The water content obtained from the Whatman No. 42 filter paper were used to process the data using the calibration curve from ASTM D5298 [12], shown in Fig. 2, to obtain the matric suction in the compacted specimen at the time it was placed in the glass jar.

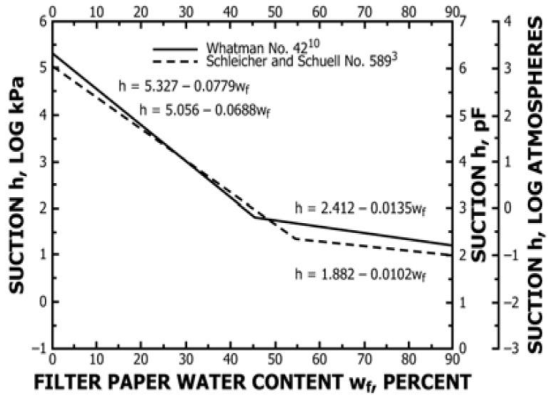

Fig. 2. Calibration Suction-Water Content Curves for Wetting of Filter Paper [12].

3.4 Desiccator Plate Test

The desiccator plate test method was used to observe the formation of cracks. The specimens for each type of compacted specimen, CCL, CL, and CPCL, were photographed during the drying process at various moisture content. Each cylindrical specimen, which has a diameter of 200 millimeters and a height of 10 millimeters, was repeatedly weighed until the target weight was achieved corresponding to the target moisture content. Moreover, the specimens were placed on a grooved acrylic desiccator plate with a circular pattern shown in Fig. 3. The grooves were 2 millimeters apart and 1 millimeter deep. The gridlines on the camera coincided with the gridlines on the specimen mold as shown in Fig. 4 (a) to ensure that the photo taken did not change in configuration and is still leveled. The photos were taken under a single source of light over the specimen, as shown in Fig. 4 (b), to prevent variability in light distribution due to varying intensity and sources of light at the time the photos were taken.

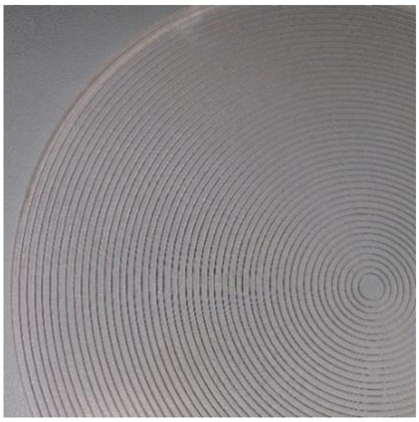

Fig. 3. Grooved acrylic desiccator plate.

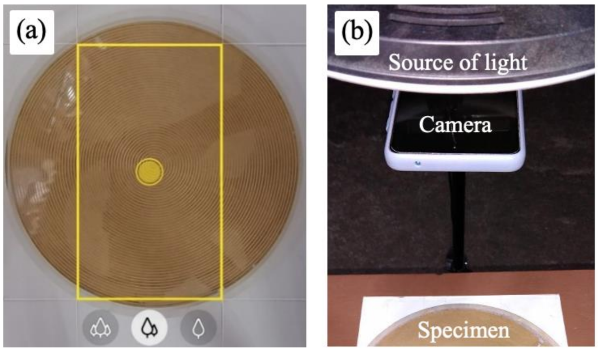

Fig. 4. (a) Image calibration, and (b) setup.

4. RESULTS AND DISCUSSION

The results and discussion are composed of the results obtained through the filter paper method to quantify the matric suction at various moisture content levels. It also contains the discussion regarding the inferred effect of matric suction on the observed crack propagation of the compacted specimen dried on a grooved acrylic plate.

4.1 Matric Suction

Compacted clay liner (CCL) and compacted liner (CL) specimens are clay that has the same initial characteristics, such as compaction water content, liquid limit, and grain size distribution. On the other hand, compacted polyurethane-clay liner (CPCL) has the same compaction effort as CCL. Fig. 5 shows the water retention curve of CCL, CL, and CPCL wherein the logarithm of the matric suction was plotted against the moisture content. Table 7 shows the values of the matric suction for the corresponding saturation levels.

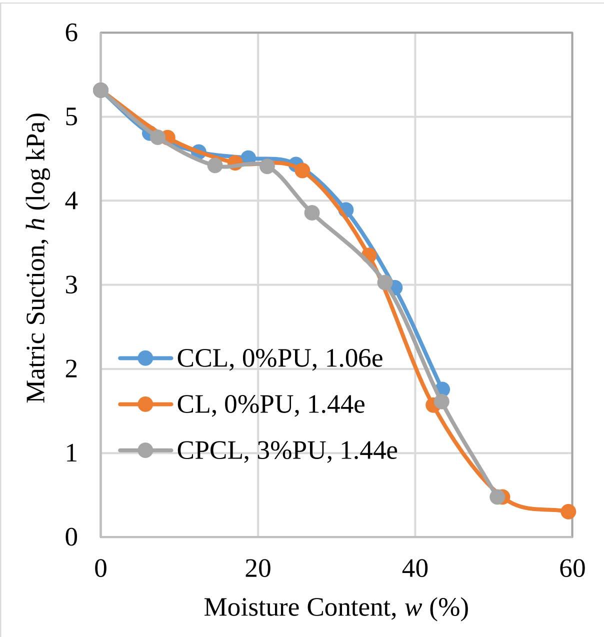

Fig. 5. Matric suction of CCL, CL, and CPCL.

Table 7. Matric suction values

Saturation levels	Matric suction, *h* (kPa)		
	CCL	CL	CPCL
Level 1	57	2	3
Level 2	924	3	41
Level 3	7,772	37	1,062
Level 4	27,096	2,245	7,163
Level 5	32,156	22,837	25,615
Level 6	38,056	28,259	26,217
Level 7	63,686	56,342	57,091
Level 8	206,968	206,829	207,035

It can be observed in Fig. 5 that the matric suction, regardless of the initial void ratio and polyurethane content, increases as the moisture content decreases. The behavior exhibited by the soil in the study agrees with the behavior of soil observed in another study wherein the water holding capacity is unaffected by the initial conditions, such as the initial void ratio [13].

It can also be observed that the varied initial void ratio did not have an effect at the higher matric suction ranges. According to several studies, the suction in the higher ranges is due to the adsorption and is more influenced by texture and specific surface of the soil particle rather than the soil structure, which includes the initial void ratio and particle size [10,13-15]. However, in the lower matric suction ranges, it can be observed that the soil structure affects the matric suction. Among the three kinds of specimen, CCL, CL, and CPCL, CCL has the highest matric suction at the lower ranges since compaction condition has a significant effect on the pore structure. The specimen with the smaller void ratio has a slower desaturation process and consequently a lower matric suction required to equilibrate the water within the matrix [13]. Table 8 shows the analysis of variance of the comparison between two clay specimens without polyurethane, which are affected by the factors such as the moisture content and initial void ratio. The confidence level used for this analysis is 90%.

Table 8. Analysis of variance of clay specimens

Source	P-value	
Model	< 0.0001	Significant
Moisture content	< 0.0001	Significant
Initial void ratio	0.5000	Significant

It can also be observed that the matric suction of CPCL has a lower value at the lower suction range compared to the clay specimens without polyurethane. The difference in matric suction was due to the difference in particle size since specimens with larger particle sizes, such as polyurethane-clay, have a lower matric suction [16]. Table 9 shows the analysis of variance of the comparison between clay specimens without polyurethane and the clay specimen with polyurethane, which are affected by the factors such as the moisture content and polyurethane content. The confidence level used for this analysis is 90%.

Table 9. Analysis of variance of compacted specimens

Source	P-value	
Model	< 0.0001	Significant
Moisture content	< 0.0001	Significant
Polyurethane content	0.0599	Significant

4.2 Desiccation Cracks

Desiccation cracks are observed on CCL, CL, and CPCL specimens. It can be observed that cracks are more evident on the CCL and CPCL specimen, shown in Fig. 6 and Fig. 7, respectively. On the other hand, cracks on the CL specimen are not noticeable if not examined very closely as shown in Fig. 8.

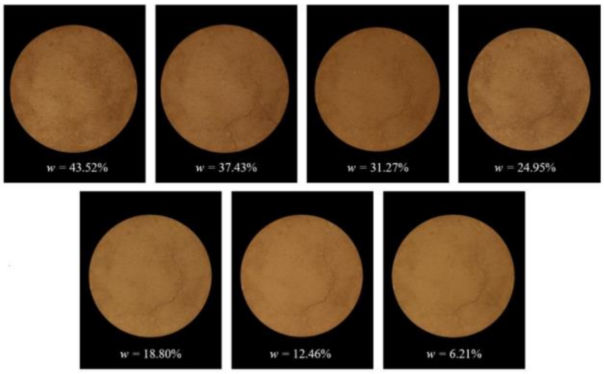

Fig. 6. Progression of CCL surface cracks.

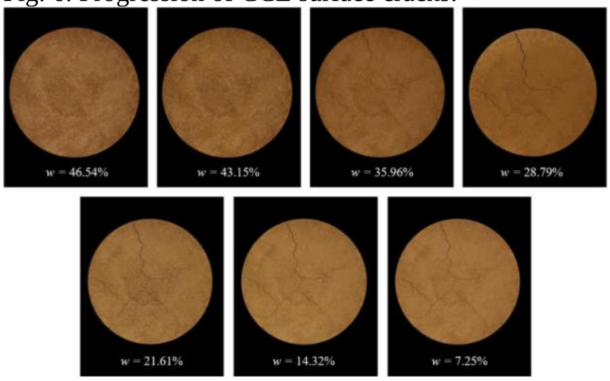

Fig. 7. Progression of CPCL surface cracks.

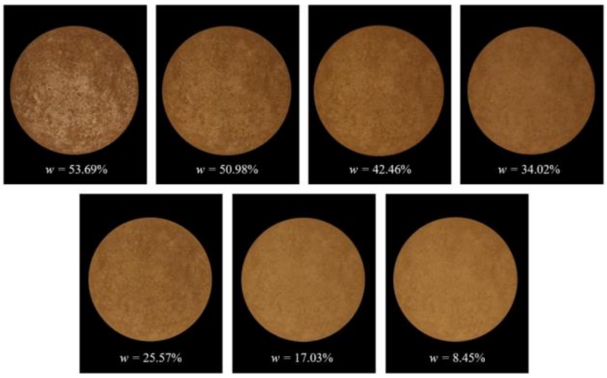

Fig. 8. Progression of CL surface cracks.

CCL, CL, and CPCL initially had greater than 90% degree of saturation upon compaction and saturation. Thus, the moisture content reflected on the first specimen of each specimen type is the moisture content at a saturated condition. Several factors may have affected the progression, length, and width of cracks at different stages of drying. According to Tang et al. [17] the size, structure, and plasticity of soil influence the cracks of clay and considering a single factor may yield an inaccurate evaluation.

Cracks are developed in three stages [17,18]. The first stage is when individual cracks are formed at weak points, usually near the edge of the boundary, which propagate towards the inner region [17]. In the second stage, the secondary cracks are formed from existing individual cracks and are terminated when the cracks intersect each other [17]. At the third stage, the geometric structure of the crack network is stabilized, and no new cracks are formed; moreover, in this stage existing cracks widen until drying is done [17]. From Fig. 6, it can be observed that stages 1 and 2 are completed and stage 3 is initiated on the CCL specimen at 37.43%, the 2nd moisture content level. On other hand, stage 1 and 2 are completed and stage 3 is initiated at the 35.86% moisture content level of the CPCL specimen, shown in Fig. 7. Moreover, it can also be observed that the cracks widened on the next moisture content level. Thus, with the development of stages 1 and 2 of the CCL and CPCL specimen, it can be inferred that the evaporation of water from the specimen affects the development of cracks considering that the said stages were completed at around the same value of moisture content. The findings agree with Tang et al. [17] wherein it was inferred that cracks develop when the soil is still saturated.

It was established in previous analyses that the matric suction increases as the water from the soil mass evaporates. According to Tang et al. [17], desiccation cracks initiate and propagate due to the accumulation of internal stresses induced by the matric suction that exceeds the strength criterion of the soil. Thus, the desiccation cracks produced was a result of failure of the soil mass to resist the internal stresses induced by the matric suction. Moreover, previous studies inferred that 80% to 90% of the cracks developed are at the small suction levels, while no new surface cracks are formed when water content is lower than 20%. The critical suction, wherein cracks are initiated, has a value smaller than 1000 kPa [17]. Considering the findings from the previous analysis, the matric suction of CCL at 37.69% moisture content is 924 kPa, while the matric suction for CPCL at 36.00% moisture content is 1062 kPa, the behavior of the soil agrees with the findings from previous studies. In addition, in the previous analysis, it was established that the matric suction of CCL is greater than the matric suction of CL at the lower suction range. Thus, it was expected that more shrinkage cracks would be produced in the CCL specimen than the CL specimen. It can be visually inspected from Fig. 9 (a) and Fig. 10 (a) that the stable crack network of CPCL is greater than the stable crack network of CCL. The increased number of cracks may be attributed to the particle size of the two soil types since specimens with a higher percentage of coarser particles, which has a diameter of greater than 0.002 mm, in clay causes larger surface crack areas [17]. Less than half, or 40% of the clay particles from the clay has a particle diameter of less than 0.002 mm based on the grain size distribution. On the other hand, 42% of the clay particles from the polyurethane-clay have a diameter of less than 0.002 mm. Thus, the behavior of the produced cracks agrees with the findings from previous studies. Moreover, it can be observed from Fig. 9 (c) and Fig. 10 (c) that the cracks at the boundary of the CCL and CPCL specimen propagated throughout the entire 10-millimeter-thick specimen.

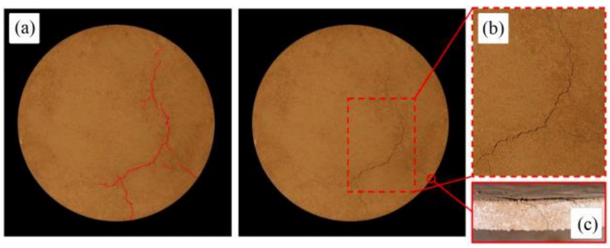

Fig. 9. (a) Outline, (b) magnified view, and (c) propagation of CCL cracks.

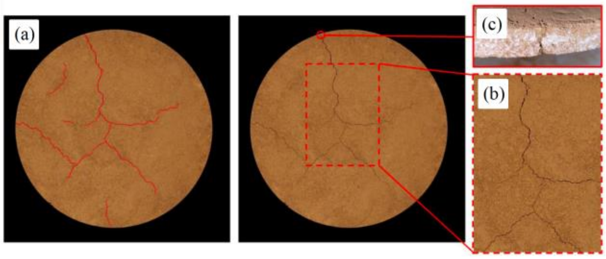

Fig. 10. (a) Outline, (b) magnified view, and (c) propagation of CPCL cracks.

5. CONCLUSION

In conclusion, this study determined the matric suction using the filter paper method. The quantified matric suction experienced by the compacted clay liner (CCL), compacted liner (CL), and compacted polyurethane-clay liner (CPCL) through varying moisture content was analyzed by establishing the water retention curve and analyzing the effect of the soil structure on low and high suction ranges. In general, the soil structure did not have an effect on the matric suction at the high suction ranges for all types of compacted specimens; however, the soil structure, such as the initial void ratio and particle size, had a significant effect on the matric suction at the lower ranges. In addition, the amount of water within the soil matrix of the compacted specimen was inferred to have a significant effect on the matric suction for any type of compacted specimen whether it is in the high suction range or low suction range.

The formation of the desiccation cracks was also observed as the compacted specimen types were dried on a grooved desiccator plate to simulate the friction that the soil layer experienced. CCL and CPCL both exhibited a more extensive crack network compared to CL, which has a lower matric suction in the lower ranges. The development of cracks through the three stages of drying shows its effect on the soil structure, such as particle size and initial void ratio, as well as the matric suction. The observation of the crack propagation was validated by existing literature, which also validates the effect of internal stresses induced by the matric suction on the propagation of desiccation cracks. The findings in this study may be utilized in optimizing the sanitary landfill liner design in order to prevent the development of preferential flow paths wherein leachate could flow to and deteriorate the environment outside the controlled disposal facility.

6. RECOMMENDATION

It is recommended to consider the desiccation cracks in determining the unsaturated hydraulic conductivity through several wet-dry cycles since it is established in previous studies that cracks increase the hydraulic conductivity or permeability of a material. It is also recommended to quantitatively analyze the cracks so that it may be determined if factors, such as polyurethane content, has a significant effect on the produced cracks. In addition, it is recommended to determine the propagation of cracks not just on the surface, but also the entire cross-section of the compacted specimen to determine internal cracks and to simulate crack propagation based on data acquired from experiments. Simulation and analysis of crack propagation may be conducted using software such as ANSYS as utilized in the study of Hasan, Amin, and Riyad [19], which analyzed the crack propagation in a beam supported reinforced concrete slab.

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