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VERTICAL PERMEABILITY OF DREDGED SOIL STABILIZED WITH FLY-ASH BASED GEOPOLYMER FOR ROAD EMBANKMENT

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ABSTRACT: This study presents the vertical permeability and strong relationship of dredged soil stabilized with fly-ash based geopolymer which is to be used for constructing road embankments. The fly-ash used for this study was a low-calcium (Class F) fly-ash. The varying effects on both properties due to the different partial replacements of geopolymer were studied. 10%, 20%, and 30% of the soil sample's mass were used as a partial replacement. The samples were prepared using the dry-mix method and subjected to 28 days of air-dried curing. Tests like the unconfined compressive strength test and the falling head permeability test were conducted. The morphological features of the samples were investigated using the scanning electron microscopy (SEM). The test results showed that as the percentage replacement of geopolymer increases, the samples become less permeable. SEM analyses confirmed the results, showing that the geopolymer tends to cover up the pore spaces of the soil, causing the water to have fewer passageways.

Keywords: Fly-ash, Geopolymer, Dredged soil, Permeability, Unconfined Compressive Strength

1. INTRODUCTION

Road infrastructure is very essential to developing countries like the Philippines. These facilitate trade, communication, and traveling purposes. The advancement of the economy is heavily reliant on these. Having bad and poorly maintained roads causes inconvenience like road damages and flooding, which cause severe traffic and leads to slow progression of the economy.

Permeability is a very important parameter to consider when designing road embankments. There should be a compromise between the strength and the permeability. Numerous studies have shown that an increase in the strength of the soil leads to a decrease in its permeability. In a country like the Philippines wherein, heavy rains are very frequent, it becomes a must for roads to exhibit good drainage. When there is low permeability, water tends to accumulate very fast and exert pore water pressure, causing ponding and the deterioration of the embankment.

The construction of roads embankments requires different materials like aggregates, lime, and cement. Unfortunately, the production of cement may impose some harm to the environment, as it generates greenhouse gases due to the emission of carbon dioxide. They can constitute the rising state of global warming [1]. Numerous studies have shown that coal combustion by-products, or more commonly known as CCPs, have been found to be a good choice because it is very abundant in the country and has a problem in disposal [2-8]. Furthermore, the use of these CCP's can bring economic and environmental benefits.

One of the most common examples of CCP's is fly-ash. It is a by-product of the coal-fired power plant and is posing a great threat to the environment. When discharged by the power plants, it is immediately considered as wastes. Only around half of it is used for recycling. The rest are thrown out into lands and bodies of water [2]. Some studies have been made to utilize these ashes in different fields. Some are used as embankment fill, cement alternative and as soil stabilizer for road embankments. Associations such as AASHTO has made several standards as the basis for the construction of road embankments.

Since dredged soil possesses weak strength, there is a need to stabilize it, for it to be used for construction purposes. The soil for this study will be stabilized using geopolymer mixed with class F fly-ash. Geopolymer is synthesized through a natural reactive property of aluminosilicate material when mixed with an alkali-activator. It is an inorganic polymer made up of covalently bonded molecules. It undergoes polymerization which involves a chemical reaction on Si-Al minerals under alkaline condition forming a series of sialate monomers like cement properties [9].

For this study, the researchers aim to analyze the relationship between the strength and permeability of the blends and give recommendations based on the results generated.

2. METHODOLOGY

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) [10]
b. Particle Size Analysis (ASTM D422) [11]
c. Standard Proctor Test (ASTM D698) [12]

Conventional materials and blended samples were individually subjected to microscopic testing to evaluate the void spaces present using the Scanning Electron Microscopy (SEM).

The geopolymer based fly ash mix used was based on the mix design formulated by Ang, et al. (2016) [9] 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.

Table 1 Geopolymer Mix [9]

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.

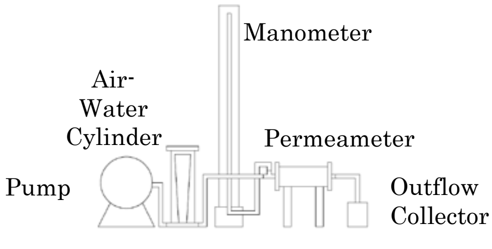


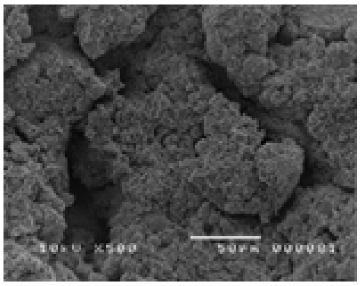
Fig. 1. Experimental Set -up for Vertical Permeability [3-7]

Falling Head Permeability Test (ASTM D5084) [13] were 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. The acquired set-up for the permeability test is shown in Figure 1.

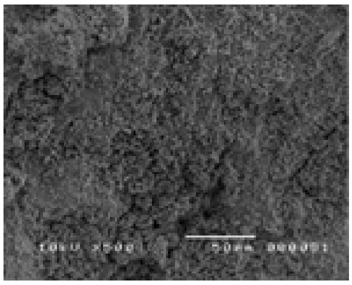
3. RESULTS AND DISCUSSION

3.1 Scanning Electron Microscopy (SEM) Results

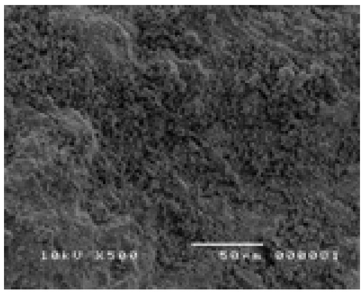
The scanning electron microscopy (SEM) is commonly used for getting a high-resolution image of the spaces between particles in the surface. Two levels of magnification, x500 and x5000, were used in the analysis to fully understand the bonds between the particles of the sample.



(a)



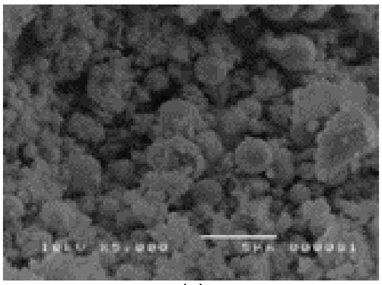
(b)



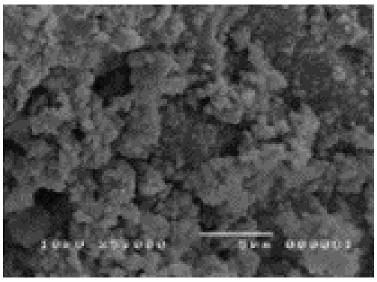
(c)

Fig. 2. a) 10% b) 20% c) 30 % replacements with magnification level of x500

Comparing the voids seen on the SEM of each blend as shown in figure 2, figures 2(b), and 2(c) are observed to have almost no voids while figure 2(a) clearly shows the presence of spaces between the particles where the water can easily pass through. This means that the sample with 10% replacement of geopolymer could be more permeable, as compared to the 20% and 30% replacements. Furthermore, the researchers have observed that there is only a small difference between the void spaces between 20% and 30% replacement.



(a)



(b)

Fig. 3. a) 20% b) 30% replacements with magnification level of x5000

An increased magnification level by x5000 was conducted to clearly distinguish the difference between the 20% and 30% replacement in terms of the void spaces present. As can be seen from the SEM photo (x5000) presented in Figure 3, voids spaces are still present that allows water to pass through. The 20% replacement is observed to have more void spaces as compared to the 30% replacement; thus, the 20% replacement is more permeable than 30%, as expected by the group. Also, the particles in 30% replacements are completely covered, as shown in figure 3(b). The case is different with the 20% replacement, wherein there can still be found some particles of fly ash that did not react with the reactors which represented by the spheres seen in figure 3(a). The geopolymer in 30% replacement was able to coat the sands and provided greater bonding with the other sand particles, blocking the passageway for the water.

3.2 Gradation

The variation of particle size of the dredged soil can be measured based on the parameters, coefficient of uniformity and curvature, as shown in Table 2. These coefficients define the grade of soil which is based on ASTM D2487. As observed, the coefficient of uniformity (Cu) of the dredged soil was found to be having values less than 6. This indicates that the soil contains particles having a uniform size. Moreover, the grain size distribution curve (GSDC) of the 3 trials was observed to have steep slopes which are almost vertical. Thus, this verifies that the variation of particles sizes is within a narrow limit.

The coefficient of curvature (Cc) of the dredged soil was found to be having an average of 2.97, which is within the range 1-3. This signifies a well-graded soil. Thus, the dredged soil could cover almost all grain sizes. Also, observed from the GSDC, there were no sudden changes of slope which would signify the absence of certain grain sizes. The dredged soil was found to be falling under the classification of poorly graded soil since the Cu was less than 6 (Cu>6, well-graded soil for sand) but the Cc was between the range 1-3 (1-3, well-graded soil) though it was already at the limit's boundary.

Table 2 Uniformity and Curvature of Dredged Soil

Trial	The coefficient of Uniformity (Cu)	Coefficient of Curvature (CC)
1	4.06	3.01
2	4.35	2.96
3	4.26	2.93
Average	4.22	2.97

3.3 Unconfined Compressive Strength

A dredged soil is mostly made up of sand particles which allows it to exhibit the property of the sand and not being able to provide confinement. Thus, it is incapable of maintaining a firm stand and form a cylindrical shape even though there has been no load being applied. Also, the dredged soil obtained has been identified to manifest poor geotechnical properties. As a result, geopolymer would be added to enhance the geotechnical properties of the dredged soil. Consequently, for that reason, the researchers are incapable to produce soil samples made up of only pure dredged soil for the unconfined compression test (UCT). The unconfined compression strength test is commonly used for determining the improvement of stabilized soils [14].

Given that the UCT cannot be done for pure dredged soil, the blending of geopolymer mix of different percentage was incorporated, specifically 10%, 20%, and 30%. By observation, the addition of geopolymer mix with the inclusion of curing for twenty-eight days showed that it was able to bind the soil particles allowing the soil to stand firmly and form a cylindrical shape without confining pressure. Based on observation, the geopolymer acts as the binder for the soil in the form of stabilization. In addition, the geopolymer mix exhibits cement-like properties that similarities on its physical properties are noticeable.

Table 3 presents the progression of the stabilized soil as more of the geopolymer is being added. It is anticipated that the unconfined compressive strength of the mixture increases with the continual addition of the geopolymer. As observed, the incremental increase of strength is exponentially related to the percent replacement of geopolymer.

Table 3 Unconfined Compressive Strength (MPa) of Mix

Classification	Unconfined Compressive Strength (KPa)
Very Soft Soil	25
Soft Soil	25-50
Firm Soil	50-100
Stiff Soil	100-200
Very Stiff Soil	200-400
Hard Soil	>400

A 10% partial replacement produced an average unconfined compressive strength of 199.9kPa. This was classified as a stiff soil, based on the classification set by Liu and Evett, 2009 [15]. The classification is shown below in Table 4. When the percentage replacement was increased to 20%, on the other hand, it resulted in an average unconfined compressive strength of 311.7kPa. This was classified as a very stiff soil. Lastly, 30% partial replacement resulted to an average unconfined compressive strength of 1430.6kPa. This was classified as a hard soil.

The strength behavior brought about by the geopolymer to the soil is because the geopolymer possesses cementitious materials. These undergo polymeric reactions, resulting in the formation of aluminosilicate three-dimensional networks whose strength can be even higher to that of conventional concrete [16].

The stress-strain diagram of each blend, specifically 10%, 20%, and 30%, with 3 different trials were conducted. The illustrations presented are the behavior of the soil mixture at different percentages when subjected to loading. By analyzing the graphs, the increase in the concentration of geopolymer had caused the mixture to become brittle with the increase in strength. It exhibits the same property with concrete wherein high compressive strength concrete produces low strain and suddenly fails.

Table 4 Standard Relationship of Consistency and Unconfined Compressive Strength of Soil [15

28 days Curing	Geopolymer Mix		
	10%	20%	30%
	Stress (MPa)		
Trial 1	0.198	0.3217	1.309
Trial 2	0.2228	0.2868	1.550
Trial 3	0.1789	0.3265	1.432
Average	0.1999	0.3117	1.4306

3.4 Vertical Permeability

Permeability is an important factor to consider when increasing the strength of the soil. The effect of the polymerization is presented in Table 5, wherein it shows the change in permeability between dredged soils with and without geopolymer present. The dredged soil alone was found to have an average hydraulic conductivity of 1.04E-02 cm/s. A 10% geopolymer replacement produced an average of 1.60E-04 cm/s. A 20% geopolymer replacement had an average of 4.32E-06 cm/s. And the 30%replacement produced an average of 5.97E-07cm/s.

The results were classified in accordance with the criteria set by Casagrande and Fadum (1940) [17].

A 10% geopolymer replacement resulted in poor permeability. The 20% and 30% replacements were considered as practically impervious.

The trend shows that the additional replacement of the geopolymer further decreases the permeability. According to Ma, Hu, and Ye (2012) [18], the pore size distribution and connectivity, including the shape and volume of the pore spaces are very important factors in the investigation of the permeability. Much of this is governed by the amount of geopolymer applied to the sample. During the process of increasing the strength of the soil through stabilization, the sample undergoes through geopolymerization. The pozzolanic reaction causes the particles to bind together. This then closes the pore spaces to increase the strength. Therefore, it becomes more difficult for water to flow through the sample.

Table 5. The coefficient of Permeability in the Vertical Direction for Varying Replacement of Geopolymer-Soil Mix (cm/s)

Trial No.	Pure	10%	20%	30%
1	9.85E-03	2.42E-04	3.90E-06	4.77E-07
2	9.51E-03	1.27E-04	4.98E-06	7.55E-07
3	1.01E-02	1.18E-04	3.94E-06	4.62E-07
4	1.16E-02	1.99E-04	4.45E-06	7.16E-07
5	1.06E-02	1.14E-04	4.34E-06	5.73E-07
Ave	1.04E-02	1.60E-04	4.32E-06	5.97E-07

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 range between 25th and 75th percentile; therefore, there is no outlier.

As discussed, there was a significant behavior that relates permeability with strength. It could be observed that the permeability is inversely related to strength. A related study conducted by Olivia and Nikraz (2011) [19], also noticed and stated that there is an inverse relationship between the strength and permeability of the geopolymer mix. As the strength increases, the permeability starts to decrease. They compared their trend to the results of Cheena, et. al (2009) [20] where both researchers got a similar trend for the permeability and unconfined strength. The researchers observed that their samples had the same trend as Olivia and Nikraz'. The same trend can also be found in the study of Wongpa et. al (2010) [21], stating that the permeability is indeed dependent on the strength of the geopolymer mix. The reason behind the trend is that as the percentage replacement of geopolymer increases, the void spaces decrease as seen from the SEM images which resulted to the increase of strength and consequently, the decrease of its permeability.

The difference between each mix's void spaces affected the permeability since more void spaces mean that water can easily flow and pass through the samples. Another observation that was made from the SEM analysis was the small difference of void spaces between 20% and 30% replacement. It can be seen from the graph that there is also a small difference between the permeability of 20% and 30% compared to 10%. The void spaces from the 10% mix can be clearly seen by the naked eyes while the void spaces of 20% and 30% mix can only be seen through SEM.

By Regression Analysis, an empirical formula was formulated to obtain the coefficient of permeability with respect to percent replacement. The coefficient of permeability can be obtained from the formula:

$$k = \mathbf{e}^{(-5.08 - 0.329G)} \quad (1)$$

where:
k = coefficient of permeability (cm/s);
G = percent replacement of fly-ash based geopolymer.

The regression was able to obtain a coefficient of correlation equal to 0.9744 which is almost equal to 1, thus, makes the empirical formula acceptable. The model or formula formulated allows the engineer to have the desired permeability characteristics for its embankment based on the geopolymer replacement. Also, it could allow engineers to approximate permeability characteristics in order to design the appropriate drainage needed for the embankment with respect to the replacement desired for the project. However, the model provided is only limited in providing the estimated hydraulic conductivity value up to 30% replacement, thus, further study must be conducted if greater geopolymer mix is needed. Also, this study is only applicable for single compaction which was based on the Proctor Test achieving a theoretical 100% relative compaction.

When using stabilized materials for constructing road pavements, there will always be a compromise between the strength and the permeability, The American Concrete Pavement Association (1994) [22]. Even though the material possesses good permeability, it may be still possible to become insufficient in supporting construction operations and carrying loads, since the strength is not that high. When stabilized materials are used, a sacrifice in its permeability comes along with the increase in strength.

This study was able to confirm that fly-ash based geopolymers are indeed capable of enhancing the strength of soil at a significant amount. Unfortunately, it has also resulted in a drastic decrease in its permeability, as discussed earlier. This raises a big concern especially that this material is to be used as road embankments in countries which experience frequent heavy rain like the Philippines. Another challenge arises on how to efficiently utilize such material with good strength but poor permeability for the construction of road embankments.

Since the stabilized soil possesses poor permeability, Lovering and Cedergren (1962) [23] suggested that there should be sufficient drainage outlets, for the embankments to be effective in draining. They strongly recommended that these drainage outlets should also be maintained regularly so that they do not become clogged and create a "bathtub" effect in the drainage layer. Past studies have come to conclusions that the drainage layer alone cannot guarantee an improved permeability performance. The entire drainage system must have enough capacity and must also be working efficiently. Thus, it is important to have the drainage layer, outlet drains, and outlet pipes to be efficient for the expected water infiltration during rainfall. Regular maintenance must also be conducted. This is to ensure that water infiltrated can be drained out as quickly as possible before they get into the embankment [24].

4. CONCLUSIONS

A pure dredged soil, in its nature, is capable of draining water at a good rate. However, it is very weak and cannot be purely used for road embankment purposes. Soil types such as this needed to be stabilized. A fly-ash based geopolymer was found to be a very good stabilizer in enhancing the strength of the soil mixture. A 10% partial replacement by mass of the geopolymer resulted in an average unconfined compressive strength of 0.1999 MPa and has been classified as a stiff soil. A 20% replacement produced an average unconfined compressive strength of 0.3117 MPa and was classified as a very stiff soil. The researchers also noticed that the 30% replacement has vastly improved the strength of the soil. Its unconfined compressive strength reached an average of 1.432 MPa. This was classified under the hard soil category. It is very evident that the strength increases along with the additional amount of geopolymer being added. The soil mixtures were observed to have almost the same properties with those of concrete.

The vertical permeability of the samples was also investigated. As expected, there was an inverse relationship between the strength and the permeability of the samples. The permeability decreases as the strength increases. Pure dredge soil has an average hydraulic conductivity of 1.04E-02 cm/s. A 10% partial replacement results in an average hydraulic conductivity of 1.60E-04 cm/s. A 20% partial replacement, on the other hand, results in an average hydraulic conductivity of 4.32E-06 cm/s. Last, a 30% partial replacement results in an average hydraulic conductivity of 5.97E-07 cm/s. The 10% replacement was classified to have poor permeability, and both the 20% and 30% were considered practically impervious.

The use of this material can be very helpful in constructing road embankments. However, engineers must take precautions in using this since the permeability is not that good. They must find a way to be able to compromise both the strength and the permeability in order to maximize the use of this material. It is important to always remember that the drainage of roads must not rely solely on the road embankments. There should always be proper surface drainage systems installed. They must also be working efficiently and frequently maintained.

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