LINEAR OPTIMIZATION OF SOIL MIXES IN THE DESIGN OF VERTICAL CUT-OFF WALLS

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ABSTRACT: In order to prevent the contamination of surrounding groundwater in a landfill, cut-off walls were recommended. Cut-off walls are walls utilized when there is a need to restrict horizontal movement of liquids. Currently, the factors in designing cut-off walls are effective permeability, and relatively inexpensive materials in containing contaminants. It was suggested to provide a mix of 96% soil and 4% bentonite in the design of cut-off walls, but bentonite is relatively expensive, thus the viability of fly ash as a replacement for bentonite was considered. Soil mixtures were proposed and 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, and were utilized for the model. A linear optimization model was generated to achieve the least cost with the minimum required permeability. The minimum permeability requirement for the cut-off wall was achieved by providing various mixtures for soil-bentonite-fly ash.

Keywords: Permeability, Fly Ash, Bentonite, Optimization, Linear Optimization

1. INTRODUCTION

Nearly a decade ago, the World Bank found that the San Mateo Landfill located in Rizal Province and Carmona Landfill in Cavite Province of the Philippines containing over 23 million cubic meters of corrupting waste were contaminating the ground water of their nearby vicinities [1]. In order to prevent the contamination of their groundwater, cut-off walls were recommended. In a waste disposal system, cut-off walls and clay liners (also known as contaminant barriers) are used to restrict movement of liquids and gases around waste-disposal facilities or site remediation projects [2]. Cut-off walls are walls utilized when there is a need to restrict horizontal movement of liquids. It is also used to provide an encapsulation for the waste to limit the inward movement of clean ground water in areas where groundwater is being pumped or being treated. It is also used to provide as long-term barrier to impede contaminant transport. The difference between cut-off wall and clay liner is that cut-off wall reduces the contaminant transport in the horizontal direction [3] while clay liner reduces the rate of contaminant transport in the vertical direction

Currently, one of the factors in designing cut-off walls is to provide an acceptable permeability of containing contaminant. Permeability generally relates to the propensity of a soil to allow fluid to move through its void spaces. Baxter [4] suggested to provide a mix of 96% soil and 4% bentonite in the design of cut-off walls, but bentonite is relatively expensive, thus the viability of fly ash as a replacement for bentonite was considered. Because of its relatively low permeability, bentonite is usually recommended mixed with non-cohesive soil like silty sand as an encapsulation material [5], however, the utilization of bentonite has made the cost high that is why bentonite is suggested to be replaced. It was proposed that fly ash is replacing bentonite 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 barrier containment material [6] but on the contrary, fly ashes generally consist of silt-sized particles and consequently possess high permeability [7]. Permeability refers to the susceptibility of a material to allow fluid to move through its pores. Tests must be performed to determine if fly ash may be viable for a containment material. The main objective of the study is to determine the most viable permeability characteristic of the various soil mixes of soil, fly ash and bentonite for cut-off wall.

2. METHODOLOGY

Varying blends were tested to check their response on the vertical and horizontal permeability, shown on Table 1.

Each soil mixture index tests such as Specific

Gravity Test [8], Atterberg Limit Tests [9], e_{max} test [10] and e_{min} tests [11] and Particle Size Analysis [12].

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. Soil particles were described according to their shape, texture and size.

Table 1. Soil Mixtures of Fly Ash, Soil, and Bentonite

Soil Mixture	Fly Ash (%)	Soil (%)	Bentonite (%)
100FA	100	0	0
75FA25S	75	25	0
50FA50S	50	50	0
25FA75S	25	75	0
100S	0	100	0
100B	0	0	100
96S4B	0	96	4
96S4FA	4	96	0
96S2B2FA	2	96	2

Energy Dispersive X-ray Spectroscopy (EDX) was used to determine the chemical composition of each soil mixture. It is expected to have Oxygen, Silicon, and Calcium. The elemental composition was in terms of percent (%).

Permeability of the different soil mixes was determined by the constant head test method and falling head test method. The direction of flow of water is also important, thus, both the vertical and horizontal orientations of the permeameter were used. A proposed set-up for the permeameter was used and modified to determine the horizontal permeability [13] of the soil mixtures, shown on Figure 1. The Eq.1 is also used in the analysis. The following were also considered:

1. It was suggested by Baxter (2004) to use a relative density of 90% to provide a very dense soil state, thus, the desired void ratio of each soil mix was determined.
2. It was proposed that the pressure head for constant head permeability test will vary during the experiment to check if there were differences in permeability. Three (3) pressure heads were tested for statistical difference for each soil mix, 200cm, 150cm and the 50cm.
3. The diameter of the soil sample will follow the diameter of the permeameter 2.5in (6.35cm). The length of the specimen is 10cm to accommodate the additional porous stones provided.
4. The standard temperature was 20C. Results were standardized once the temperature varied.

$$k = Ql/Aht \qquad (1)$$

where:

k = coefficient of permeability, cm/s; Q= quantity (volume) of water discharged during test, cm^3; 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.

A Linear Optimization Model was also proposed to achieve the optimized mixture that will give an acceptable permeability value with the least cost.
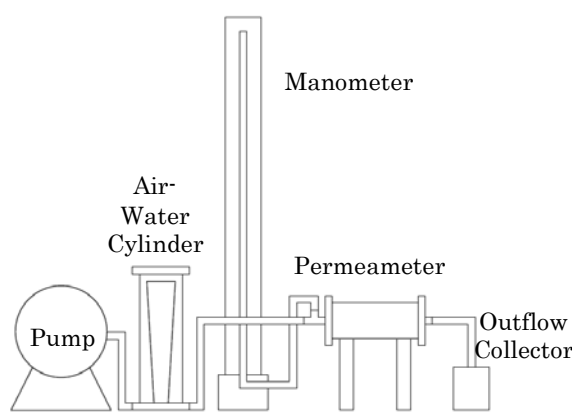

Fig. 1: Horizontal Permeability Set-up

3. RESULTS AND DISCUSSIONS

3.1 Index Properties and Chemical Properties

The specific gravity of each soil blend was determined. The summary of the specific gravity of various soil mixtures are shown in Table 2. The specific gravity of a particular soil shall be reduced by the addition of fly ash [7] since the usual of the specific gravity of fly ash is low.

Table 2. Specific Gravity of Each Mixture

Mixture	G_s
100FA	2.02
75FA25S	2.11
50FA50S	2.31
25FA75S	2.49
100S	2.58
100B	2.75
96S4B	2.61
96S2B2FA	2.60
96S4FA	2.52

The addition of fly ash reduces the specific gravity of a soil mixture, thus we can agree with the

statement of Prabakar [14], this is due to the light weight property of fly ash. Furthermore, it can be noticed that 100B is the heaviest of all the soils. Bentonite being a high density material, an increasing weight by adding bentonite to a soil mix can be noticed.

ASTM D4253 [10] and ASTM D4254 [11] were used to determine the maximum and minimum void ratios of the different mixes. 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. It can be noticed that the minimum void ratio is much less that the reference [15], this is due to the meticulous laboratory execution. The allotted time for the vibratory table exceeded to determine the extent of the minimum void ratio.

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

Soil Mixture	e_{min}	e_{max}
100S	0.84	1.78
100FA	0.27	1.99
100B	0.36	1.98
96S4B	0.8	1.80
50FA50S	0.47	1.94
75FA25S	0.37	1.98
25FA75S	0.72	1.93
96S4FA	0.76	1.80
96S2B2FA	0.78	1.81

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.

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

Table 4. Summary of Particle Size Analysis Results

Soil Mixture	% Passing #200	D_{10}	D_{30}	D_{60}
100S	21.84	0.01	0.4	1.2
100F	61.83	0.029	0.03	0.04
100B	58.36	0.0022	0.0055	0.032
96S4B	29.33	0.018	0.043	0.125
50FA50S	29.79	0.032	0.0375	0.12
75FA25S	50.78	0.019	0.032	0.06
25FA75S	25.79	0.015	0.042	0.15
96S4FA	22.27	0.035	0.09	0.13
96S2B2FA	23.82	0.03	0.08	0.25

All soil mixture followed the suggested fines content. Geo-con [16] provided the complete technical specifications on soil-bentonite trench cut-off wall, they stated that the cut-off wall must have at least 15% fines content. Fine materials are particles that passed through #200 sieve during the particles size analysis test (ASTM D422). Evans [17] agrees that the cut-off wall mix must contain at least 15% fines to garner a low coefficient of permeability (commonly less than 9.9x10-7 cm/s) because the percentage of fines present affects the hydraulic conductivity [18].

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. In the Energy Dispersive X-ray Spectroscopy (EDX), chemical composition of soil is determined to give information on the elements present in the soil. 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.

As shown in Fig. 2, 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.
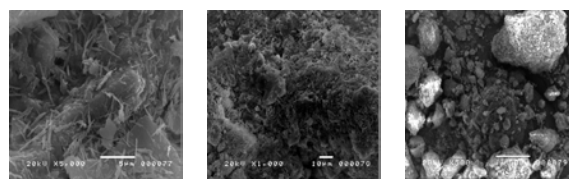

Fig. 2. Microfabric of 100S (5000x, 1000x and 500x Magnification)

As shown in Fig. 3, 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.
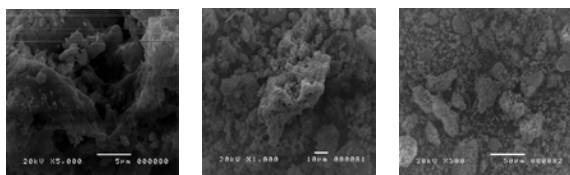

Fig. 3. Microfabric of 100FA (5000x, 1000x and 500x Magnification)

As shown in Fig. 4, 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 not 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.
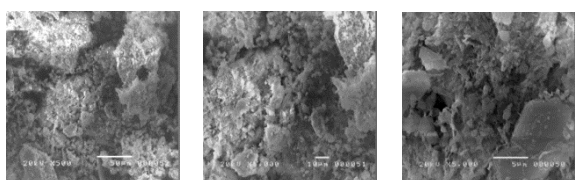

Fig. 4. Microfabric of 50FA50S (5000x, 1000x and 500x Magnification)

As shown in Figure 5, with 500x magnification for 96S2F2B, it is a combination of extremely strandy grains, large angular grains, silt grains and elongated smooth grains formed the micro fabric. The particles are still well-graded microscopically. Looking closer to magnification of 1000x and 5000x, strand-like particles are present, this indicates that these elongated particles also fill the voids, giving small passageways for water to permeate.
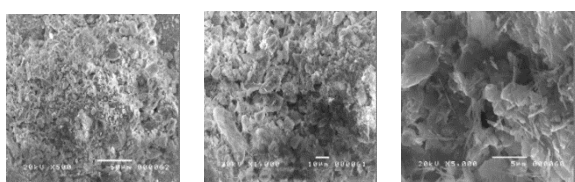

Fig. 5. Microfabric of 96S2F2B (5000x, 1000x and 500x Magnification)

Also the smooth surface of bentonite particles gave a smaller inter particle-void which the permeability is reduced but counter-acted by the presence of fly ash's silt grains which contributed to additional drainage.

3.2 Permeability

A proposed approach in determining the horizontal permeability of the various soil mixtures was utilized, it was referred [13] and was modified. Shown in Table 5 are the range of permeability values gathered for the vertical oriented constant head permeability test.

Table 5. Range of permeability values for vertical oriented permeability test

Soil Mixture	Min K, cm/s	Max K, cm/s
100FA	4.51E-05	5.35E-05
75FA25S	2.93E-05	3.97E-05
50FA50S	2.81E-05	2.98E-05
25FA75S	2.05E-05	2.50E-05
100S	1.66E-05	1.90E-05
100B	6.13E-09	2.48E-08
96S4B	1.16E-07	2.98E-07
96S2B2FA	6.90E-07	7.79E-07
96S4FA	1.93E-05	2.40E-05

It is clear that the permeability is increased when the amount of fly ash is increased. It now agrees with the study of Prashanth [7] that fly ashes generally consists of silt-sized particles and consequently possesses high permeability. Thus, the amount of fly ash increases the permeability of the soil mixes.

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

Soil Mixture	Min K, cm/s	Max K, cm/s
100FA	6.15E-05	7.29E-05
75FA25S	4.19E-05	5.46E-05
50FA50S	3.70E-05	4.34E-05
25FA75S	3.39E-05	3.49E-05
100S	2.25E-05	2.66E-05
100B	1.30E-08	3.53E-08
96S4B	1.65E-07	2.72E-07
96S2B2FA	8.04E-07	9.87 E-07
96S4FA	2.52E-05	2.70E-05

The horizontal permeability of the various soil mixtures is important, because for cut-off walls, it can discern how long the contaminated water will penetrate in the horizontal direction. Shown in Table 6, are the range of permeability values gathered for the horizontally oriented constant head permeability test.

Soil is the usual majority component of the soil mixture since the study followed the suggested mix [6] to reduce its cost, the soil excavated from the cut-off wall trench can be utilized as the soil

element for the backfill. If the soil is contaminated or does not meet the requirements, the excavated soil can be removed and treated. 100S is not a viable candidate for the cut-off wall. 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 to form the cut-off wall mix, since waste materials are aimed to be utilized but the addition of fly ash to soils changes the inter-particle void ratio [14], 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.

Bentonite has low hydraulic conductivity. Its microfabric usually composed of a combination of smooth elongated grains and smaller grains, thus, smaller inter-particle voids are present.

Baxter [4], 96% soil is mixed with 4% bentonite to form the cut-off wall mix. In the study, 96S4B was used as a control specimen, its permeability is above the minimum requirement of 9.9x10-7 cm/s for a cut-off wall. It is a combination of extremely strandy grains, large angular grains and elongated smooth grains formed the micro fabric. In its microscopic structure, strand-like particles are present, this indicates that these elongated particles also fill the voids, giving small passageways for water to permeate. Since, the attained permeability is above the minimum required value, fly ash was incorporated in the mix. Fly ash may increase the drainage but a certain amount of fly ash can be added but still attaining the minimum required permeability.

3.3 Linear Optimization Model

To check the effect of fly ash and bentonite when added to soil, the mixtures were tested for specific gravity, soil index property, relative density, microscopic characterizations, elemental composition and permeability. Many models may also be considered [20, 21, 22, 23]. In the study, their permeability values were used to generate linear optimization model. Equations 2 to 7 are considered in the constraint.

Objective Function: Min. x_3 (Bentonite)　　(2)

Constraints:

$$x_1 \leq 1, \; x_2 \leq 1, \; x_3 \leq 1 \; (3)$$

$$x_1 + x_2 + x_3 = 1 \; (4)$$

(5)

(6)

$$x_i \geq 0 \; (7)$$

where:
x_1 = Amount of Soil;
x_2 = Amount of Fly Ash;
x_3 = Amount of Bentonite.

This proposed linear optimization model was used to achieve the optimized mixture, x_1=38.43% and x_2=62.57%, that will give the permeability value with the least cost.

In order to validate the model, equations 5 and 6 were used. A plot of residuals was considered, shown on Figure 6 and 7.
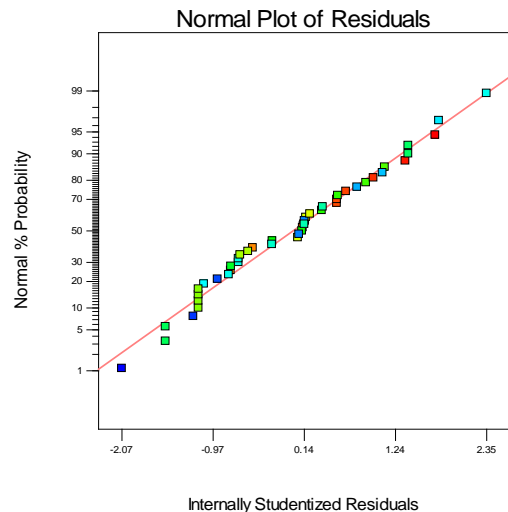

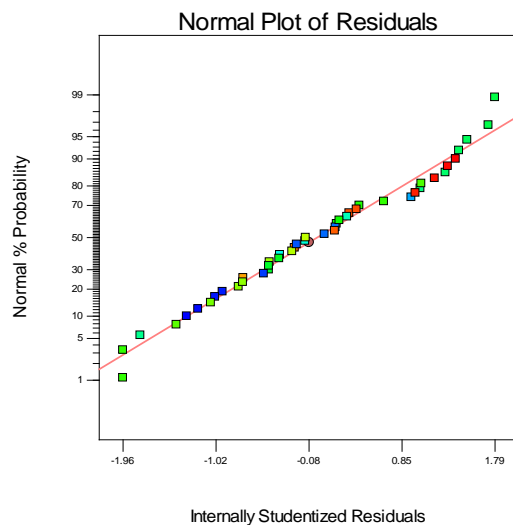Figure 6. Normal Plot of Residuals for Equation 5

Figure 6. Normal Plot of Residuals for Equation 6

4. CONCLUSIONS AND RECOMMENDATIONS

As a criterion in selecting the viable mixture for the cut-off wall, Baxter [4] recommended that the minimum permeability requirement of $x10^{-7}$ cm/s for a cut-off wall. Also, it was suggested to provide a mix of 96% soil and 4% bentonite (96S4B) in the design of cut-off walls, but bentonite is relatively expensive, thus the viability of fly ash as a replacement for bentonite was considered. Fly ash is the recommended addition to the soil mixtures, since waste materials are aimed to be utilized. But the addition of fly ash to soils changes the inter-particle void ratio [14], it increases the permeability, thus, the microscopic characteristics of the soil mixtures may contribute to the increase in permeability. Since, 96S4B's attained permeability is above the minimum required value, fly ash was incorporated in the mix. Fly ash may increase the drainage but a certain amount of fly ash can be added and still attaining the minimum required permeability.

Given the linear optimization model, the optimized mixture, $x_1=38.43\%$ and $x_2=62.57\%$, that will give the permeability value with the least cost was achieved.

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