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MODELLING OF PERMEABILITY CHARACTERISTICS OF SOIL-FLY ASH-BENTONITE CUT-OFF WALL USING RESPONSE SURFACE METHOD

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ABSTRACT: In order to prevent the contamination the groundwater, by restricting the horizontal movement of leachate, cut-off walls were recommended [1]. Currently, one of the factors in designing cut-off walls is to provide efficient and relatively inexpensive means of containing contaminants. In order to obtain acceptable permeability, it was suggested by Baxter [2] 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 were performed to determine the individual properties of the said soil mixtures. Tests for specific gravity, soil index property, relative density, microscopic characterizations, elemental composition and permeability were performed to garner data that were utilized for the Response Surface Method Permeability models. The minimum permeability requirements for the cut-off wall were achieved using various mixtures of soil-bentonite-fly ash.

Keywords: Permeability, Fly Ash, Bentonite, Waste Utilization, Environment

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 contained over 23 million cubic meters of corrupting waste combined and were contaminating the ground water of their nearby Barangays [3]. The Philippines was given financial incentives to manage their landfills [4] but still, these landfills pose threats to the groundwater supply. In order to prevent the contamination of the groundwater by restricting the horizontal movement of water, cut-off walls were recommended [1]. These can be useful as they are both an efficient and relatively inexpensive means of containing contaminants.

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 [x]. 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 [6]. The difference between cut-off wall and clay liner is that cut-off wall reduces the contaminant transport in the horizontal direction [6] while clay liner reduces the rate of contaminant transport in the vertical direction [7]. In order to obtain acceptable permeability, Baxter [2] suggested to provide a mix of 96% soil and 4% bentonite in the design of cut-off walls. Bentonite is usually recommended mixed with non-cohesive soil like silty sand as an encapsulation material [8] but bentonite is relatively expensive, thus the viability of fly ash as a replacement for bentonite was considered. 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 [9]. The utilization of fly ash may be a viable alternative for porous backfill material because fly ashes generally consists of silt-sized particles and consequently possesses high permeability [7]. Tests were performed to determine the viable mixture, and data garnered were utilized as references for the Response Surface Method Permeability Model, which will be discussed in the future sections.

2. METHODOLOGY

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

Table 1. Soil Mixtures

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

Each soil mix underwent rigorous laboratory tests, such as Specific Gravity Test [10], Atterberg Limit Tests [11], e_{max} test [12] and e_{min} tests [13] and Particle Size Analysis [14].

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 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 [15] of the soil mixtures, shown on Fig. 1. The equation utilized for the permeability set-up is Eq. 1.

A proposed Response Surface Methodology (RSM) model based on the data garnered was formulated. Response Surface Methodology (RSM) 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.

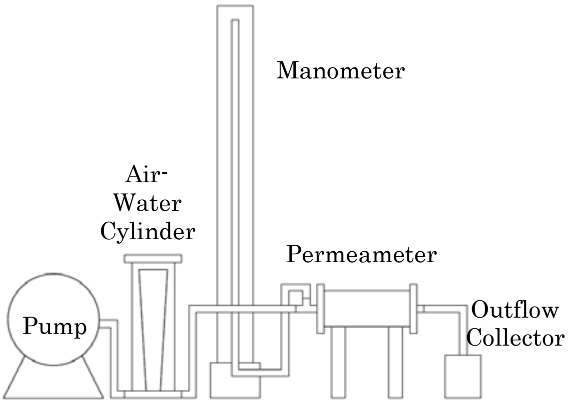

Fig. 1: Horizontal Permeability Set-up

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.

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

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.

3. RESULTS AND DISCUSSIONS

3.1 Physical and Chemical Properties

Using ASTM D854 [10] 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 low specific gravity of the fly ash contributed to the specific gravity of the various soil mixtures [16]. With the results shown in Table 2, the addition of fly ash reduces the specific gravity of a soil mixture.

Table 2. Summary of Specific Gravity

Soil 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

ASTM D4253 [12] and ASTM D4254 [13] 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.

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 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.

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

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.

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. 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.

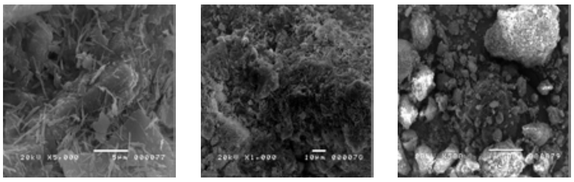

Fig. 2. Microfabric of 100S (5000x, 1000x and 500x Magnification)

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.

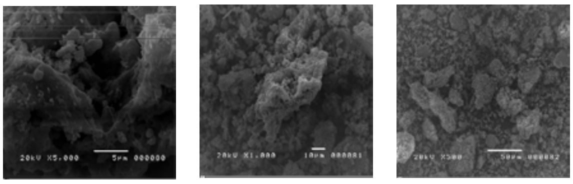

Fig. 3. Microfabric of 100FA (5000x, 1000x and 500x Magnification)

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.

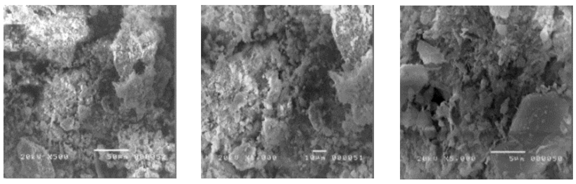

Fig. 4. Microfabric of 50FA50S (5000x, 1000x and 500x Magnification)

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. 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.

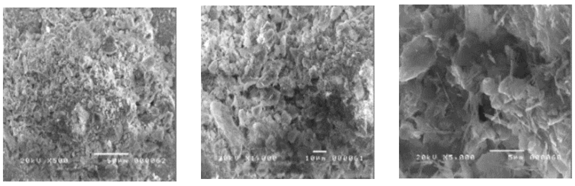

Fig. 5. Microfabric of 96S2F2B (5000x, 1000x and 500x Magnification)

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 [15] 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.

These results show that the horizontal permeability values are larger than the vertical permeability values. This agrees with the collected data of Das [17], 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 in a slower flow of water.

The values of permeability for silty sand (100S) ranges: (1) $1.66x10^{-05}$ cm/s to $1.90x10^{-05}$ cm/s for vertical oriented and (2) $2.21x10^{-05}$ cm/s to $2.70x10^{-05}$ cm/s for horizontal oriented. The extremely strandy grains, large angular grains and abundant rough-surfaced silt grains contributes to the drainage of 100S.

Fly ash (100F) 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 [16x], which is evidenced by 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.

Bentonite has a hydraulic conductivity of $1x10^{-6}$ cm/s to $1x10^{-12}$ cm/s [18]. Its microfabric usually composed of a combination of smooth elongated grains and smaller grains, thus, smaller inter-particle voids are present. In the study permeability of pure bentonite ranges: (1) vertical oriented $6.13x10^{-09}$ cm/s to $1.97x10^{-08}$ cm/s and (2) horizontal oriented $1.30x10^{-08}$ cm/s to $3.30x10^{-08}$ cm/s. Bentonite is a viable candidate for the cut-off wall since it attained the minimum permeability requirement of $9.9x10^{-7}$ cm/s for a cut-off wall. The price of 100B is relatively high that is why pure bentonite is not recommended for a cut-off wall.

96S2B2FA was the soil mix proposed in the study, its permeability ranges: (1) vertical oriented $6.29x10^{-07}$ cm/s to $9.60x10^{-07}$ cm/s and (2) horizontal oriented $8.04x10^{-07}$ cm/s to $9.87x10^{-07}$ cm/s. 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. Thus, this mixture of soil, fly ash and bentonite is a viable candidate for the cut-off wall. The addition of fly ash may reduce the permeability of the 96S4B mixture, but still, incorporating the 2% fly ash as the replacement of bentonite, the minimum requirement of 9.9×10^{-7} cm/s for the permeability of cut-off wall is still attained.

3.3 Response Surface Methodology (RSM) 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. Their permeability values were used to generate RSM models. The said models were able to establish a relationship between the percentage of fly ash, bentonite, soil and permeability. The delineated RSM models are shown on Figs. 6 and 7.

It can be noticed that the RSM models follow the trend that was observed with the experimental values of the soil-fly ash-bentonite 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.

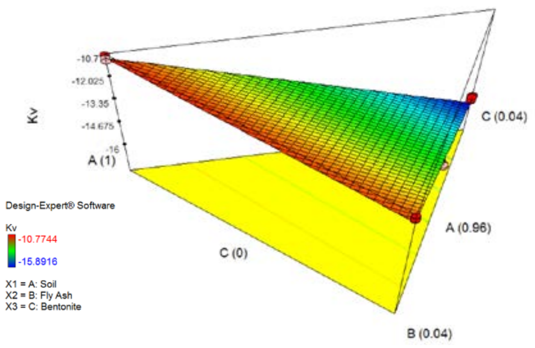

Fig. 6. RSM Model for Kv

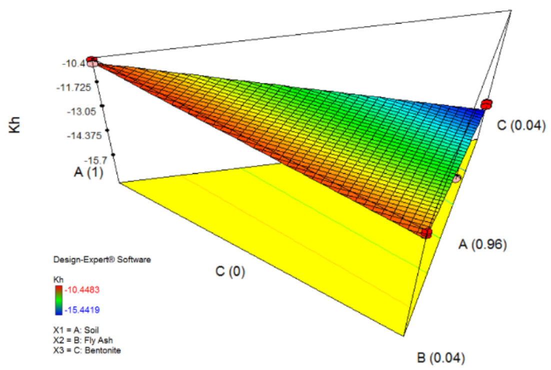

Fig. 7. RSM Model for Kh

The models utilize the percentage of fly ash, bentonite and soil as the independent variables, 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-bentonite mix, once the percentages of fly ash, soil and bentonite are available.

$$k_v = exp^{-10.943*\%S} * exp^{-16.795*\%FA} * exp^{-136.648*\%B} \quad (2)$$

$$k_h = exp^{-10.644*\%S} * exp^{-16.191*\%FA} * exp^{-136.853*\%B} \quad (3)$$

where:

kv = vertical permeability, cm/sec; kh = horizontal permeability, cm/sec; %S = percentage of soil; %FA = Percentage of fly ash; %B = Percentage of bentonite.

3.4 Validation

To check the Experimental Data vs. RSM Model, the measured Coefficients of Permeability for each soil mix were compared with the predicted Coefficient of Permeability of RSM Model.

A line that shows equality between the variable measured (Experimental Data) on the horizontal axis of a diagram and the variable predicted (RSM Model Data) on the vertical axis. The equality line graph is shown on Fig. 8 and 9.

Furthermore, the capability of our proposed Regression model of permeability may be validated by various references.

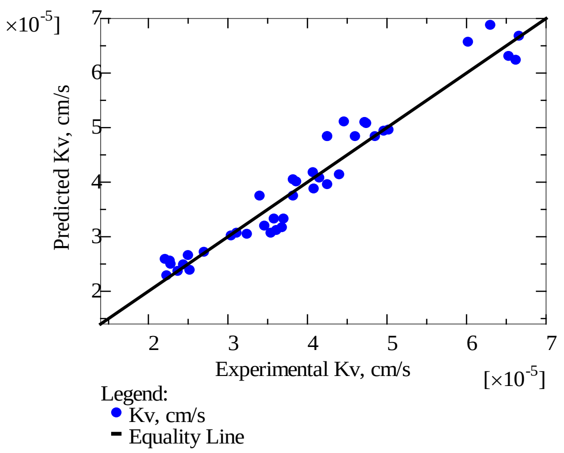

Fig. 8. RSM Equality Line for Kv

4. CONCLUSION

Each soil mixture (100S, 100FA, 100B, 96S4B, 50FA50S, 75FA25S, 25FA75S, 96S4FA and 96S2B2FA) underwent rigorous laboratory tests such as specific gravity tests, particle size analysis, Atterberg limit tests (liquid limit and plastic limit), relative density tests (e_{max} and e_{min} tests) and permeability tests to determine the most viable permeability characteristic of the various soil mixes of soil, fly ash and bentonite for cut-off wall.

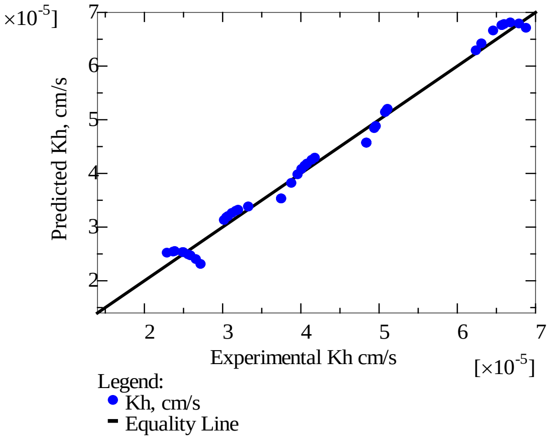

Fig. 9. RSM Equality Line for Kh

As a criterion in selecting the viable mixture for the cut-off wall, it was recommended that the minimum permeability requirement of x10^{-7} cm/s for a cut-off wall. In the previous study of Baxter [2], it 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 [16], 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 [2]. 96S2B2FA was tested, it uses 2% fly ash, which replaces half of the recommended bentonite percentage of Baxter [2]. 96S2B2FA's permeability ranges: (1) vertical oriented 6.29x10^{-07} cm/s to 9.60x10^{-07} cm/s and (2) horizontal oriented 8.04x10^{-07} cm/s to 9.87x10^{-07} cm/s which is relatively above the minimum requirement. Thus, 96S2B2FA is a viable mixture for the cut-off wall.

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