Horizontal Permeability of Soil-Fly Ash Mix

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Abstract: Permeability is vital to every project where the flow of water through soil is a concern (e.g. dam seepage, cutoff wall and diaphragm wall). There are numerous studies about the vertical permeability of soil since ASTM D2434 Standard Test Method for Permeability of Granular Soils (Constant Head & Falling Head) is being followed. On the contrary, there are only a few studies that focused on the horizontal permeability of soils. Five (5) soil samples with different mixes of silty sand and fly ash were obtained for comparison. Rigorous laboratory tests was performed to determine the individual properties. Tests such as specific gravity tests, Atterberg limit tests (liquid limit, plastic limit and plasticity index), e_{max} and e_{min} test/relative density tests, particle size analyses, microscopic characterizations, elemental composition tests and permeability tests were performed to garner data that were utilized for the model. A new permeability set-up was used in the determination of the horizontal permeability. A relationship between the percentage of fly ash and the coefficient of permeability was established, the said relationship was utilized to develop a model that will predict the coefficient of permeability when the percentage of fly ash is available.

Key Words: fly ash; permeability; horizontal permeability; waste; regression;

1. INTRODUCTION

The properties of soil changes over time, it can be influenced by its physical content, climate and weather. It can reveal a lot of information by just analyzing the soil profile of a certain area.

When designing structures, it is very important for engineers to understand the soil underneath because it will affect the way it is designed. It is used by geotechnical engineers in designing foundations, retaining walls, etc. Without its knowledge, lives would be at stake. Geotechnical properties include the grain size distribution, Atterberg limits, specific gravity, maximum and minimum index densities, soil classification, permeability, shear strength and compressibility.

Permeability is vital to every project where the flow of water through soil is a concern (e.g. dam seepage, cutoff wall and diaphragm wall). Permeability refers to the susceptibility of a material to allow fluid to move through its pores. In the context of soil, permeability generally relates to the propensity of a soil to allow fluid to move through its void spaces (Liu, et al., 2000).

It was proposed that fly ash is mixed with silty sand since power plants discharge large amounts of fly ash as waste but only half of them are used and the remaining half is trashed to land and sea, its disposal became an environmental concern. The utilization of fly ash may be a viable alternative for porous backfill material because fly ashes generally consist of silt-sized particles and consequently possess high permeability (Prashanth, J. 2001). Tests must be performed to determine the permeability of soil-sly ash mixture since there was a lack of information on the horizontal permeability of the said mixes.

2. METHODOLOGY

Prashanth (2001) said that fly ashes generally consist of silt-sized particles and consequently possess high permeability. To check the effect of fly ash on soil, varying amounts [0% (100S), 25% (25FA75S), 50% (50FA50S), 75% (75FA25S) and 100% (100FA)] of fly ash were utilized.

Each soil mix underwent rigorous laboratory tests: specific gravity test based on ASTM D854 was utilized, it is the standard of determining the density of the soil. Atterberg limit tests based on ASTM D4318 for determining the Liquid Limit, Plastic Limit and the Plasticity Index of the Soil. For e_{max} and e_{min} Tests and Relative Density, ASTM D4253 and ASTM D4254 were used to determine the maximum and minimum index densities for soils. Particle size analysis uses ASTM D422 to determine the percentage of different grain sizes in a soil.

The scanning electron microscopy (SEM) was used to evaluate the microscopic characterization of each soil mixture. Scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (SEM/EDX) is the best known of the surface analytical techniques. High resolution images of surface topography are produced using these tests. Using the Energy Dispersive X-ray Spectroscopy (EDX), chemical composition of soil is determined to give information on the elements present in the soil.

Permeability of the different soil mixes were determined by the constant head test method and falling head test method. The direction of flow of water is also important, thus, vertical and horizontal orientations of permeameter were used. A proposed set-up by Smith (2010) for permeameter was used and modified to determine the horizontal permeability of the soil mixtures, shown on Fig. 1. The equation utilized for the permeability set-up is Eq. 1.

A proposed Regression model based on the data garnered was formulated. Regression modelling is a statistical process for estimating the relationships among variables. It includes many techniques for modeling and analyzing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables.

The said models were validated using Equality Line and other Models. Validation using equality line usually involves a 45-degree line as a guideline that provides insight into the measured variables and as a critical part of the analysis. When the data are near the 45-degree line, this means that the residual is small and the predicted coefficient of permeability is near the measured coefficient of permeability. Validation using other previous models developed such as works of Hazen (1982) and Shamsai (2007) were considered for comparison. Once models were valid, the research provided conclusions and a recommendations.

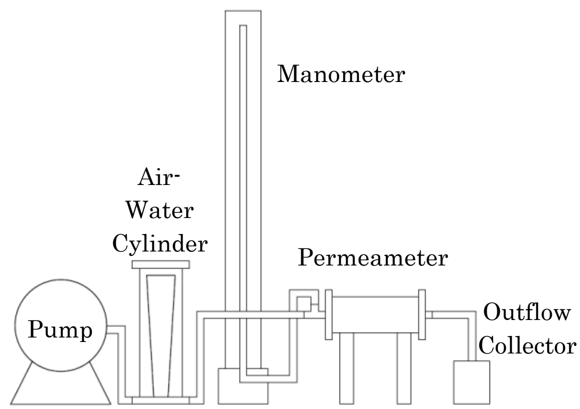

Fig. 1. Horizontal Permeability Set-up

$$k = Ql/Aht \qquad \text{(Eq. 1)}$$

where:

k	=	coefficient of permeability, cm/s;
Q	=	quantity (volume) of water discharged during test, cm3;
l	=	length between manometer outlets, cm;
A	=	cross-sectional area of specimen, cm^2;
h	=	head (difference in manometer levels) during test, cm;
t	=	time required for quantity Q to be discharged during test, s.

3. RESULTS AND DISCUSSION

3.1 Physical and Chemical Characteristics

Using ASTM D854 the specific gravity of each soil blend was determined. The summary of the specific gravity of various soil mixtures are shown in Table 1:

Table 1. Summary of Specific Gravity

Soil Mixture	G_s
100FA	2.02
75FA25S	2.11
50FA50S	2.31
25FA75S	2.49
100S	2.58

The specific gravity of the soil mixes was reduced by the addition of fly ash (Prabakar, et al., 2004) since the usual of the specific gravity of fly ash is low. With the results shown on Table 1, the addition of fly ash reduces the specific gravity of a soil mixture, thus we can agree with the statement of Prabakar (2004), this is due to the light weight property of fly ash.

Table 2. Summary of Atterberg Limits

Soil Mixture	LL	PL	PI
100FA	66	65	1
75FA25S	64	57	7
50FA50S	61	49	12
25FA75S	59	45	14
100S	52	32	20

The effect of adding fly ash in the mixture, due to its silty property, is that it reduced the plasticity of a soil mixture. Based on established literatures (e.g. Prabakar, et al. (2004)), fly ash is considered as silt material, it is expected to have a plasticity index less than 1. Results are shown in Table 2.

ASTM D4253 and ASTM D4254 were used to determine the maximum and minimum void ratios of the different soil-fly ash mixes.

Table 3. Summary of e_{min} and e_{max}

Soil Mixture	e_{min}	e_{max}
100FA	0.27	1.99
75FA25S	0.37	1.98
50FA50S	0.47	1.94
25FA75S	0.72	1.93
100S	0.84	1.78

It can be noticed from Table 3, the Maximum Void Ratio (e_{max}) ranges from 1.78 to 1.99 because the fine contents of the fly ash contributed to the percentage of voids. 100S has the lowest value while 100FA has the highest, also from Table 3, 100S has the lowest fines content, while 100FA garners the highest. Their fines content and microfabric may have contributed to the minimum and maximum void ratio.

These minimum and maximum void ratios together with the target relative density of 90% were used to determine the void ratio to be utilized for the permeability specimens.

Table 4. Summary of Particle Size Analysis Results

Soil Blend	% Passing #200	D_{10}	D_{30}	D_{60}
100F	61.83	0.029	0.03	0.04
75FA25S	50.78	0.019	0.032	0.06
50FA50S	29.79	0.032	0.0375	0.12
25FA75S	25.79	0.015	0.042	0.15
100S	21.84	0.01	0.4	1.2

Summary of results from the particle size analyses are shown on Table 4. 100FA has the greatest percentage of fines compared with other blends. Fly ash and soil are considered fines but the classification differ, fly ash is silt and soil is plastic. It can also be noticed that mixing fly ash with other soils increases the fines content.

In the Energy Dispersive X-ray Spectroscopy (EDX), chemical composition of soil is determined to give information on the element present in the soil, shown in Table 5. Oxygen (O) is very abundant, followed by Silicon (for Silty Sand) and Calcium (for Fly Ash). Silicon and Calcium are predominant in the soil elemental composition. Due to the presence of Oxygen and other dominant elements: Silica (from Silicon), Lime (from Calcium) and Alumina (from Aluminum) are the dominant minerals in the soil sample.

Table 5. Summary of Elemental Composition

Element	Composition (%) for Silty Sand	Composition (%) for Fly Ash
C, Carbon	17.39	5.41
O, Oxygen	46.65	40.64
Al, Aluminum	11.52	5.26
Si, Silicon	15.63	9.1
K, Potassium	1.05	0.78
Ca, Calcium	0.24	21.82
Fe, Iron	5.72	16.34

Element	Composition (%) for Silty Sand	Composition (%) for Fly Ash
Cu, Copper	1.8	0.26
S, Sulfur	0	0.39

Most of the soil properties and characteristics like strength, compressibility and permeability are ascribed by its microfabric or microstructure. The scanning electron microscopy (SEM) was used to evaluate the microfabric of soil, fly ash and bentonite. Scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (SEM/EDX) is the best known of the surface analytical techniques. High resolution images of surface topography, are produced using these tests.

Pure soils were initially tested to check their microscopic characteristics, mixed soils were also tested thereafter.

As shown in Fig. 1, with 500x magnification for 100S, it is a combination of extremely strandy grains, large angular grains and abundant silt grains formed the micro fabric. The silt grains have a rough surface. The particles are well-graded microscopically. The smaller particles tend to fill the voids created by the larger particles shown in the figure, thus creating a smaller inter-particle void. Looking closer to magnification of 1000x and 5000x, strand-like particles are present, his indicates that these elongated particles also fill the voids, giving small passageways for water to permeate.

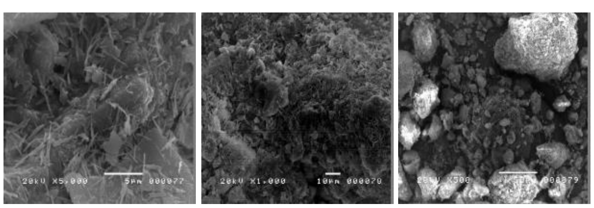

Fig. 1. Microfabric of 100S (5000x, 1000x and 500x Magnification)

As shown in Fig. 2, with 500x magnification for fly ash, it is a combination of larger silt grains and smaller silt grains to form the micro fabric. Fly ash is a silt thus normally 0.002-0.05 mm in size. As seen on the 500x magnification, particles have almost similar size, forming larger inter-particle void, compared with silty sand and bentonite, to allow water to pass through. On the 1000x and 5000x magnification, the surface of the particle is not smooth, this create passageway/voids for water to pass through.

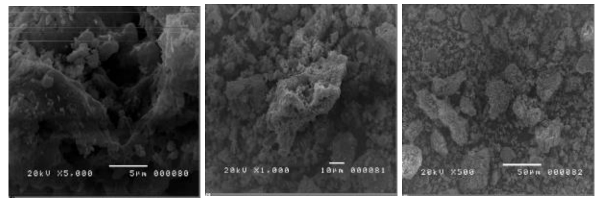

Fig. 2. Microfabric of 100FA (5000x, 1000x and 500x Magnification)

As shown in Fig. 3, with 500x magnification for 50FA50S, it is a combination of extremely strandy grains, large angular grains and abundant larger silt grains and smaller silt grains formed the micro fabric. The silt grains have a rough surface. Looking closer to magnification of 1000x and 5000x, strand-like particles are present but noy prevalent compared with the pure soil, the soil particles may contribute to the reduction of permeability but the silt grains of fly ash will counteract to allow water to drain faster.

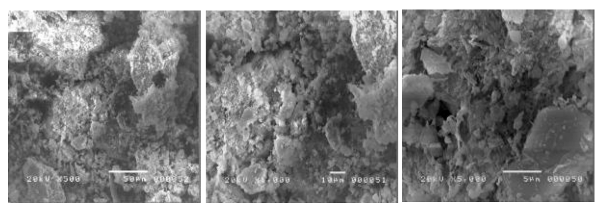

Fig. 3. Microfabric of 50FA50S (5000x, 1000x and 500x Magnification)

3.2 Permeability Characteristics

A proposed approach in determining the vertical permeability of the various soil mixtures was utilized, it was referred on the study of Smith (2010) and was modified. Shown in Table 6, are the range of permeability values gathered for the vertical oriented constant head permeability test, to determine the effect of fly ash when added to soil, a box and whisker plot is delineated, shown on Fig. 4.

Table 6. Range of permeability values for vertical oriented permeability test

Soil Mixture	Minimum k, cm/s	Maximum k, cm/s
100FA	4.53E-05	5.52E-05

Soil Mixture	Minimum k, cm/s	Maximum k, cm/s
75FA25S	3.40E-05	3.80E-05
50FA50S	2.55E-05	3.16E-05
25FA75S	2.05E-05	2.51E-05
100S	1.47E-05	2.09E-05

It is prevalent that the permeability is increased when the amount of fly ash is increased. It now agrees with the study of Prashanth (2001) that fly ashes generally consist of silt-sized particles and consequently possess high permeability. Thus, the amount of fly ash increase the permeability of the soil mixes.

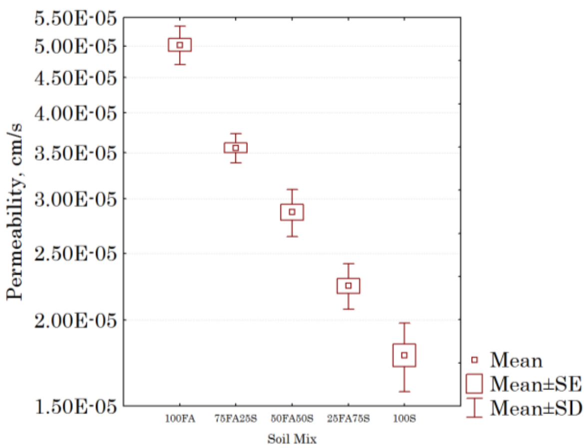

Fig. 4. Effect of fly ash on the vertical permeability when added to soil

The horizontal permeability of the various soil mixtures is important because it can discerned how long the contaminated water penetrated in the horizontal direction. Shown in Table 7, are the range of permeability values gathered for the horizontal oriented constant head permeability test. To determine the effect of fly ash in the horizontal permeability when added to soil, a box and whisker plot is delineated, shown on Figure 5.

Table 7. Range of permeability values for horizontal oriented permeability test

Soil Mixture	Minimum k, cm/s	Maximum k, cm/s
100FA	6.02E-05	7.28E-05
75FA25S	4.25E-05	5.02E-05
50FA50S	3.40E-05	4.04E-05
25FA75S	3.04E-05	3.70E-05
100S	2.21E-05	2.70E-05

It can also be noticed that the horizontal permeability values are larger than the vertical permeability values. This agrees with the collected data of Das (2008), where he stated that the horizontal permeability is always larger than the vertical permeability. This is due to the pressure head induced during the permeability test. The specimen is laid in a horizontal position, which experiences no pressure drop within its body, unlike the vertical specimen, which experiences pressure drop, resulting to a slower flow of water.

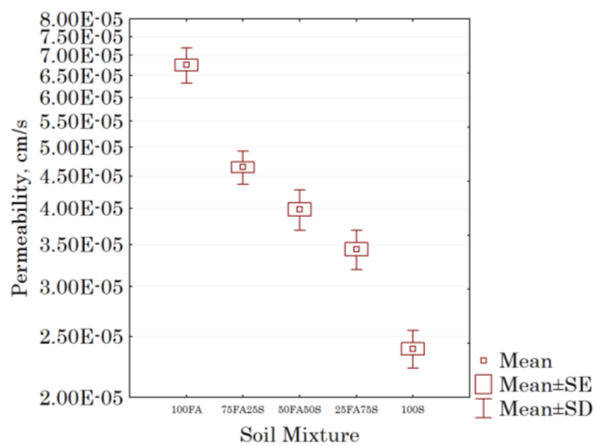

Fig. 5. Effect of fly ash on the horizontal permeability when added to soil

The permeability of silty sand ranges: (1) vertical oriented 1.47×10^{-05} cm/s to 2.09×10^{-05} cm/s and (2) horizontal oriented 2.21×10^{-05} cm/s to 2.70×10^{-05} cm/s. 100S' microfabric having a combination of extremely strandy grains, large angular grains and abundant rough-surfaced silt grains contributed to the drainage.

Fly ash is the recommended addition to the soil mixtures since waste materials are aimed to be utilized and the addition of fly ash to soils changes the inter-particle void ratio (Prabakar, Dendorkar, & Morchhale, 2004), which is prevalent to the microscopic characterization test for 100F. It is a combination of larger silt grains and smaller silt grains to form the micro fabric. Silt particles have almost similar size, forming larger inter-particle void, contributing to a much larger inter-particle voids. Due to a larger inter-particle voids, the permeability of pure fly-ash ranges: (1) vertical oriented 4.51x10^{-05} cm/s to 5.35x10^{-05} cm/s and (2) horizontal oriented 1.93x10^{-05} cm/s to 7.29x10^{-05} cm/s.

75FA25S, 50FA50S, 25FA75S, 96S4FA are the mixtures that include fly ash and soil, their microfabric is a combination of extremely strandy grains, large angular grains and abundant larger rough-surfaced silt grains and smaller rough-surfaced silt grains. Shown on Figure 4 and Figure 5, as the amount of fly ash is increased, the drainage also increased. Due to the contribution of fly ash to the inter-particle voids of the soil mixtures, the permeability of mixture of soil and fly-ash ranges: (1) vertical oriented 1.93x10^{-05} cm/s to 3.80x10^{-05} cm/s and (2) horizontal oriented 2.52x10^{-05} cm/s to 5.02x10^{-05} cm/s.

To validate the results of the vertical oriented and the horizontal oriented permeability tests, their ratio must be within the given range of Das (2008). The collected usual ratio of horizontal and vertical permeability of soils by Das (2008) is with the range of 1.2-3.3, thus, the data gathered are between 1.3-1.5, thus ratios are within Das' desired range.

3.3 Regression Model

To check the effect of fly ash when added to soil, soil-fly ash mixtures such as 100F, 75FA25S, 50FA50S, 25FA75S and 100S were tested. Their permeability values were used to generate regression models. The said models were able to establish a relationship between the percentage of fly ash and permeability. The delineated regression models are shown on Figures 6 and 7.

It can be noticed that the regression models follow the trend that was observed with the experimental values of the soil-fly ash mixtures - because of the silty property of fly ash, once it is increased, the drainage is also increased. The increase in drainage is due to its microfabric, which is a combination of extremely strandy grains, large angular grains and abundant larger rough-surfaced silt grains and smaller rough-surfaced silt grains that contributes to a much larger inter-particle void.

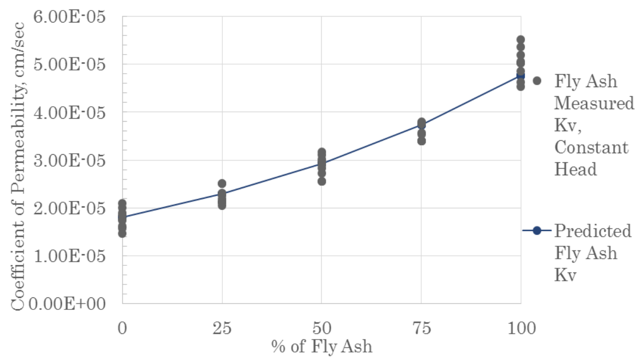

Fig. 6. Regression Model for Kv and % of Fly Ash

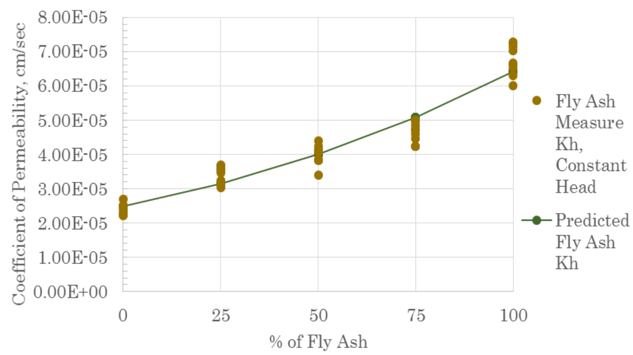

Fig. 7. Regression Model for Kh and % of Fly Ash

The models utilize the percentage of fly ash as the independent variable, while the vertical and horizontal permeabilities, kv and kh, are the dependent variables, respectively. These models can predict the permeability (vertical or horizontal oriented) of any soil-fly ash mix, once the percentage of fly ash is available.

$$k_v = exp^{-10.924} * exp^{9.708x10^{-3} * \%FA} \quad \text{(Eq. 2)}$$

$$k_h = exp^{-10.600} * exp^{9.475x10^{-3} * \%FA} \quad \text{(Eq. 3)}$$

where:

k_v = vertical permeability, cm/sec;

k_h = horizontal permeability, cm/sec;

$\%FA$ = Percentage of fly ash.

Eqs. 2 and 3 were the generated equations of the regression models. The equations were utilized to predict the values of permeability (vertical and horizontal oriented).

3.4 Validation

To check the Experimental Data vs. Regression Model, the measured Coefficients of Permeability for each soil mix were compared with the predicted Coefficient of Permeability of Regression Model. A line that shows equality between the variable measured (Experimental Data) on the horizontal axis of a diagram and the variable predicted (Regression Model Data) on the vertical axis. The equality line graph is shown on Fig. 8.

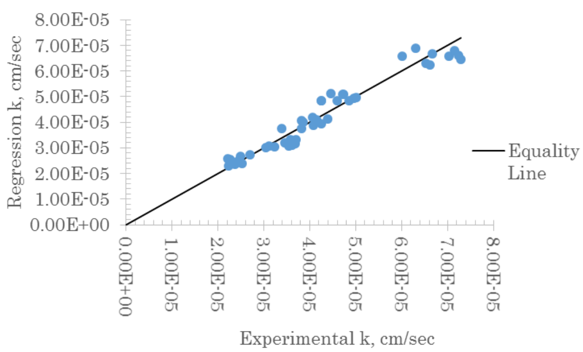

Fig. 8. Regression Model Equality Line

Furthermore, the capability of our proposed Regression model of permeability may be validated by various references. Models developed by Hazen (1982) and Shamsai (2007) were considered. The equation developed by Hazen (1982), which utilizes values of D_{10} of the different soil mixtures. Shamsai's formula was also applied to validate. The equation utilizes the percentage of fines, particles passing Sieve #200.

To validate, data gathered during the series of experiments have been utilized. It is shown in Figure 9. The two (2) models, Hazen's and Samsai's, were compared with the model developed during the study. It can be noticed that the predicted k follows the same trend as the equations from Shansai's (2000) and Hazen's (1982). Hazen's equation does not rely with the value of void ratio.

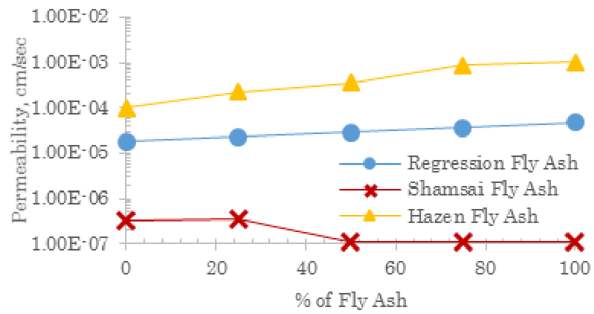

Fig. 9. Comparison with other Models

Based on Figure 9, Hazen's model has the lowest peameability, the equation only relies on the D_{30}, which is a rough estimate on the range of permeability that can be attained. Hazen's formula can be a boundary of the permeability values that are desired. While Shamsai's model utilizes the void ratio (e) as an independent parameter, it gave unusual lower values of permeability of fly ash. Compared to Hazen's and Shamsai's, the regression model is near the experimental data, which signifies that the generated model is valid

4. CONCLUSIONS & RECOMMENDATIONS

4.1 Conclusions

Fly ash is the recommended addition to silty sand, since waste materials are aimed to be utilized. The addition of fly ash to soils changes the inter-particle void ratio (Prabakar, Dendorkar, & Morchhale, 2004), it increases the permeability, thus, the microscopic characteristics of the soil mixtures may contribute to the increase in permeability.

Based on the tests, fly ash is a combination of larger silt grains and smaller silt grains to form the micro fabric. Silt particles have almost similar size, forming larger inter-particle void, contributing to a much larger inter-particle voids. Due to a larger inter-particle voids, the permeability of pure fly-ash ranges: (1) vertical oriented $4.51\text{x}10^{-05}$ cm/s to $5.35\text{x}10^{-05}$ cm/s and (2) horizontal oriented $1.93\text{x}10^{-05}$ cm/s to $7.29\text{x}10^{-05}$ cm/s.

75FA25S, 50FA50S, 25FA75S, 96S4FA are the mixtures that include fly ash and soil, their microfabric is a combination of extremely strandy grains, large angular grains and abundant larger rough-surfaced silt grains and smaller rough-surfaced silt grains. As the amount of fly ash is increased, the drainage also increased. Due to the contribution of fly ash to the inter-particle voids of the soil mixtures, the permeability of mixture of soil and fly-ash ranges: (1) vertical oriented 1.93x10-05 cm/s to 3.80x10-05 cm/s and (2) horizontal oriented 2.52x10-05 cm/s to 5.02x10-05 cm/s.

4.2 Recommendations

A proposed regression model was formulated to determine the permeability of the soil-fly ash mixture, when the percentage of fly ash is available.

The set-up fabricated in the study is recommended to be utilized for future researches on permeability, since it can accommodate higher pressure heads using pumps (compared with the existing permeameters) and can test two (2) specimens simultaneously. Also, the proposed permeability set-up can also accommodate both constant head and falling head permeability tests. Also, for the purpose of ground improvement engineering, testing the shear strength and the compressibility of the soil mixtures in relation to the permeability is recommended.

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6. REFERENCES

Adajar, M. Q., & Zarco, M. H. (2012). An analytical Model for estimating the coefficient of permeability of mine tailings. PICE 2012 National Midyear Convention. Palawan.

Adams, T., Baxter, D., Boyer, R., Britton, J., Henry, L., Heslin, G., & Filz, G. (1997). The mechanical and hydraulic behavior of soil-bentonite cut-off wall. Virginia Polytechnic Institute and State University, Department of Civil Engineering. Virginia: Virginia Polytechnic Institute and State University.

Alday, J. C., Barretto, M. F., Bauzon, M. G., & Tolentino, A. N. (2012). Permeability Characteristics of Road Base Materials Blended with Fly Ash and Bottom Ash. De La Salle University, Civil Engineering. Manila: De La Salle University.

Al-Tabbaa, A., & Wood, D. (1991). Some measurements of the permeability of kaolin. Geotechnique, 499-503.

American Society for Testing and Materials. (n.d.). Standard classification of soils for engineering purposes (Unified Soil Classification System). ASTM D2487.

American Society for Testing and Materials. (n.d.). Standard Test Method for Particle-Size Analysis of Soils. ASTM D422.

American Society for Testing and Materials. (n.d.). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM D698.

American Society for Testing and Materials. (n.d.). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM D4318.

American Society for Testing and Materials. (n.d.). Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table. ASTM D4253.

American Society for Testing and Materials. (n.d.). Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density. ASTM D4254.

American Society for Testing and Materials. (n.d.). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM D854. Retrieved from ASTM D854.

American Society for Testing and Materials. (n.d.). Test Method for Shrinkage Factors of Soils by the Mercury Method. ASTM D427.

Autrailian Geomechanics Society and Austrailian Tunnelling Society. (n.d.). Diaphragm walls - design and construction. Australia: Menard Bachy.

Baker, R. F. (1946). Memo on Porous Backfill. Kentucky, USA.

Barrier containment technologies for environmental remedial purposes. (1995). New York, USA: John Wiley and Sons, Inc.

Baxter, D. Y. (2000, April 14). Mechanical behavior of soil-bentonite cut-off wall. Virginia Polytechnic Institute and Stat University, Department of Civil Engineering. Blacksburg, Va: Virginia Polytechnic Institute and Stat University.

Bowders, J. J., Usmen, M. A., & Gidley, J. S. (1987). Stabilized fly ash for use as low permeability barriers. Geotechncial practice for waste disposal, 320-333.

Caplano, J. (2001, December 30). Closed landfills contaminating groundwater, World Bank warns. (Philippine Star) Retrieved November 2013, from Philippine Star: http://www.philstar.com/nation/145333/closed-landfills-contaminating-groundwater-world-bank-warns

Celik, K., Jackson, M., Mancio, M., Emwas, A., Mehta, P., & Meonteiro, P. (2014). High-volume natural volcanic pozzola and limestone powder as partial replacements for portland cement in self-compacting and sustainable concrete. Cement & concrete composites, 136-147.

Cirriello, V., Federico, V., Archetti, R., & Longo, S. (2013). Effect of variable permeability on the propagation of thin gravity currents in porous media. Internation journal of non-linear mechanics, 168-175.

Cokca, E., & Ylmaz, Z. (2004). Use of rubberand bentonite added fly ash as a liner material. Waste Manage, 153-164.

D' Appolonia, D. (1980). Soil-bentonite slurry trench cut-offs. Journal of Geotechnical Engineering Division, 106(4), 399-417.

Daniel, D. E. (1993). Clay Liners. Geotechnical practice for waste disposal, 137-163.

Daniel, D. E., & Koerner, R. M. (2007). Vertical cut-off walls. In A. Press, Waste containment facilities: Guidance for construction quality assurance and construction quality control of liner and cover systems (pp. 281-311). Rexton, Virginia, USA: ASCE.

Daniel, D., & Choi, H. (1999). Hydraulic conductivity evaluation of vertical barrier walls. Geoengineering for Underground Facilities (pp. 140-161). Reston, Va.: Geoengineering for Underground Facilities.

Das, B. M. (2008). Advanced soil mechanics. New York: Taylor & Francis.

Duncan, J. M., & Chang, C. Y. (1970). Non-linear analysis of stress and strain in soils. Journal of Soil Mechanics and Foundations Division, 96, 1629-1653.

Dzeng, R.-J., & Pan, N.-F. (2006). Learning Heuristics for determining slurry wall panel lengths. Automation in Construction, 15, 303-313.

Edil, T. B., Sandstrom, L. K., & Bertheoux, P. M. (1992). Interaction of inorganic leacheate with compacted pozzolanic fly ash. Journal of Geotechncial Engineering, 1410-1430.

Edil, T., Berthouex, P., & Vesperman, K. (1987). Fly ash as potential waste liner. In R. D. Wood (Ed.), Geotechnical Practice for Waste Disposal. 110(6), pp. 447-461. New York: ASCE.

Elaiw, A., Ibrahim, F., & Bakr, A. (2009). Variable permeability and inertia effect on vortex instability of natural convection flow over horizontal permeable plates in porous media. Commun nonlinear sci numer simulat, 2190-2201.

Evans, J. C. (1993). Vertical cut-off walls. (D. Daniel, Ed.) London, United Kingdom: Chapman and Hall.

Evans, J. C. (1994). Hydraulic conductivity of vertical cut-off walls. ASTM STP 1142 (pp. 79-94). Philadelphia: American Society for Testing and Materials.

Filz, G. M. (1996). Consolidation stress in soil-bentonite backfilled trenches. In M. Kamon (Ed.), 2nd International Congress on Environmental Geotechnics, (pp. 497-502). Balkelma, ROtterdam.

Filz, G., Boyer, R., & Davidson, R. (1997). Bentonite-water slurry rheology and cut-off wall trench stability. In-Situ Remediation of Geoenvironment, GSP No. 71 (pp. 139-153). Reston, Va: ASCE.

Geo-con. (n.d.). Technical specification of soil-bentonite slurry trench cut-off wall. Retrieved from Geo-con: http://www.geocon.net/pdf/sbswtech.pdf

Geo-Slope International. (n.d.). Seep/W Example Files. Retrieved December 10, 2013, from Geo-Slope International: http://downloads.geo-slope.com/geostudioresources/examples/8/x/2/SeepW/Seepage%20thru%20an%20earth%20embankment.pdf

Ghabezloo, S., Sulem, J., Guedon, S., & Martineau, F. (2009). Effective stress law for the permeability of a limestone. International journal of rock mechanics & mining science, 297-306.

Guo, J., Nie, R., & Jia, Y. (2012). Deual permeability flow behavior for modeling horizontal well production in fractured-vuggy carbonate reservoirs. Journal of hydrology, 281-293.

Hadia, N., Mitra, S., & Vinjamur, M. (2012). Estimation of permeability heterogeneity in limestone outcrop by pressure measurements: experiment and numericals ituation. Experimental thermal and fluid science, 177-184.

Helwany, S. (2007). Applied Soil Mechanics with ABAQUS Applications. USA: John Wiley & Sons, Inc.

Horiuchi, S., Kawaguchi, M., & Yasuhara, K. (2000). Effective use of fly-ash as a fill material. Journal of Hazardous Materials, 6, 301-337.

IBECO. (1998). Bentonit-Technologie. Bentonit im Tiefbau GmbH, 1.

Icsan, A., Kok, M., & Bagci, A. (2006). Estimation of permeability and rock mechanical properties of limestone reservoir rocks under stress conditions by strain gauge. Journal of petroleum science and engineering, 13-24.

Jansen, R. B. (1988). Advanced Dam Engineering for Design, Construction, and Rehabilitation. (R. B. Jansen, Ed.) USA: Van Nostrand Reinhold.

Kansas Health Department. (n.d.). Kansas Health Department Website. Retrieved October 10, 2013, from Kansas Health Department - Waste Management: http://www.kdheks.gov/waste/techguide/EPA_QA-QCforWasteContainmentFacilitiesCH7.pdf

Koch, D. (1989). Einsatzmoglichkeiten bentonithaltiger Systeme zur Deponieabdichtung. BR Baustoff-Recycling and Deponietechnik (pp. 6-89). BR Baustoff-Recycling and Deponietechnik.

Koch, D. (2002). Bentonites as basic material for technical base liners and site encapsulaion cut-off walls. Applied Clay Science, 21, 1-11.

Krishna, R. R. (n.d.). Engineering properties of soils based on laboratory testing . Retrieved from CME315 Soil Mechanics Laboratory: http://www.uic.edu/classes/cemm/cemmlab/

Liu, C., & Evett, J. B. (2000). Soil Properties: Testing, Measurement and Evaluation. (E. Francis, Ed.) Charlotte, North Carolina, USA: Prentice Hall.

Millet, R., Perez, J., & Davidson, R. (1992). USA practice slurry wall specifications 10 years later. In D. Paul, R. Davidson, & N. Cavalli (Ed.), Slurry Walls: Design, Construction and Quality Control. Philadelphia: ASTM STP 1129.

Muskat, M. (1937). The Flow of Homogeneous Fluids Through Porous Media. McGraw-Hill Book Company, Incorporated.

Nemati, K. (2007, Winter). University of Washington. Retrieved from CM 420-Temporary Structures: http://courses.washington.edu/cm420/Lesson6.pdf

Nhan, C. T., Graydon, J. W., & Kirk, D. W. (1996). Utilizing coal fly ash as a landfill barrier material. Waste Manage, 587-595.

Nhan, C., Graydon, J., & Kirk, D. W. (1996). Utilizing coal fly ash as a landfill barrier material. Waste Management, 16, 587-595.

O'Brien, S., Dann, C., Hunter, G., & Schwermer, M. (n.d.). Construction of plastic concrete cut-off wall in Hinze Dam. ANCOLD Proceedings of Technical Groups (pp. 1-9). Australia: ANCOLD.

Prabakar, J., Dendorkar, N., & Morchhale, R. (2004). Influence of fly ash on strength behavior of typical soils. Construction and Building Materials, 18, 263-267.

Prashanth, J., Sivapullaiah, P., & Sridharan, A. (2001). Pozzolanic fly ash as a hydraulic barrier in land fills. Engineering Geology, 60, 245-252.

Roulier, S., Baran, N., Mouvet, C., Stenemo, F., Morvan, X., Albrechtsen, H., . . . Jarvis, N. (2006). Controls on atrazine leaching through a soil unsaturated fracture limestone sequence at Brevilles, France. Journal of contaminant hydrology, 81-105.

Saba, S., Delage, P., Lenoir, N., Cui, Y., Tang, A., & Barnichon, J.-D. (2014). Further insight into the microstructure of compacted bentonite-sand mixture. Engineering geology, 141-148.

Saranswami, G. (1991). Behavior of reinforced sand samples in triaxial shear. Indian Geotechnical Conference, IGC91 (pp. 359-361). Surat, India: Indian Geotechnical Conference.

Smith, C. B. (2010). Horizontal Permeameter. Magna Cum Laude Honors Research Project, University of Florida, Department of Civil and Coastal Engineering, Gainesville, Florida.

Soroush, A., & Soroush, M. (2005, April). Parameters affecting the thickness of bentonite cake in cut-off wall construction: case study and physical modelling. Canadian Geotechnical Journal, 42(2), 646-654.

Supit, S., Shaikh, F., & Sarker, P. (2014). Effect of ultrafine fly ash on mechanical properties of high volume fly ash mortar. Construction and building materials, 278-186.

U.S. Army Corps of Engineers (USACE). (1996). ngineering and design checklist for design and vertical barrier walls for hazardous waste sites. Technical Letter, ETL 1110-1-163, Appendix B. Washington D.C., USA: U.S. Army Corps of Engineers (USACE).

Usmen, M. A., Bowders, J. J., & Gidley, J. S. (1988). Low permeability liners incorporating fly ash. Disposal and utilization of electric wastes, 50-65.

Wong, L., Lin, H., & Patron, B. (n.d.). Design of diaphragm walls for the TRTS deep excavations. Taipei Metropolitan Rapid Systems Symposium (pp. 319-328). Taipei: Taipei Metropolitan Rapid Systems.

World Bank. (2012, October 24). Philippines: Toward Greener Waste Management. Retrieved November 2013, from World Bank: http://www.worldbank.org/en/news/press-release/2012/10/24/philippines-toward-greener-waste-management

Xanthakos, P. (1994). Slurry walls as structural systems. New York, USA: McGraw Hill.

Xiao-Dong, W., Ying-Fang, Z., & Wang-Jing, L. (2010). A study on transient fluid flow of horizontal wells in dual-permeable media. Journal of hydrodynamics, 44-50.

Yang, Z. (1972). Strength and deformation characteristics of reinforced sand. University of California. Los ANgeles: University of California.

Ye, W., Borell, N., Zhu, J., Chen, B., & Chen, Y. (2014). Advances on the investigation of the hydraulic behavior of compacted GMZ bentonite. Engineering geology, 41-49.

Ye, W., Xu, L., Chen, B., Ye, B., & Cui, Y. (2014). An approach based on two-phase flow phenomenon for modeling gas migration in saturated compact bentonite. Engineering geology, 124-132.

Yehesis, M. B., Shang, J. Q., & Yanful, E. K. (2010). Feasibility of using fly ash for mine waste containment. Journal of environmental engineering, 682-690.