

RADIAL FLOW PERMEAMETER: A PROPOSED APPARATUS TO MEASURE HORIZONTAL HYDRAULIC GRADIENT OF FLY-ASH BASED GEOPOLYMER-SOIL MIX

* Jonathan R. Dungca¹, Winchell Dunley T. Lao², Matthew Lim², Wilson D. Lu² and Juan Carlos P. Redelicia²

^{1,2} Department of Civil Engineering, College of Engineering, De La Salle University, Philippines

*Corresponding Author, Received: 22 June 2018, Revised: 15 Dec. 2018, Accepted: 15 Jan. 2019

ABSTRACT: Fly-ash based geopolymer has been proven by many scholars as a viable material to replace cement. Due to its high compressive strength and abundance in industrial areas, it was advocated to partially replace the conventional material in constructing infrastructure, especially in road embankment. Merely consider the load capacity or strength of the materials in designing a road embankment may overlook the durability of the infrastructure. One vital parameter that leads to the deterioration and failure of the road is the permeability of the materials. The flow of water in the road structure comes in a different direction but commonly runs in the horizontal way or longitudinal along the road. Neither ASTM nor AASHTO has established a standard procedure in the determination of the horizontal hydraulic gradient of the soil. Hence, a proposed radial flow permeameter was adopted to determine the permeability of the fly-ash based geopolymer-soil mix. The mixes included dredged soil with 10% (G10), 20% (G20), and 30% (G30) replaced by geopolymer in mass. The interpretation of the test is quantified using a theoretical model and verified using graphical and statistical analysis. The computation was then further verified through anisotropy factor ratio of k_h/k_v with the data that provided in literature with similar geopolymer-soil blend mix. The outcome of the model displayed the degree of the permeability of G10, G20, and G30 was $\times 10^{-4}$, $\times 10^{-6}$, and $\times 10^{-7}$ in cm/s, respectively. Lastly, the proposed permeameter was found out to be permissive in determining the horizontal permeability of the specimen with low permeability having a degree of 10^{-4} or lower.

Keywords: Horizontal Coefficient of the Permeability, Radial Flow Permeameter, Geopolymer, Fly ash

1. INTRODUCTION

Engineers often overlook the drainage capacity of road embankments, which can lead floods in some areas in the Philippines. The Philippines often experiences floods because it is in the typhoon belt. The soil's drainage property is important because with low performance of drainage can cause floods when insufficient surface drainage is provided. For engineers, considering good drainage is one of the fundamental design considerations for a road to minimize road maintenance costs and maximize the service life of the road during operation [1].

In analyzing the permeability of road embankments, both directions, vertical and horizontal, should be considered because the water will flow not only downward but also horizontally. To have good drainage, horizontal permeability should be considered because the water entering the road embankment should have an exit through the sides. Most of the tests for the permeability are for vertical permeability since it is easier to conduct compared to the horizontal permeability because in getting the horizontal permeability the flow of water should be horizontal only. Most of the set up that is being used in getting the horizontal permeability are rectangular [2-6], which is not common to some of the manufacturers. In some studies, the set up for

the horizontal permeability test is custom made, which is difficult to do. Another problem is that in this study, geopolymer will be used as soil stabilizers which will result in a low permeability soil. Most of the set up for the horizontal permeability test is for high permeability soils so it would be difficult for the researchers to use the setups proposed given the limited time.

The objective of this study is to be able to identify the horizontal permeability of the stabilized soil with fly ash based geopolymer. It also aims to propose a new set up for getting the horizontal permeability that will give credible results.

2. METHODOLOGY

Neither ASTM nor AASHTO has established a standard apparatus and standard way of measuring the horizontal permeability. Hence, a proposed new permeameter set-up based from a well-concept (confined aquifer) incorporating with Darcy's Law, see Eq. 1, was used to measure the horizontal permeameter.

$$Q = k_i A \quad (1)$$

The sample will be a hollow cylinder which is shown in Figure 1:

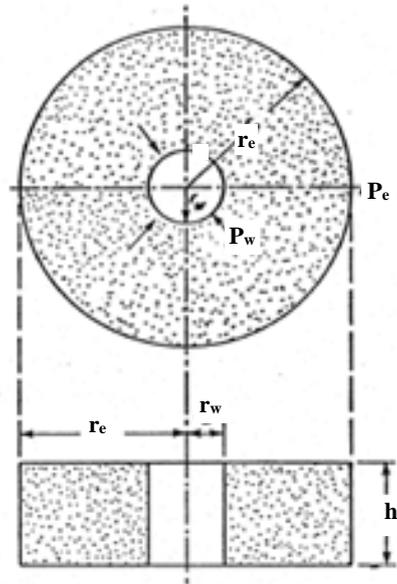


Fig. 1. Model for radial flow of fluids to the wellbore [7]

As shown in figure 1, an external boundary pressure, P_e , is located at the outer radius and internal pressure, P_w , is located at the inner radius. The two pressures will give the general equation of Darcy's Law two boundary conditions. Given that there is a constant change in pressure, the change in pressure head along the horizontal direction can be expressed as,

$$i = dP/dr \quad (2)$$

The area that will be considered in the formula is the area of the external radius which is expressed as,

$$A = 2\pi rh \quad (3)$$

Substituting the area and hydraulic gradient into Darcy's Law will give,

$$Q = 2\pi rhK \frac{dP}{dr} \quad (4)$$

Integrating the equation with the boundary condition,

$$Q \int_{r_e}^{r_w} \frac{dr}{r} = 2\pi hK \int_{P_e}^{P_w} dP \quad (5)$$

Which gives

$$Q \ln \left(\frac{r_e}{r_w} \right) = 2\pi hK (P_e - P_w) \quad (6)$$

Rearranging the equation, the coefficient of permeability can be solved by using the equation,

$$k = \frac{Q \ln \left(\frac{r_e}{r_w} \right)}{2\pi h (P_e - P_w)} \quad (7)$$

where:

k = coefficient of permeability (cm/s);

Q = flowrate (cm³/s);

r_e = interior radius of the cell or boundary radius (cm);

r_w = interior radius of the wellbore (cm);

h = height of the medium (cm);

P_e = pressure head at the boundary radius (cm);

P_w = pressure head at the wellbore radius (cm);

use atmospheric pressure, $P_w = 0$.

In figure 2, the graphical model of the new horizontal permeameter was designed with the specimen having a height of 65mm and a diameter of 60 mm in total including the PVC pipe. The new set-up will also be using the same acrylic glass used in vertical permeability test with a wooden base at the bottom that will keep the sample in place when being poured and tamped. A space between the specimen and acrylic glass was provided to allow the water to flow into the side and permeate horizontally. The topmost part of the specimen was covered with sealant ensure that the water will enter the space at the side and will pass horizontally through the sample. The permeameter was constructed with PVC pipe on the center having a diameter of 20mm. The PVC pipe was subjected to 4 holes within the height of the specimen having a diameter of 8mm. The holes were made at every quarter of the PVC pipe. On top of the PVC pipe, the hole was wrap with sealant and left to dry and solidify to prevent the water from going into the holes. It was then glued to the base having a 10mm thickness and 65mm diameter. The actual model of the proposed and actual set-up is seen the figure is presented in Fig. 3.

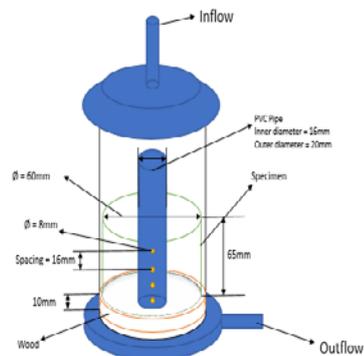


Fig. 2a. Graphical Model of the New Horizontal permeameter



(b)

Fig.2b. Picture of the Horizontal permeameter.

For the preparation of the stabilized soil with fly ash based geopolymer, in order to provide a standard uniformity between samples, the dredged soil and fly ash was obtained only from a thermal power plant in Mindanao. The dredged soils were sieved to have up to the required maximum sizes, particularly sieve number 4 or a nominal opening of 4.76mm followed by the removal of its moisture content thru oven-drying. The fly ash obtained was classified as Class F.

The index properties of the dredged soil were determined by conforming to the ASTM procedures:

- a. Specific Gravity of Soils (ASTM D854) [8]
- b. Particle Size Analysis (ASTM D422) [9]
- c. Standard Proctor Test (ASTM D698) [10]

Conventional materials and blended samples were individually subjected to microscopic testing in order to evaluate the void spaces present using the Scanning Electron Microscopy (SEM) [11-13].

The geopolymer based fly ash mix used was based on the mix design formulated by Ang, et al. (2016) [15] which were used for the preparation of samples for the testing of strength and permeability tests of each blend. The geopolymer mix design is presented in Table 1:

Geopolymer Concentration (%)	Alkaline Activator/ Fly Ash	Sodium Silicate/ Sodium Hydroxide	NaOH Concentration
10, 20, 30	0.4	2	14 M

The blended samples vary from 10%, 20% and 30% of partial replacement of geopolymer to the total weight of dredged soil. The blended samples are obtained by providing first the dredged soil to

attain its maximum dry unit weight based on optimal moisture content (OMC) that was determined through the Standard Proctor Test.

Constant Head Permeability Test was conducted to evaluate the drainage characteristics of all the blends considering relative compaction of 100%. However, relative compaction of 100% is somehow unattainable due to tamping constraints, each sample was just subjected to a constant of 25 blows per 3 layers using hand tamping.

There are some advantages in using the proposed new set-up in getting the horizontal permeability. According to the study of Dungca and Galupino (2015) [6], the horizontal permeability is expected to have a higher value because of the pressure that was induced in the sample, but the layers were not able to take into account. In the new set-up, the layers caused by the tampering was considered. Another set-up that the researchers compared is the set-up made by Baretto et. al. (2015) [3]. Their set-up was a rectangular permeameter, unfortunately, the researchers did not use their set-up due to the fact that their sample has properties similar to concrete like shrinkage. The researcher designed their set-up by making sure that sidewall leakage will not affect the results. One limitation of the set-up is that it can only be used to low permeability samples such as geopolymers. The set-up takes up less time compared to the others because the passageway of the water is much shorter compared to the other proposed set-ups.

3. RESULTS AND DISCUSSIONS

3.1 Scanning Electron Microscopy

In the graphical analysis, scanning electron microscopy (SEM) was used to evaluate the morphology of the specimen. It provided a high-resolution image of the spaces formed between the particles inside the specimen. Two levels of magnification, x500 (see Figure 3) and x5000 (see Figure 3), were used in the analysis to fully understand the bonds between the particles of the sample.

Figure 3 showed the microstructure of the three blends under magnification of x500. As shown in Figure 3, the voids present in Figure 3 (a) were more visible compared to the voids seen in Figures 3(b), and 3(c). This meant that G10 could be more permeable as compared to the G20 and G30 because the presence of spaces between the particles was the path for the water to easily pass through. Furthermore, it was observed that the void spaces presented in G20 and G30 were exiguous, making the microstructure of both blends indistinguishable under x500 magnification.

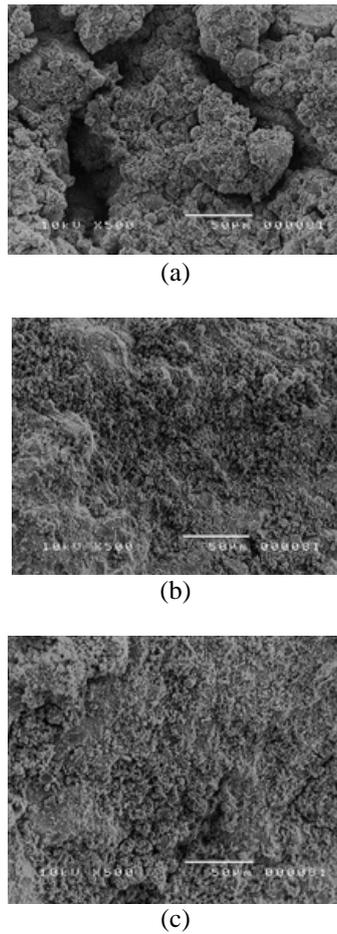


Fig. 3. a) 10% b) 20% c) 30 % replacements with magnification level of x500

To clearly distinguish the difference between G20 and G30 in terms of the void spaces, an increased magnification level of x5000 was conducted. As can be seen from the SEM photo (x5000) presented in Figure 3, voids spaces were still present in both blends that allowed water to pass through. Under a magnification of 5000, G20 was observed to have more void spaces as compared to the G30; thus, the G20 replacement was more permeable than the G30. In addition, there was a great difference in the bonding formations of the particles between G20 and G30. Under G20, there still some particles of fly ash that could be seen in the SEM photo. They were the spherical particles easily seen in Figure 2(a). Those particles implied that the fly-ash did not completely react with the alkaline activator. Unlike in G30, the sand and fly-ash particles in G30 were completely reacted. The geopolymer in 30% replacement could coat the sands particles and provided greater bonding with the other sand particles, blocking the passageway for the water.

From the microstructure of each blend, it could forecast that as the percentage replacement increase the permeability of that blend would decrease. This

observation would be later on proven through the experimental result.

3.2 Horizontal Permeability

As stated, a proposed radial flow permeameter was used in determining the horizontal permeability of the dredged soil stabilized with fly-ash based geopolymer under 10, 20, and 30 percent replacement in mass. As shown in Table 2, where the ranges of permeability value gathered from the proposed constant head radial flow permeameter test. G10 produced an average of 2.72E-04 cm/s. G20 had an average of 5.25E-06 cm/s. G30 produced an average of 7.86E-07 cm/s. The lower the degree in the value implied a slower flow of water through the voids of the specimen.

Table 2. Ranges of Horizontal Permeability

Soil Mixture	Minimum Kh, cm/s	Maximum Kh, cm/s	Average Kh, cm/s
G10	1.66E-04	3.62E-04	2.72E-04
G20	4.89E-06	5.52E-06	5.25E-06
G30	6.35E-07	9.27E-07	7.86E-07

To determine the effect of the amount of geopolymer replaced in the soil, a box and whisker plot was delineated, as shown in Figure 4. Box and whisker plot provided the midspread values of each replacement. Using an IQR of 1.5, the obtained coefficient of permeability was fall in the ranges; therefore, there is no outlier.

As expected from the SEM photo, it was observed from Figure 4 that the permeability decreases as the percentage replacement of geopolymer mixed to the sample increases. Due to the increased geopolymerization took place in the blends, the void spaces between the soil particles were coated and bonded with the geopolymer, hence, blocking the passage of the water. Dungca & Jao (2016) [1] and Galupino (2015) [6] also result with a decrease of permeability as fly ash increased in the fly-ash-soil mix.

Classifying the blend with drainage characteristics defined by Casagrande and Fadum (1940) [15], G10 fall in poor drainage, meanwhile, G20 and G30 fall under practically impervious. With the classification, engineers must design with enough drainage system in road embankment to prevent water ingress in the road pavement.

3.3 Anisotropy Ratio, kh/kv

To further validate the results of the horizontal permeability tests, the anisotropy ratio must be within the given range of Das

(2008) [16]. The collected usual ratio of horizontal and vertical permeability of soils by Das

(2008) [1] is with the range of 1.2-3.3, thus, the data gathered must be within the range.

Vertical permeability of the soil-geopolymer mix investigated [18] was utilized and tabulated in Table 4. From the value of the permeability, it is shown that horizontal permeability was slightly higher than the vertical permeability.

Table 4. Ranges of Vertical Permeability [17]

Soil Mixture	Minimum Kv, cm/s	Maximum Kv, cm/s	Average Kv, cm/s
G10	1.14E-04	2.42E-04	1.60E-04
G20	3.90E-06	4.98E-06	4.32E-06
G30	4.62E-07	7.55E-07	5.97E-07

Computing the anisotropy ratio tabulate in Table 5, the ratio for all the blends ranges between 1.2-1.7, thus, ratios are within Das's desired range. The proposed permeability was viable to obtain the horizontal permeability of the soil.

Table 5. Anisotropy ratio of kh/kv

Soil Mixture	Average Kh, cm/s	Average Kv, cm/s	Average Kh/Kv
G10	2.72E-04	1.60E-04	1.70
G20	5.25E-06	4.32E-06	1.21
G30	7.86E-07	5.97E-07	1.32

4. CONCLUSION

The study investigated the effect of the geopolymer on the soil, particularly on the drainage characteristics. SEM analysis was conducted to provide a better understanding of the formulation and construction of pores spaces on the mix. The SEM showed a graphical progression of the effect of the amount of geopolymer on the soil. With the increasing percentage replacement, the pore spaces are being covered up. Consequently, the water will have a limited passageway to flow through, resulting in a lower permeability.

A proposed radial flow permeameter was used to determine the horizontal coefficient permeability of the mix. The experiment obtained the degree of the permeability of G10, G20, and G30, the values were $\times 10^{-4}$, $\times 10^{-6}$, and $\times 10^{-7}$ in cm/s, respectively. As expected from the SEM, the permeability decreases along with the increase of geopolymer.

With the given set of data, the soil-geopolymer mixes were classified with their respective drainage characteristics. With the criteria provided by Casagrande and Fadum (1940), G10 fall in poor drainage, meanwhile, G20 and G30 fall under practically impervious. Based on the evaluation, the

soil mixtures were concluded to be poor in drainage. However, it still can be used as an embankment material, given that the engineers must design properly the drainage system to prevent deterioration and failure of the road caused by the ingress of water.

To validate the horizontal permeability, anisotropy ratio of kh/kv must be fall in within Das' desired range (1.2 to 3.3). The computed ratios of all mixtures were ranged from 1.2 to 1.7, hence, the obtained horizontal permeability was acceptable. In addition, it was observed that horizontal permeability is much higher than the vertical permeability which means the flow of water in the horizontal direction is much faster compared to the vertical direction.

Lastly, with all the validation made, the proposed permeameter is viable in determining the horizontal permeability. However, the apparatus is only limited to permeability having a degree of 10^{-4} or lower.

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