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

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ABSTRACT: Sanitary landfills (SLFs) are usually employed as final waste disposal facility to protect public health and the environment. As a result of rapid population growth and urbanization, there is currently a great demand to construct SLFs in the Philippines. The hydraulic conductivity characteristics of remolded samples of a locally abundant fine-grained soil compacted at different compaction energy level is investigated to determine the suitability of the soil as landfill liner material. The hydraulic conductivity of lining system is one very salient feature of the SLF to prevent contamination of nearby soil and water sources. The physical properties of the soil are determined through a series of laboratory tests which includes the grain-size distribution, specific gravity, Atterberg limits, soil classification, Cation Exchange Capacity (CEC), X-ray powder diffraction (XRD) and scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS). The falling head laboratory test was conducted to determine the saturated coefficient of hydraulic conductivity. A numerical model was formulated that can predict hydraulic conductivity as a function of the void ratio. The resulting coefficient of hydraulic conductivity ranges from 1.98 x 10^{-6} to 1.0 x 10^{-7} cm/sec meet the Philippine standard requirement. The soil being classified as clay loam can readily be used as top lining material. However, additional study on unconfined compressive strength and volumetric shrinkage among other parameters is recommended prior to use of the fine-grained soil as bottom lining material as soil amendment maybe necessary.

Keywords: Hydraulic conductivity, Permeability, Landfill Liner, Sanitary Landfill

1. INTRODUCTION

Sanitary landfills (SLFs) are usually employed as final waste disposal facility to protect public health and the environment. As a result of rapid population growth and urbanization, there is currently a great demand to construct SLFs in the Philippines on top of the statutory requirement set forth by Republic Act (RA) 9003 otherwise known as the “Ecological Solid Waste Management Act of 2000”. This law requires 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 February 2020, only 108 sanitary landfills or 6 percent of the total required number of 1700 landfills nationwide as reported in the Philippine Environmental Management Bureau website. The construction for more SLFs gives rise to the need for sustainable materials especially for the lining system. The lining system in SLF is one of the most important features of the facility to provide containment against environmental degradation that may cause adverse effect to public health. Compacted clayey layer, geomembrane, geosynthetic clay layer or a composite of these may constitute the barrier component of the liner which should have a low hydraulic conductivity and the ability to attenuate pollutants migrating through.

In this study, the saturated hydraulic conductivity of a locally abundant fine-grained soil is explored as part of a much bigger study on the possible use of that soil as compacted soil lining material for a municipal SLF. The use of compacted soil lining with or without admixture of clay is common due its relatively low cost, accessibility, durability, high resistance to heat, and other factors among other liner materials [1]. Some marginalized materials are also studied as potential landfill liners such as residual soil [2], dredged marine soils [3], compost [4], fly ash used as soil treatment in combination with bentonite [5] among others. Published literature on the use of compacted soil in the Philippines as landfill liner is limited.

Compacted soil liner consists of a mineral layer which satisfies hydraulic conductivity and thickness requirements along with other technical requirements such as cation exchange capacity (CEC) which varies for different countries. The hydraulic conductivity is the principal factor that affects hydraulic barrier performance. Typical hydraulic conductivity value must be less than or equal to 1 x 10^{-7} cm/sec for soil liners and covers to contain hazardous waste, industrial waste and municipal solid waste. Other considerations in choosing the soil liner material include but not limited to shear strength, swelling and volumetric shrinkage. Most soils that possess the properties shown in Table 1 will meet these requirements [6].

Table 1 Specifications for Soil Liner Materials [6]

Soil Property	Range of Values
Percentage of Fines (%)	≥ 39-50
Plasticity Index (%)	≥ 7-10
Percentage Gravel (%)	≤ 20-50
Maximum Particle Size (mm)	25-50 mm

Hydraulic conductivity or permeability of soil is the capacity of soil to allow water to pass through it. Soils are permeable due to the existence of interconnected voids through which water flow from points of high energy to points of low energy. Permeability of soils are affected by particle size, void ratio, properties of pore fluid, shape of particles, structure of soil mass, degree of saturation, absorbed water, entrapped air and organic impurities in water, temperature, and stratification of soil. Reduction in void ratio will result to decrease in permeability. For the same soil sample, only the void ratio will be the most significant factor. In compacted soils, the compaction variables also greatly influence the hydraulic conductivity.

In this paper, the saturated hydraulic characteristics of a local fine-grained soil as potential landfill liner material compacted at three different compaction energy level were investigated. The values obtained from the test is compared to the requirements of RA 9003 and its implementing rules and regulations (IRR) as shown in Table 2. Relations to estimate the saturated hydraulic conductivity in terms of the corresponding void ratio at the different compactive efforts were developed and validated with the previous related studies.

Table 2. RA 9003 and its IRR Hydraulic Conductivity and Soil Thickness Requirements

Landfill Category	Capacity (tons/day)	Min. Requirement for k (cm/sec) and thickness (cm)
I	≤ 15	1×10^{-5} & 60
II	> 15 ≤ 75	1×10^{-6} & 75
III	> 75 ≤ 200	1×10^{-7} & 75 or 60*
IV	> 200	1×10^{-7} & 60*

Note: *Build together with synthetic liner of 1.5 mm thick

The findings will be used for initial assessment and design purposes of the local fine-grained soil for possible utilization as soil liner without discounting the need of an actual conduct of 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 the Fine-Grained Soil Sample

The soil sample used was excavated from a proposed sanitary landfill site in the municipality of Kauswagan, Lanao del Norte, Philippines. The sample was taken at a depth of least 2 meters to exclude organic matters. The soil looks to be reddish-brown. The soil consistency is sticky, plastic when moist and firm when dry. Figure 1 shows the soil sample used in the study.

Fig. 1 Moist Soil Sample

2.2 Experimental Program

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). Cation Exchange Capacity (CEC) conducted through the Sodium Acetate Distillation-Titration Method employed to determine exchangeable ions. X-ray powder diffraction (XRD) was performed on soil sample to obtain a mineralogical analysis of the sample. The analysis used manually ground oven-dried soil sample of fine powder passing sieve No. 200. The sample was scanned from 3° to 70° at a scanning rate of 1 degree per minute. Scanning electron microscopy was done to provide a broad character of the soil microfabric**.** Soil samples oven-dried at 105°C of grains passing sieve No. 200 were used to remove moisture, coarse and organic material are used for this as well as in Energy Dispersive X-ray spectroscopy **(**EDX) analysis which was used to determine the elemental composition of the surface of the soil specimen. The laboratory compaction test was carried out using Modified Proctor Test, Standard Proctor Test and Reduced Proctor Test [7] to represent varying compaction energy of equipment in the field. Three runs of test for each compactive efforts. The preliminary laboratory tests in the study is summarized in Table 3.

Table 3 Preliminary Experimental Program

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	
Compaction Test	
-Reduced Proctor	Daniel&Benson [7]
-Standard Proctor	ASTM D698
-Modified Proctor	ASTM D1557
CEC	US EPA 9081*

Note: *United States Environmental Protection Agency

The permeability test was carried out on remolded samples with compaction energies corresponding to the three compactive efforts in a rigid wall permeameter with a cross-sectional area of 5.73 square centimeter and height of soil specimen of 7.60 centimeters using distilled water as permeant. Further, the permeability test was performed under a falling head condition under a hydraulic gradient of around 20. The hydraulic conductivity coefficient was calculated using Darcy’s law.

3. RESULTS

3.1 Grain Size Distribution

The grain size distribution (GSD) is graphically depicted in Fig. 2 with mechanical and hydrometer test combined. The mechanical sieve analysis yielded a small 2% of fine sand and majority 98% of silt and clay. The GSD curve exhibits a poorly graded soil. Considering 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.

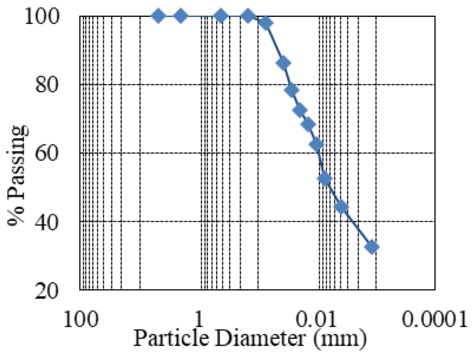


Fig. 2 Grain Size Distribution Curve

3.2 Soil Constants

The various laboratory tests resulted to the values for soil physical properties as shown in Table 4. The resulting experimental specific gravity value falls within the range of 2.6 to 2.9 typical for clayey and silty soils. The value of the Plasticity Index (PI) falls within the range of 20-40 which is for the highly plastic soils. The values for liquid limit and plasticity index are subsequently used as inputs for soil classification in addition to the percentage fines discussed in the previous subsection.

Table 4. Soil Constants [8]

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

In accordance with the Unified Soil Classification System (USCS), the soil sample is classified as elastic silt 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%. However, the said soil is classified as clay loam according to the United States Department of Agriculture and are good landfill cover or top lining material [9].

3.4 XRD Result

The resulting XRD pattern shows sharp peaks as depicted in Fig. 3. The result suggests that the soil sample comprises mainly of the crystal phases of kaolinite, biotite, antigorite, and goethite.

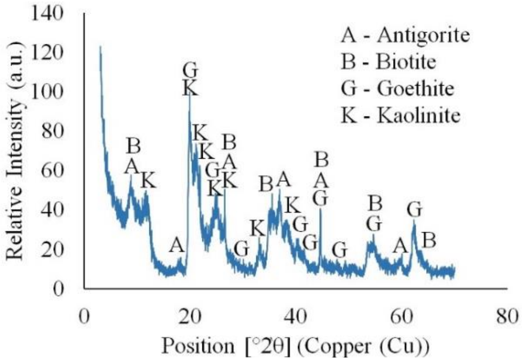


Fig. 3 X-ray Diffractogram of the Soil Sample

3.5 SEM-EDX

A micrograph for the soil sample at 100, 000x magnification factor is exhibited by Fig. 4. The image shows sub-angular and sub-rounded shapes like those of granular soils. It also reveals large intergranular voids. Also 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.

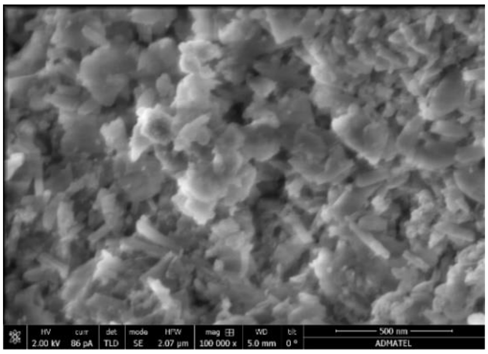


Fig. 4 SEM Micrograph at 100, 000x magnification of the Soil Sample

The elemental analysis yields that oxygen, aluminum, and silicon comprised most of the soil sample with traces of iron, carbon, titanium and calcium which are among the most abundant elements in the Earth's crust. These are the elements which compose the family of phyllosilicates. The weight percentage distribution is as shown in Table 5.

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

3.6 Compaction Tests

A set of the typical compaction curves for the soil sample compacted with the three compactive efforts is shown in Fig. 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.

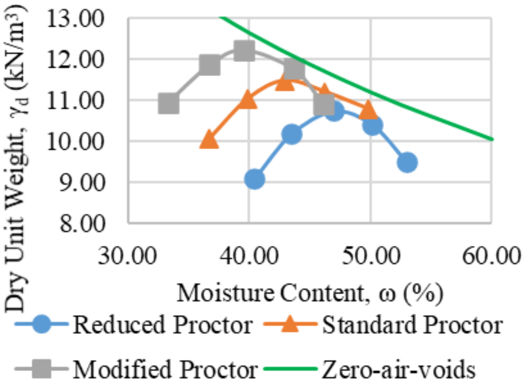


Fig. 5 Typical Compaction Curve

3.7 Cation Exchange Capacity

The resulting laboratory test for CEC yield a value 7.76 cmol/kg which falls within typical value for kaolinite of 5-15 cmol/kg.

3.8 Hydraulic Conductivity

The saturated hydraulic conductivity result ranges for the three compactive efforts from 1.98 x 10^{-6} to 1.0 x 10^{-7} cm/sec which can be said to be of low hydraulic conductivity. This range falls within the typical values for elastic silt [9]. The values meet the Philippine requirement depending on the targeted category of the SLF. Figure 6 shows a typical plot of the hydraulic conductivity, *k* versus the moisture content, ω at the three compaction efforts. It can be observed that the values of the hydraulic conductivity decrease as the compactive effort is increased. It is notable that the values of *k* is lowest to the left of the optimum moisture content. This agrees to the earlier finding of a similar study that soils that are more plastic and have a great quantity of fines yield lower hydraulic conductivity when compacted wet of the optimums [10].

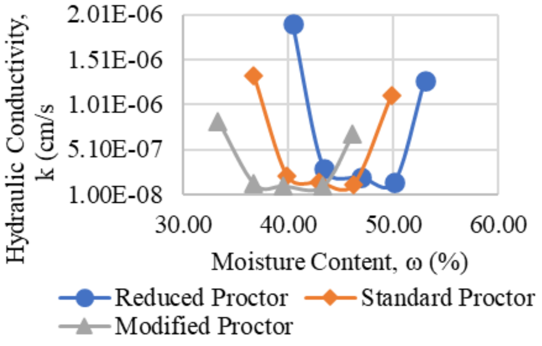


Fig. 6 Hydraulic Conductivity versus Moisture Content

4. PREDICTIVE MODELS

Predicting the hydraulic conductivity, *k* of soils accurately and dependably is among the lingering problem for geotechnical engineering as laboratory studies have shown that hydraulic conductivity is influenced by a lot of parameters as discussed in the introduction section. One equation widely used is the Kozeny-Carman relation wherein *k* is a function of the void ratio of soils, shape constant, specific surface area of particles, particle density of soil, unit weight and viscosity of the fluid permeant. However, the model is not appropriate for clayey soils as it assumes no electrochemical reactions between the solid particles and permeant. Research studies have been made on possible relationships between hydraulic conductivity and void ratio, *e* of fine-grained soils. One relationship established is that a linear relation between the logarithm of the hydraulic conductivity and the void ratio for clays [11]-[12]. In this study, a linear regression analysis on the void ratio and logarithm of the hydraulic conductivity per compactive effort to develop a predictive model. The output of the test is presented in a semi-log plot, the hydraulic conductivity in a logarithmic scale and the void ratio in arithmetic scale as ordinate abscissa, respectively. Figure 7 depicts the plots of the log *k* versus the void ratio at the three compactive efforts.

The equation can take form:

$$\boldsymbol{k = cf_e} \tag{1}$$

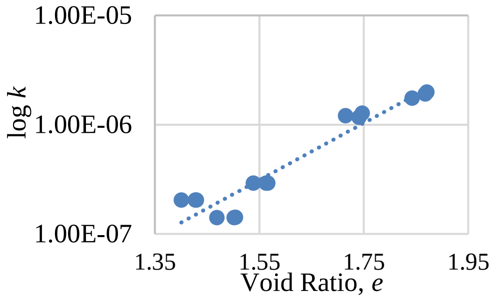
where:

c = material constant
k = hydraulic conductivity in cm/sec
f_e = function describing the effect of void ratio, e

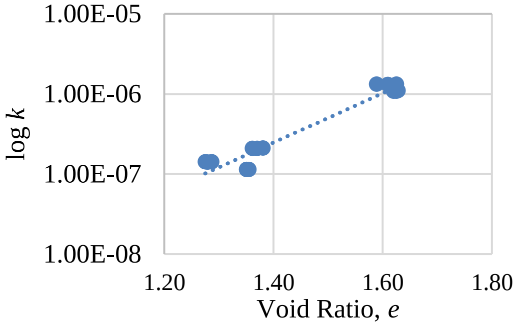
The regression analysis yielded the quantities in Table 6 together with the coefficient of determination R^2. A high correlation coefficient, i.e. close to +/-1.0 suggests a strong linear relationship exist between the variables. This underpins the strength of the linearity of the regression equation.

Table 6 Coefficients for the Regression Model

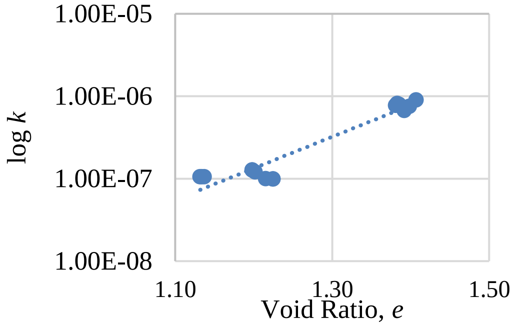
Compactive Effort	c	f_e	R^2
Reduced Proctor	$3.0x10^{-11}$	$exp^{6.00e}$	0.92
Standard Proctor	$1.0x10^{-11}$	$exp^{7.10e}$	0.93
Modified Proctor	$3.0x10^{-12}$	$exp^{8.81e}$	0.92



a. Reduced Proctor



b. Standard Proctor



c. Modified Proctor

Fig. 7 Plot of the log *k* versus *e* for the Three Compactive Efforts

The high values of the coefficient of determination R^2 indicates that the model fits the data well. The values are comparable to similar studies [13]-[14].

The models can be useful to soil similarly situated and the strength lies on the simplicity with only void ratio as the parameter. Those can be helpful to specify field compaction.

5. CONCLUSIONS

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

The fined-grained soil as elastic silt based on USCS or clay loam based on USDA. The soil being classified as clay loam can readily be used as top lining material or cover. The soil is said to be of high plasticity. The soil sample composition consists mainly of the crystal phases of kaolinite, biotite, antigorite, and goethite from the XRD analysis and consistent from the SEM-EDX results.

The resulting coefficient of hydraulic conductivity ranges from 1.98×10^{-6} to 1.0×10^{-7} cm/sec meet the Philippine standard requirement depending on the SLF Category. A strong correlation was developed between the logarithm of the hydraulic conductivity and the void ratio at the three compactive efforts.

Further study is warranted on field hydraulic conductivity test, unconfined compressive strength and volumetric shrinkage to provide baseline information for design and quality assurance purposes. Those are additional information necessary for soil modification as maybe desired for the utilization of the soil as marginalized bottom SLF lining material.

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