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Feasibility of the use of physical modeling to estimate the permeability of the soil-waste sludge mixture

Faisabilité de l'utilisation de la modélisation physique pour estimer la perméabilité du mélange sol-boues résiduaires

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ABSTRACT: One of the major problems associated with population growth, urban expansion and industrial development is the generation of urban and industrial solid waste. In this context, the growing generation of waste sludge has become a major concern worldwide. Taking into consideration that landfills require a large amount of cover material, the evaluation of the feasibility of using this waste for the construction of landfill cover layers becomes an important research subject. The present work aims to evaluate the permeability behavior of waste sludge mixed with soil by conducting permeability tests using conventional and centrifuge tests. Results of this research demonstrate that for the same compaction conditions of the layers, the centrifuge tests allow estimating the permeability coefficient. Moreover, this tool allows performing tests much faster than conventional tests.

RÉSUMÉ:L'un des principaux problèmes liés à la croissance démographique, à l'expansion urbaine et au développement industriel est la génération de déchets solides urbains et industriels. Dans ce contexte, la génération croissante de boues de déchets est devenue une préoccupation majeure dans le monde entier. Considérant que les sites d'enfouissement nécessitent une grande quantité de matériau de couverture, l'évaluation de la faisabilité de l'utilisation de ces déchets pour la construction de couches de couverture de décharge devient une question de recherche importante. Le présent projet de recherche vise à évaluer le comportement de la perméabilité des boues résiduaires mélangées au sol en effectuant des tests de perméabilité à l'aide de tests classiques et de centrifugation. Les résultats de cette recherche démontrent que, pour les mêmes conditions de compactage des couches, les tests de centrifugation permettent d'estimer le coefficient de perméabilité. De plus, cet outil permet d'effectuer des tests beaucoup plus rapidement que les tests conventionnels.

Keywords:waste sludge; landfill; permeability; centrifuge test;

1 INTRODUCTION

One of the major problems associated with population growth, urban expansion and industrial development is the generation of urban and industrial solid waste. The decomposition of this waste gives rise to gases and liquids that contain substances capable of contaminating soils, surface water and groundwater. In this context, the growing generation of waste sludge

from wastewater treatment plants (WWTP) has become a major concern worldwide. This is because the disposal of this waste can lead to environmental contamination and when destined to sanitary landfills can quickly consume the useful life of these structures. Taking into consideration that landfills require a large amount of cover material, such as natural soil deposits exploited at a high financial and energy cost, the evaluation of the feasibility of using this waste for the construction of landfill cover layers becomes an important research question.

Biosolid is the techinal term of waste sludge resultant of treatment process. One treatment method consists in mixing lime to the waste sludge in proportions between 30% and 50% of the dry weight of the sludge. This process increases the temperature at an early stage and causes a change in the pH of the sludge, reducing the presence of pathogens and, consequently, making it possible to recycle the treated sludge (SANEPAR, 1999).

In this sense, the present research project aims to evaluate the geotechnical behavior of biosolid from wastewater treatment plants, mixed with soil by conducting geotechnical characterization and permeability behavior. Permeability will be conducted using conventional permeability tests and geotechnical centrifuge tests.

Physical modeling through centrifuge tests is an available tool in geotechnical engineering where soils can be analyzed using a model that simulates an event related to a defined prototype. Singh and Gupta (2011) showed that permeability values estimated by centrifuge tests may be representative mainly for falling head method.

The results of this work will be used for the development of a physical model to evaluate, through centrifugal tests, the behavior of permeability in a compacted layer. Besides that, centrifuge modeling is an excellent alternative to accelerate the measurement of permeability in the laboratory. This approach differs from various studies that have been carried out, since it allows the evaluation of field conditions through physical modeling.

2 MATERIALS AND METHODS

2.1 Materials

The biosolid was colected from Alvorada Wastewater Treatment Plants (WWTP) located in North Region of Maringa city, Parana state, Brazil (Figure 1) under administration of Sanitation Company of Paraná (SANEPAR). The sewage sludge is submit to an alkaline stabilization process through lime addition (30% to 50% of dry mass).

Figure 1. Alvorada Wastewater Treatment Plants (WWTP).

The natural soil is from a site located in the city of Mandaguaçu, Northern region of Parana state, Brazil. The soil was collected in a superficial layer from the Caiua Sandstone composed of sand clayey and classified as a red dystrophic latosol (Silva et al, 2015). Figure 2 shows the soil and biosolid used in this work.

2.2 Geotechnical characterization

Figure 3 shows the grain size distribution of the natural soil (S), biosolid (B) and the S_B mixture using 50% proportion of each material. The soil is a clayey sand classified as SC (SUCS Classification). Biosolid is composed of 34.3% of organic material. Thus, the biosolid and the mixture are classified as silty sand (SM) with fine

organic. Table 1 present the results of the geotechnical characterization of the materials.

Figure 2. Materials.

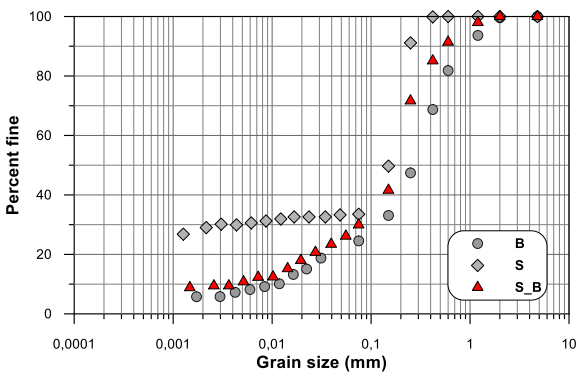


Figure 3. Grain size distribution.

Table 1. Results of geotechnical characterization of materials.

Geotechnical parameters	S	B	S_B
Gravel content (%)	0	0	0
Sand content (%)	66.7	72.8	72.8
Silt content (%)	4.7	21.7	17.8
Clay content (%)	28.6	5.5	9.4
Liquid limit (%)	28	NP*	NP*
Plasticity index	12	NP*	NP*
Particle density (g/cm³)	2.70	2.14	2.46

NP*: Non-plastic material.

2.3 Compaction parameters and specimens

Compaction tests were carried out to assess optimum water content and maximum dry unit weight for the natural soil (S), biosolid (B), and soil-biosolid (S_B) mixture. Proctor compaction tests were performed using standard effort. Natural soil, biosolid, and soil-biosolid mixture compaction test results are shown in Table 2 and Figure 4.

Table 2. Results of compaction parameters.

Parameter	S	B	S_B
γ_{dmax} (kN.m^{-3})	18.79	9.08	13.62
w_{op} (%)	12.57	35.25	22.55

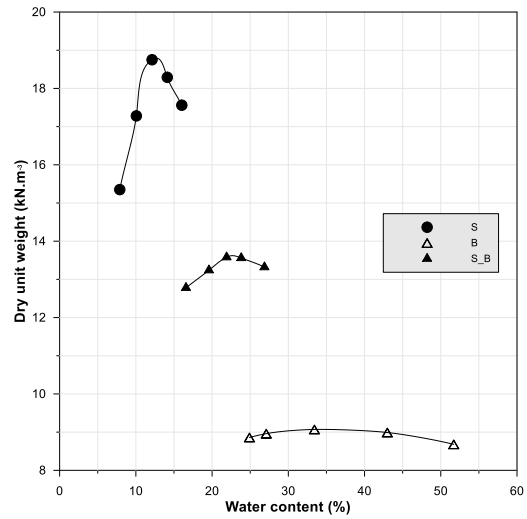


Figure 4. Compaction curves.

Results show that the maximum dry unit weight is higher for natural soil and the water content is higher for biosolid. During the compaction, it was observed that biosolid shows a hydrophobic behavior which makes the homogenization process harder. This behavior might be related with the presence of organic grease or oil in this material. By this factor, the points of the curve were separated by more than 2%, as recommended by Brazilian Standard (ABNT, 2016). The compaction parameters of biosolid found in the literature are very variable,

but show similar behavior: higher optimum water content and lower maximum dry unit weight.

Initially, for specimen preparation, soil and biosolid were mixed. Next, water was added, in a mixture reaching a water content similar to the optimum water content corresponding to the equivalent compaction curve. The sample diameter and height were 50 mm and 100 mm, respectively (Figure 5). The specimens were wrapped in waterproof plastic and stored (wet room) before testing.

(a) molding of specimens

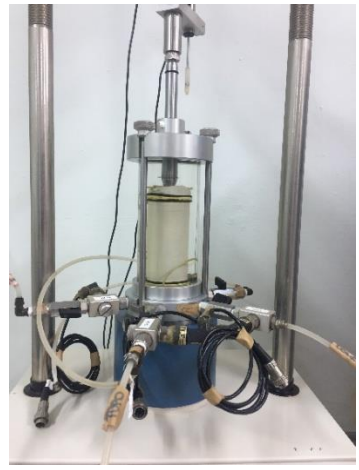
(b) specimens

Figure 5. Specimens preparation.

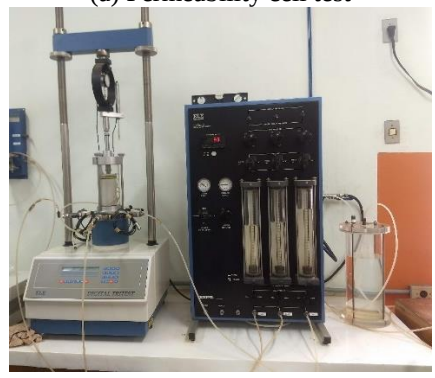
2.4 Permeability tests (Flexible wall permeameter)

Permeability of the materials was measured using Tri-Flex test system (Figure 6) according to procedures of ASTM D5084-03. The saturation started with initial pressures of 50, 40 and 30 kPa for confining, bottom and top pressure of sample, respectively. The direction of water flow is from the bottom to top of sample. The increment of pressure was 50 kPa until reaching 250 kPa of confining pressure.

The sample was considered saturated when the bottom and top graduated burrete readings have maintained the same rate of variation in the same time interval.



(a) Permeability cell test



Tri-Flex system

Figure 6. Permeability test.

The permeability (k) was calculated by Equation 1, where a is the burette (water reservoir) area, A and L are the soil sample cross-sectional area and length, t is the time interval t_2 - t_1, $h(t_1)$ and $h(t_2)$ are the head loss across the sample at times t_1 and t_2, and PB is the applied pressure.

$$k = \frac{aL}{2At} \cdot ln[\frac{PB+h\,(t_1)}{PB+h\,(t_2)}] \qquad (1)$$

2.5 Centrifuge tests

The Federal University of Rio de Janeiro (UFRJ) mini geotechnical beam centrifuge (Figure 7)is a piece of equipment that can work under high acceleration (around 300 times inertial acceleration), subjecting small-scale geotechnical model to tests that are representative of real conditions in accordance with well-established dimensional and time scaling rules (Lukiantchuki et al., 2018).

Figure 7. Geotechnical beam centrifuge (Almeida et al., 2014).

Permeability was measured using an internal and external tank connected in a hydraulic pump (capacity of 100 kPa) to suck up the percolated liquid (Figure 8). Tests were conducted using a 50 times gravity acceleration (N=50).

The saturation phase was conducted through the water percolation equivalent to two times the void volume ($2V_v$). After that, water was percolated and the volume of the waterwas collected at predefined time intervals.

Permeability coefficient was estimated by Darcy law and using the falling head method. After tests, the saturation of the layer was confirmed by water content.

The compaction of layer was done using compaction curve parameters and reaching a compaction degree not less than 95%. The control of compaction was based on water content and dry unit weight of the material. Figure 9 illustrates the procedure of compaction layer used in this work.

3 RESULTS AND DISCUSSION

3.1 Permeability tests (Flexible wall permeameter)

Figure 10 shows the permealibity values for natural soil. The average value was about 4.65×10^{-6} cm.s^{-1}, the standard deviation (SD) and the coefficient of variation (CV) was about $1.40 \times 10^{-6}$and 30,1%, respectively

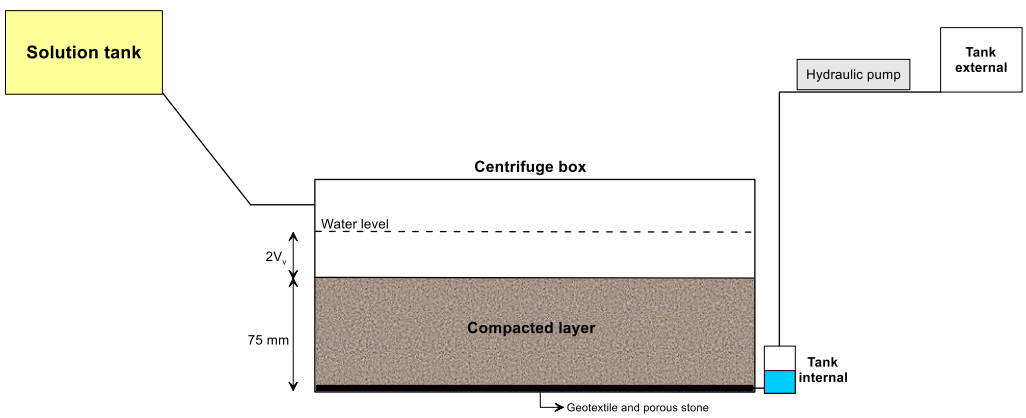


Figure 8. Centrifuge system to collected the leachate.

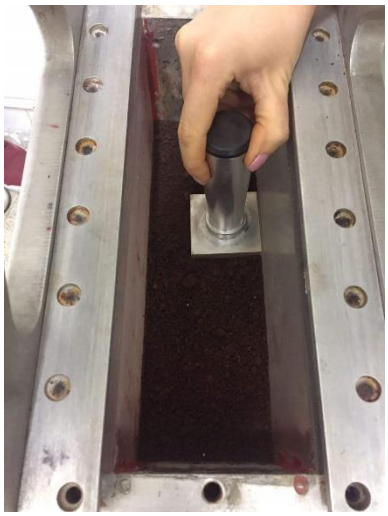


Figure 9. Manual procedure for compaction layer.

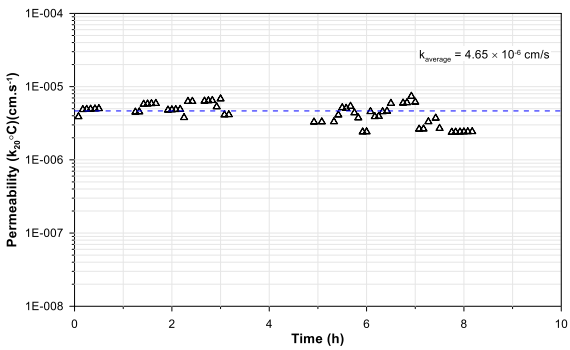


Figure10. Permeability for natural soil.

Results were evaluated considering three different tests. Table 3 and Figure 11 demonstrate a good agreement between the results.

Table 3. Statistical results.

Test	$k_{average}$ (cm.s^{-1})	SD	CV (%
1	2.18×10^{-6}	4.47×10^{-7}	21
2	6.38×10^{-6}	1.52×10^{-6}	24
3	4.66×10^{-6}	1.25×10^{-6}	27

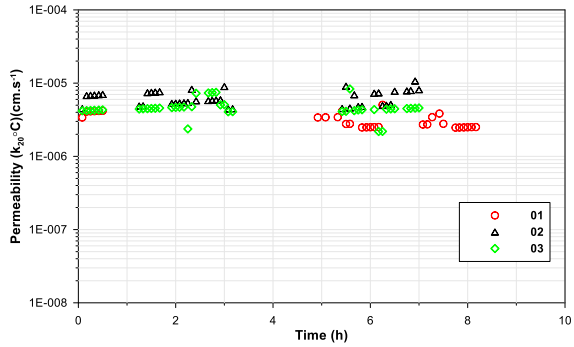


Figure 11. Permeability for natural soil.

Figure 12 shows the permealibity values for soil and biosolid mixture. The average value was about 3.36 × 10^{-6} cm.s^{-1}, the standard deviation (SD) and the coefficient of variation (CV) was about 1.40 × 10^{-6} and 41.4%, respectively. Results show that permeability values of soil and soil_biosolid mixture are very similar.

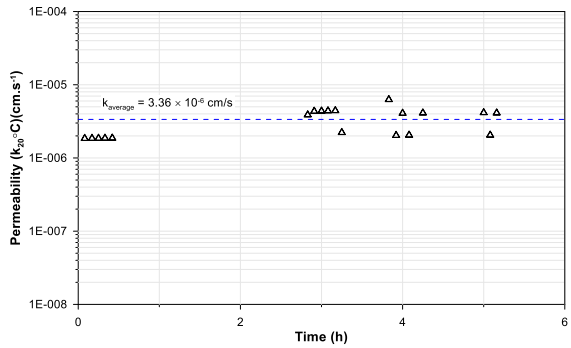


Figure 12. Permeability for soil and biosolid mixture.

3.2 Centrifuge tests

According to Madabhushi (2014) the permeability coefficient (k) is the same in model and prototype conditions which leads to a ratio between seepage velocity in model and prototype scales equal to N and a ratio between seepage time in model and prototype scales equal to N^2.

Permeability values were evaluated considering thefalling head method. The leachete was collected every 10 minutes. As the area of centrifuge box is fixed, the variation of hydraulic head was calculated by controlling the volume

percolated through the compacted layer. The hydraulic gradient was about 1.44 to 1.84.

Figure 13 shows the permeability values for natural soil. The average value was about 1.40×10^{-6} cm.s^{-1}, the standard deviation (SD) and the coefficient of variation (CV) was about 2.41×10^{-7} and 1.7%, respectively.

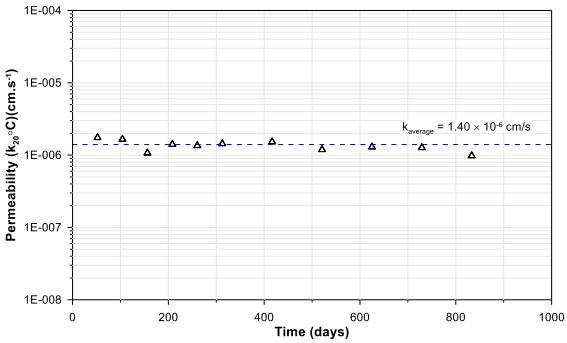


Figure 13. Permeability for natural soil (prototype).

Comparison between flexible wall permeameter and centrifuge results for the natural soil show that the coefficient of permeability values (k) are similar. Centrifuge tests allowed to estimate a value around30% of flexible wall permeameter tests. Considering that the coefficient of permeability is a geotechnical parameter that shows a significant variability, results were considered satisfactory.

Figure 14 shows the permeability values for soil and biosolid mixture. The average value was about 3.19×10^{-5} cm.s^{-1}, the standard deviation (SD) and the coefficient of variation (CV) was about 8.10×10^{-6} and 25.4%, respectively.

Comparison between flexible wall permeameter and centrifuge permeability results for the S_B mixture show that centrifuge tests values were around 4 times those of the flexible wall permeameter tests. However, this different behavior may be associated with the preparation of the mixturetested. Centrifuge tests were very fast and performed immediately after the compacted layer, leavingno time for cure to happen. On the other hand, flexible wall permeameter tests were performed after 30 days of cure. As, biosolid is composed of 30 to 50% of lime, it is expected that the permeability decreases after cure time atributted to the creation of chemical bonds and aggregation (Galvão et al., 2004). The cure time allows the slow continuing chemical reaction and develops additional cementing products sufficient to fill the voids at least partially. Figure 15 shows a microscope image where it is possible to see the presence of lime filling the pores.

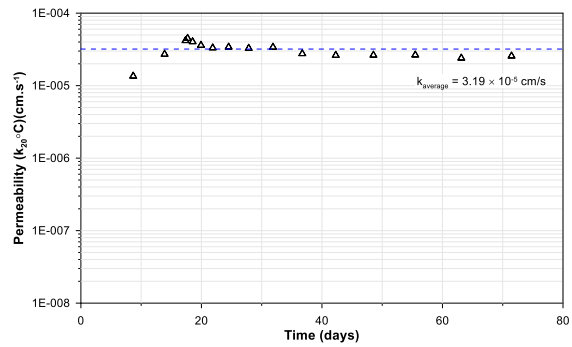


Figure 14. Permeability for soil and biosolid mixture (prototype).

4 CONCLUSIONS

The suitability of centrifuge tests for estimating permeability coefficient was evaluated through a series of tests. Tests were performed using a soil compacted layer and a soil-biosolid mixture compacted layer. The coefficient of permeability was estimated by a conventional flexible wall permeameter and a mini geotechnical beam centrifuge. By analyzing the data, the following conclusions can be drawn.

1. Geotechnical characterization tests show that biosolid is basically composed of organic material with granulometry similar to sand. Material does not show a plastic behavior;
2. Compaction parameters show that the maximum dry unit weight is higher for natural soil and the water content is higher for biosolid;
3. For natural soil, the coefficient of permeability estimated by conventional flexible wall permeameter and a mini geotechnical beam centrifugeweresimilar;

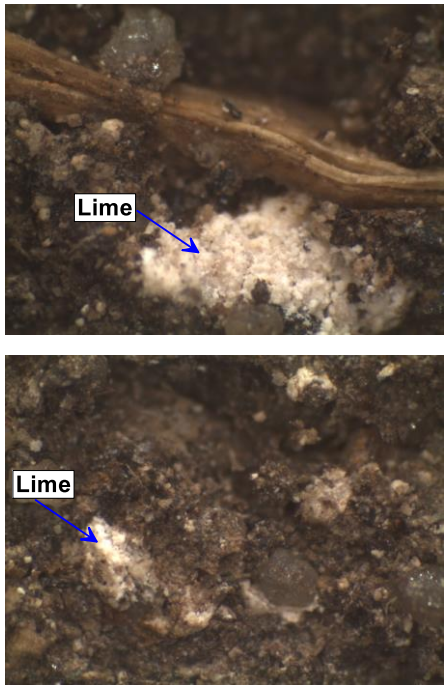


Figure 15. Lime filling the matrix pores

4. For soil and biosolid mixture, the coefficient of permeability estimated by centrifuge tests was 4 times higher than those from the flexible wall permeameter tests. Difference can be associated with the cure time of the compacted layer, since biosolid is composed of lime and chemical bonds and aggregation can develop with the time;

5. The behavior of the permeability of the mixtures should be better evaluated considering the same conditions of curing time.

The results of this research demonstrate that for the same compaction conditions of the layers, the centrifuge tests allow estimating the permeability coefficient. Moreover, this tool allows performing tests much faster than conventional tests and with lower variability of results.

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