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COMPACTION CHARACTERISTICS OF A FINE-GRAINED SOIL POTENTIAL FOR LANDFILL LINER APPLICATION

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ABSTRACT: Increasing population growth and urbanization results in increased demand for waste disposal processes and facilities that can protect public health and the environment. In the Philippines, there is a great demand to construct sanitary landfills (SLF) with only 387 local government units (LGUs) or equivalent to 23.86% compliant to date with Republic Act 9003 which mandates all LGUs to use the sanitary landfill. The compaction characteristics of a locally abundant fine-grained soil at different compaction energy levels were investigated as part of a broader study in the suitability of the soil as a landfill liner material. Compaction is essential in the preparation of a well-compacted soil liner in a sanitary landfill to avoid or minimize the migration of leachate and thereby reduce the risk of groundwater pollution. The physical properties are determined through a series of laboratory tests which covers the grain-size distribution, specific gravity, Atterberg limits, soil classification, XRD and SEM-EDX. Correlations to estimate the compaction characteristics at any rational compaction energy (E) are developed. The maximum dry unit weight values at different compactive efforts were used to determine void ratios which were then utilized to compute for the saturated hydraulic conductivity using numerical model for hydraulic conductivity for the same soil type. The resulting hydraulic conductivity ranges from 2.30 x 10-7 to 1.20 x 10-7 cm/sec well above the required value in the Philippines as per RA 9003 and its IRR for the intended Category I and II SLFs application.

Keywords: Compaction, Compaction Energy, Landfill Liner, Sanitary Landfill

1. INTRODUCTION

Solid waste management is one of the major problems worldwide as a result of the ever-increasing population and urbanization. This results in an increased demand for waste disposal processes and facilities that can protect public health and the environment. Sanitary landfill (SLF) remains the top choice as the final disposal facility. In the Philippines, the Republic Act (RA) 9003 otherwise known as the "Ecological Solid Waste Management Act of 2000" mandates all local government units (LGUs) to transition from open dumpsite to controlled dumpsite, and eventually to a sanitary landfill (SLF) not later than February 2006. However, as of July 2019, only 387 LGUs equivalent to 23.68% of the total number of LGUs have access to the 182 operating SLFs as published in the Philippine Environmental Management Bureau website. Thus, construction for more SLFs is in the offing and the need for sustainable materials, especially for the lining system. The lining system in SLF is one of the most salient features of the facility to protect environmental degradation that can eventually affect public health. The barrier component of the liner may comprise of compacted clayey layer, geomembrane, geosynthetic clay layer or a composite of these.

In this study, a locally abundant fine-grained soil is explored as possible compacted soil lining material for a municipal SLF. The compacted soil lining with or without admixture of clay is often used because of its relatively low cost, accessibility, durability, high resistance to heat, and other factors among other liner materials [1]. Very scanty published literature is available on the use of compacted soil in the Philippines as landfill liner. A study was made utilizing local materials from Bais City, Negros Oriental as clay liner in the implementation of SLF [2]. Other studies considered some marginalized materials as landfill liners such as residual soil [3], dredged marine soils [4], compost [5], fly ash used as soil treatment in combination with bentonite [6] among others.

Compaction is essential in the preparation of a well-compacted soil liner in a sanitary landfill to avoid or minimize the migration of leachate and thereby reduce the risk of groundwater pollution [7]. Soil compaction is one of the ancient and efficient ways to improve the physical and mechanical soil properties. The soil particles are pressed to pack more closely together through a reduction in the air voids between the particles commonly through mechanical means. Compaction increases soil unit weight that results in an increase in shear strength, reduction in settlement and decrease in hydraulic conductivity [8]. Many engineering structures constructed on soils, such as buildings, highways, railway subgrade, airfield pavements, earth dams, and earth-retaining structures require compaction. Compaction increases the soil strength properties, which in turn increases the bearing capacity of foundations built on them. It reduces the amount of unwanted settlement of structures and improves the stability of slopes of embankments.

The maximum dry unit weight (γdmax) and optimum moisture content (ωopt) are the compaction characteristics of a soil obtained from a laboratory compaction test. These parameters are salient considerations during landfill design and construction to achieve low hydraulic conductivity for the liner material. However, field compaction of fine-grained soils frequently involves diverse equipment which varies significantly in compaction energy. Hence the need to obtain the compaction characteristics at different compaction energies. Information on the compaction behavior and characteristics at different compaction energy levels don great relevance for practical application [9].

In most preliminary assessment of the suitability of soils for projects, the use of correlations involving engineering properties with easily obtainable physical properties such as Atterberg limits can be economically useful. Previous study developed an empirical method for estimation of maximum dry unit weight and optimum water content of clayey soils at different compactive effort. One variation of the method uses the liquid limit (LL) and one compaction curve while the other uses the liquid limit (LL) [10]. Relations were also developed on the compaction behavior and prediction of its characteristics using plastic limit with particular reference to variations in compacting energy levels [9].

In this paper, the compaction characteristics of a local fine-grained soil as potential landfill liner material at different compaction energy level were investigated. This is a prelude to a broader study on the suitability of the soil as a landfill liner material. The physical properties were determined through a series of laboratory tests which are the grain-size distribution including both the mechanical and hydrometer analysis, specific gravity, Atterberg limits covering the plastic limit, liquid limit and shrinkage limit and soil classification as per Unified Soil Classification System (USCS). X-ray powder diffraction (XRD) and scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS) were also carried out. The physical properties and material composition influence the compaction behavior of the soil. The laboratory compaction test was carried out using Modified Proctor Test, Standard Proctor Test and Reduced Proctor Test [11]. Relations to estimate the compaction characteristics at any rational compaction energy (E) were developed and validated with the previous related studies. The void ratio from compaction tests at different compactive efforts was utilized to compute for the saturated hydraulic conductivity using predictive models for hydraulic conductivity from the previous study of authors for the same type of soil [12]. The hydraulic conductivity values were then compared with the standard with the requirement set forth by RA 9003 and its implementing rules and regulation (IRR) as shown in Table 1.

Table 1. RA 9003 and IRR Hydraulic Conductivity Requirements

Land fill Category	Capacity (tons/day)	Min. Requirement for k (cm/sec)
I	≤ 15	1×10^{-5}
II	> 15 ≤ 75	1×10^{-6}
III	> 75 ≤ 200	1×10^{-7}
IV	> 200	1×10^{-7}

The findings will aid in the initial assessment purposes of the local fine-grained soil without prejudice to the actual conduct of laboratory and field hydraulic conductivity test as well as other requirements set forth by the aforementioned law and its IRR. The information can be utilized as a part of the basis for soil modification whenever needed prior to utilization as a construction material.

2. MATERIALS AND METHODS

2.1 Source of Fine-Grained Soil Sample

a. Moist Soil b. Oven-dried Soil

Fig. 1 Soil sample used in this study

The soil sample was obtained from a borrow pit at the proximity of the proposed sanitary landfill site in the municipality of Kauswagan, Lanao del Norte, Philippines. Figure 1 shows the soil sample used in the study. The soil belongs to the Adtuyon soil series which is clay loam and derived from weathering of basalts, andesites and other igneous rocks [13]. The sample was taken at a depth of least 2 meters to exclude organic matters. Disturbed samples are used as compacted soils as what is used in actual landfills which are from excavated materials or hauled to the actual landfill site. The soil appears to be reddish-brown. The soil consistency is sticky, plastic when moist and firm when dry.

2.2 Soil Property Tests

The physical properties of soil sample were determined following the ASTM standards as presented in Table 2. Classification of soil sample is in accordance with the USCS. X-ray diffraction (XRD) was also performed on soil sample to obtain a mineralogical analysis of the sample as it provides detailed information about the atomic structure of crystalline substances. It is a powerful tool in the identification of minerals in rocks and soils [14]. Scanning electron microscopy (SEM) test was employed in this study. It can play a valuable reconnaissance role that provides an indication of the broad character of the soil microfabric, over a wide range of magnification, which aids in the selection of the appropriate programme and methods of quantification [15]. Energy dispersive X-ray (EDX) analysis was used to determine the elemental composition of the surface of the soil specimen. In a properly equipped SEM, the atoms on the surface are excited by the electron beam, emitting specific wavelengths of X-rays that are characteristic of the atomic structure of the elements. An energy dispersive detector can analyze these X-ray emissions. Appropriate elements are assigned, yielding the composition of the atoms on the specimen surface [16].

Table 2. Physical Soil Properties Tests

Test	Test Standard
Grain Size Analysis	
-Mechanical Method	ASTM D6913
-Hydrometer Method	ASTM D7928
Specific Gravity Test	ASTM D854
Liquid Limit Test	ASTM D4318
Plastic Limit Test	ASTM D4318
Shrinkage Limit Test	ASTM D427
Min. Index Density Test	ASTM D4254
Max. Index Density Test	ASTM D4253
XRD	
SEM-EDX	

2.3 Compaction Tests

The compaction tests are carried out using three compactive energy levels in a 4-inch Proctor mold embodied by Modified, Standard Proctor and Reduced Proctor Tests. The modified Proctor effort represents an upper limit on the field compactive effort, the standard Proctor effort represents a field medium compactive effort, and reduced Proctor effort represents a minimum field compactive effort respectively for most geotechnical landfill earthworks [17]. Compaction curves are plotted with the dry unit weight on the vertical axis and the water content on the horizontal axis for the different compaction energy levels. Regression analysis was performed for each set of curves considering the curves as second degree polynomial. The peak value of the dry density is the maximum dry density and corresponding water content is called optimum water content of the generated curve. The tests are summarized in Table 3 with the corresponding test standard references.

Table 3. Comparison of Proctor Tests

Criteria	Type of Proctor Test		
	Modified	Standard	Reduced
Test Standard	ASTM D1557	ASTM D698	Daniel and Benson
Hammer Weight, N	45	24	24
Drop Distance, mm	450	300	300
No. of Layers	5	3	3
Blows per Layer	25	25	10
Specific Energy, kN-m/m^3	2690	590	360

3. RESULTS

3.1 Particle Size Distribution

The mechanical sieve analysis yielded 2% of fine sand and 98% of silt and clay. Figure 2 depicts the particle size distribution with the inclusion of the hydrometer test result and exhibits a poorly graded soil. With the percentage of soil grains passing No. 200 sieve more than 50%, the soil is said to be fine-grained and is expected to respond poorly to compaction.

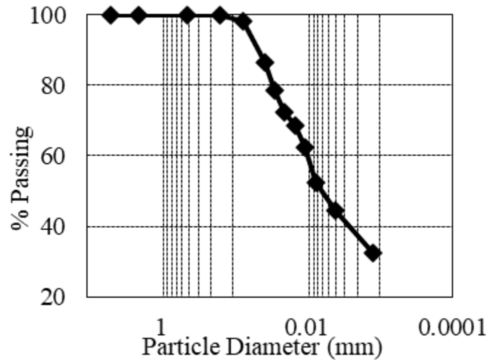


Fig. 2 Particle Size Distribution Curve

3.2 Soil Constants

The series of tests resulted to the values for soil physical properties as shown in Table 4. The specific gravity value falls within the typical range of 2.6 to 2.9 for clayey and silty soils [18]. The value of the Plasticity Index (PI) falls within the range of 20-40 which is for the highly plastic soils [19]. The values for liquid limit and plasticity index are subsequently used as inputs for soil classification.

Table 4. Soil Constants

Soil Property	Value
Specific Gravity, Gs	2.66
Liquid Limit, LL,	88.49
Plastic Limit, PL	55.68
Plasticity Index, PI	32.81
Shrinkage Limit, SL	29.69
Min. Void Ratio, e_{min}	1.07
Max. Void Ratio, e_{max}	1.55
Min. Dry Unit weight, γ_{dmin}, kN/m^3	10.24
Max. Dry Unit weight, γ_{dmax}, kN/m^3	12.59

3.3 Soil Classification

The soil sample is classified as elastic silt in accordance to the Unified Soil Classification System (USCS) with designation MH. The values of the soil properties being percent finer passing No. 200 > 50%, liquid limit >50%, plasticity index plots below the "A" line and percentage passing of sand or gravel < 15 to 29%. Typical names are inorganic silts, micaceous fine sands or silts, or elastic silts. Soils classified as such contains, mica, iron oxide and kaolinitic clay. This type of soil is semi-pervious to impervious when compacted [20]. Typical values of hydraulic conductivity for this type of soil ranges from 1x10^{-5} to 1 x 10^{-7} cm/sec [21]. These values fall within the requirement for compacted soil landfill liner as per RA 9003 and its IRR discussed in the previous section.

3.4 XRD Result

Oven-dried soil sample was manually ground to produce fine powder passing sieve No. 200 was used in the analysis. The sample was scanned from 3° to 70° at a scanning rate of 1 degree per minute. The resulting XRD pattern shows sharp peaks as shown in the Figure 3. The result suggests that the soil sample comprises mainly of the crystal phases of kaolinite, biotite, antigorite, and goethite.

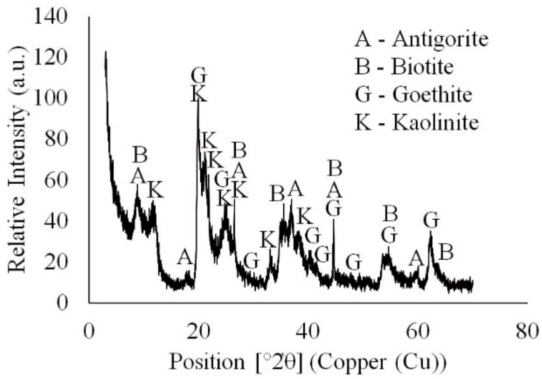
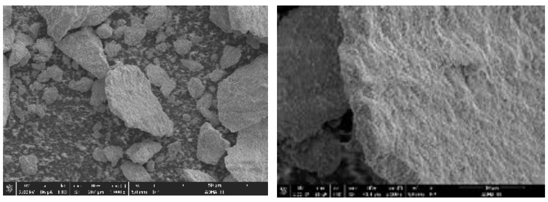
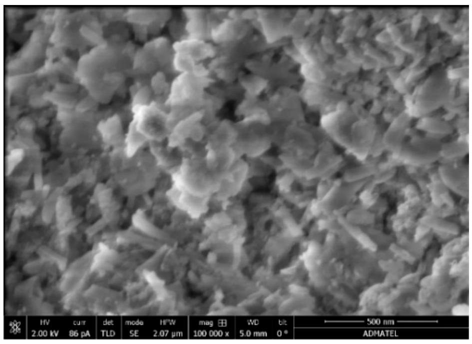


Fig. 3 X-ray Diffractogram of the Soil Sample

3.5 SEM-EDX



a. 1,000x Magnification b. 5,000x Magnification



c. 100,000x Magnification

Fig. 4 SEM Micrographs of the Soil Sample

A set of micrographs for the soil at various magnification factor is exhibited by Figure 4. Soil samples oven-dried at 105ºC of grains passing sieve No. 200 were used to remove moisture, coarse and organic material. The image of Figure 4a at 1000x magnification shows sub-angular and sub-rounded shapes like those of granular soils. It also reveals large intergranular voids. At higher magnification, Figures 4b and Figure 4c, 5000x and 100 000x respectively, visible are flakey, spheroidal, tubular morphological attributes and inter granular voids usually associated to clay minerals. A flakey configuration in the soils is common in fine-grained varieties such as clay and silt enabling those types of soil to have large surface areas for moisture adsorption. The image gives an impression that the soil contains many components such as mica, clay species (silicates) occurring in platy, sheet, flake structure in the family of phyllosilicates and few organic materials.

Table 5. EDX Elemental Distribution

Element Name	Symbol	Weight Percentage
Oxygen	O	52.4
Aluminum	Al	16.6
Silicon	Si	16.6
Iron	Fe	6.9
Carbon	C	6.7
Titanium	Ti	0.7
Calcium	Ca	0.1

The elemental analysis yields that oxygen, aluminum, and silicon comprised most of the soil sample with traces of iron, carbon, titanium and calcium as shown in Table 5. These elements are among the most abundant elements in the Earth's crust [22]. The EDX result indicates the presence of phyllosilicates and is consistent with the main minerals identified in the XRD analysis. Kaolinite is a clay mineral which is one of the polytypes in in the kaolin group [23]. Kaolinite is the most abundant member of the kaolin group and is also one of the most abundant clay minerals on Earth [24, 25]. Biotite sometimes called black mica is a common phyllosilicate mineral within the mica group [26]. Antigorite is one of the polymorphs of serpentine mineral and is widespread in nature [27]. Goethite is the most common of the iron oxyhydroxides [28]. Goethite is the most ubiquitous iron oxide mineral in soils and a major component of many ores and sediments due to its high stability. Iron oxides are common minerals that are produced from aqueous processes at different redox and pH conditions [29]. Kaolinite had been known as non-expandable for a long time until studies showed some polar molecules could indeed be intercalated in its interlayer spaces [30, 31]. Its interlayer chemistry is much less developed than for smectite; specifically, montmorillonite since its interlayer spaces are not easily accessible.

3.6 Compaction Tests

The typical compaction curves of the soil sample for the three compactive efforts exhibit a bell shape as shown in Figure 5. It is observable that the maximum dry unit weight increases with the increase in compactive effort while the optimum water content decreases with the increase in compactive effort. All the curves are well below the zero-air voids curve. The pattern shown by the compaction curves of the soil under study have shown similar results for compacted kaolin clay [32].

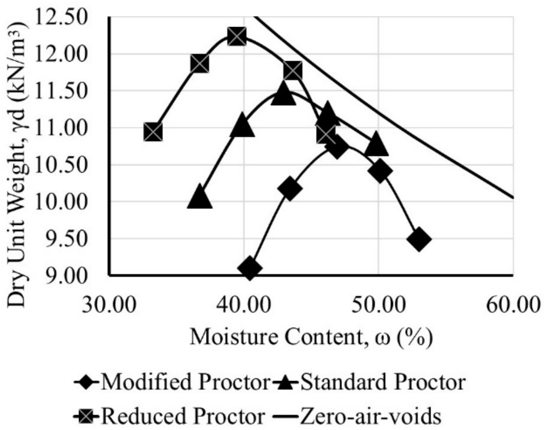


Fig. 5 Typical Compaction Curve

The experimental values of the maximum dry density and corresponding optimum moisture content are summarized in Table 6. The maximum dry unit weight values are within the range for typical silty soils [20]. Higher compactive effort than the standard Proctor test increases the maximum dry unit weight and reduces the optimum water content [33].

Table 6. Proctor Test Results

Run	Item	Proctor Test Type		
		Modified	Standard	Reduced
1	MDD[1]	12.18	12.16	12.17
	OMC[2]	39.65	39.92	39.80
2	MDD[1]	11.44	11.44	11.45
	OMC[2]	43.11	44.05	43.55
3	MDD[1]	10.72	10.68	10.93
	OMC[2]	47.18	47.25	45.59

Note: 1 – unit in kN/m^3, 2 – in %

3.7 RELATIONSHIPS

3.7.1 Relationships Between Dry Unit Weight and Compaction Energy

The maximum dry unit weight and the logarithm of the compaction energy exhibits a linear relationship similar to a previous study [10]. There is a strong correlation based on the coefficient of determination value R^2 equal to 0.922. It is apparent that the maximum dry unit weight value increases with increasing compaction energy as shown in Figure 6.

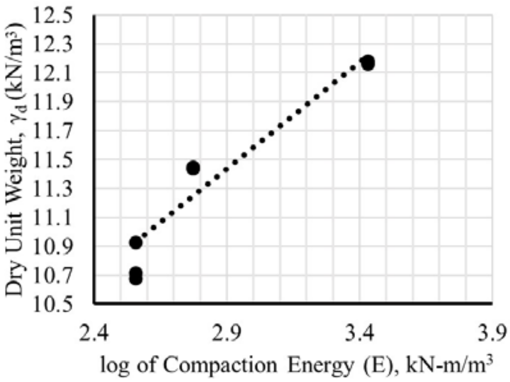


Fig. 6 Plot of the Dry Unit Weight and Logarithm of Compaction Energy

The maximum dry unit weight at any value of compactive energy can be predicted using Eqn. 1:

$$\gamma_{dmax} = 1.4792\log(E) + 7.1455 \qquad (1)$$

where:
γ_d = maximum dry unit weight in kN/m^3
E = compaction energy in kN-m/m^3

The predicted value of MDD by the equation can be used to specify field compaction for this soil type with fines greater than 50% and plasticity index between 20 to 40.

3.7.2 *Relationship Between Optimum Moisture Content and Compaction Energy*

The optimum moisture content and the logarithm of the compaction energy exhibits a linear relationship similar to a previous study [10] as shown in Figure 7. The OMC value decreases with the increasing compaction energy. There is a strong correlation based on the coefficient of determination value R^2 of 0.9196.

The OMC can be predicted for a given value of compactive energy using Eqn. 2:

$$\boldsymbol{\omega = -7.3757 log + 64.874} \qquad (2)$$

where:
OMC = Optimum Moisture Content in %
E = compaction energy in kN-m/m^3

The predicted value of OMC by the equation can be used to specify field compaction for this soil type with fines greater than 50% and plasticity index between 20 to 40.

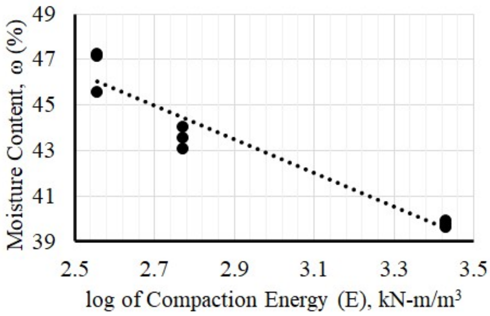


Fig. 7 Plot of the OMC and Compaction Energy

3.7.2 *Relationship Between Dry Unit Weight and Moisture Content*

The line of the optimums is shown in Figure 8. The dry unit weight decreases with the increasing moisture content with a strong correlation based on coefficient of determination value R^2 equal to 0.9906.

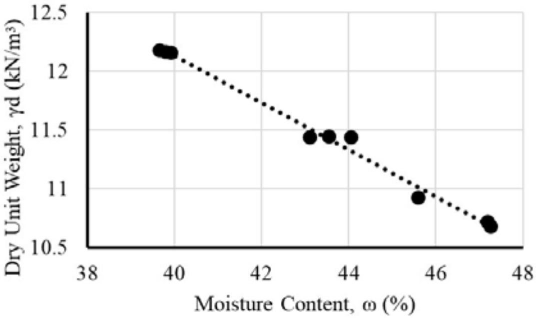


Fig. 8 Line of the Optimums

The maximum dry unit weight can be predicted using Eqn. 1:

$$\boldsymbol{\gamma_{dmax} = -0.1993\,\omega + 20.104} \qquad (3)$$

where:
γ_d = maximum dry unit weight in kN/m^3
ω = moisture content in percent

The MDD and OMC values predicted by the equation can be used to specify field compaction for this soil type with fines greater than 50% and plasticity index between 20 to 40.

3.8 Void Ratio Values from Proctor Test and Saturated Hydraulic Conductivity

The maximum dry unit weights are used to compute for the corresponding void ratio using Eqn. 4 [4]:

$$e = \frac{G_s \gamma_w}{\gamma_d} - 1 \tag{4}$$

where:
γ_d = maximum dry unit weight in kN/m^3
γ_w = Unit weight of water in kN/m^3
G_s = specific gravity of the soil solids
e = void ratio

The void ratio values were used to compute for the saturated hydraulic conductivity using the predictive relation of the hydraulic conductivity Eqn. 5 [12]:

$$k = 1.0 \ x\ 10^{-7} exp^{2.1337e} \tag{5}$$

where:
k = saturated hydraulic conductivity in cm/sec
e = void ratio

Table 7 gives the values of the void ratio, *e* obtained from Proctor Tests at different compaction energy levels and predicted values of hydraulic conductivity.

Table 7 Computed *e* and *k* from MDD at Different Compactive Efforts

Proctor Test	MDD (kN/m^3)	Void Ratio, e	k (cm/sec)
Reduced	10.68	1.4433	2.26 x 10^{-7}
	10.72	1.4342	2.30 x 10^{-7}
	10.93	1.3874	2.04 x 10^{-7}
Standard	11.44	1.2810	1.62 x 10^{-7}
	11.44	1.2810	1.62 x 10^{-7}
	11.45	1.2790	1.61 x 10^{-7}
Modified	12.16	1.1459	1.20 x 10^{-7}
	12.17	1.1442	1.21 x 10^{-7}
	12.18	1.1424	1.20 x 10^{-7}

The range of the computed values of *k* are within the acceptable values of hydraulic conductivity set by RA 9003 and its IRR for the targeted application which are Categories I and II as bottom landfill liner.

4. CONCLUSION

Based on this study, the following conclusions can be drawn:

The fined-grained soil as elastic silt based on USCS. The soil sample comprises mainly of the crystal phases of kaolinite, biotite, antigorite, and goethite from the XRD analysis and in congruence from the SEM-EDX results.

Strong correlation was developed between the compaction characteristics and the logarithm of the compactive energies. The dry unit weight ranges 10.72 to 12.18 kN/m^3 with corresponding moisture content 47.25% to 39.65%. The dry unit weight used to compute for the void ratio gives values in the range from 1.1442 to 1.4342. These values yield the predicted hydraulic conductivity of soil in the range of 2.30 x 10^{-7} to 1.20 x 10^{-7} cm/sec which conforms to the requirement in the Philippines as per RA 9003 and its IRR for the intended Category I and II SLFs application.

Further study is warranted on its actual laboratory hydraulic conductivity, unconfined compressive strength and volumetric shrinkage to provide baseline information for soil modification as maybe desired for the utilization of the soil as marginalized material for SLF lining.

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