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EVALUATION OF WATER PERMEABILITY IN COMPACTED SAND-BENTONITE LINERS FROM LANDFILL USING PLANNING AND FACTORIAL ANALYSIS

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Highlights:

- the use of an experimental design with two approaches, making it possible to carry out a minimum number of tests with a high level of confidence (95%). This guarantees the viability of experimental research, especially for primary analysis of the influence of variables in models;
- designs with response surfaces (flat and curved) were obtained to understand the behavior of water permeability, varying the geotechnical factors for simulated compacted clay liners. Thus, it is possible to predict the behavior of permeability in these layers with other soils in the region and optimize the process of design and execution of basement waterproofing for landfills;
- according to the study carried out, it was found that the factors that most influence water permeability are the compaction energy and the percentage of bentonite added to the layer. With this, it is possible to control such factors, in order to guarantee the best waterproofing in the CCL of the sanitary landfills and guarantee the environmental safety in the landfills. However, the results also show the need to control for other factors not addressed in this study, indicated in the results and discussions section.

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Abstract. Compacted Clay Liners (CCL) are designed to prevent environmental contamination in landfills. These layers are designed with low permeability soils, which are difficult to obtain. To this end, bentonite can be added. The objective of this work is to evaluate the reliability of factor analysis on the hydraulic performance of sand-bentonite mixtures. Two types of designs were used, with the variables controlled: compaction energy (CE), water content (U) and percentage of bentonite (B). Experimental layers were made to obtain water permeability (kw). The results showed that CE and B are, respectively, the factors that most influence permeability. The application of adequate energy promotes better accommodation of bentonite soil particles in the voids in the sand, which, when moistened, undergo an expansion process, reducing the voids in the layer. All of these parameters can be optimized by using a curvature design to obtain kW. Therefore, knowledge of CCL kw is essential to ensure the safety of the local environmental environment.

Keywords: landfill, compacted clay liner, water permeability, bentonite, factorial analysis, response surface.

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1. Introduction

Compacted clay liners (CCL or liners) are used as a secondary linning for waterproofing the base of Sanitary Landfills, as a strategy of isolation between the external environment of the Urban Solid Waste cells (MSW) and the contaminating compounds contained inside the sanitary cell. Commonly, these compacted liners can be built by clayey soils that present low water permeability coefficient values. This permeability must present values lower than 10^{-9} m/s, as specified by United States Environmental Protection Agency (USEPA, 1993), or 10^{-8} m/s, as established by ABNT (1997) to brazilian soils, with the aim of providing environmental safety to the system (Daniel, 1993; Meier & Shackelford, 2017; Fu et al., 2021).

When the soil deposits near the work being implemented, used for the base liner, do not comply with the technical parameters of permeability, materials that improve this waterproofing capacity can be added, such as bentonite (Wu et al., 2017; Arifin & Sambelum, 2019; Gupt et al., 2020). The use of this bentonite soil is justified by its mineralogical characteristics of high cation exchange capacity, high specific surface and expansion capacity (Gleason et al., 1997).

The increase of bentonite in base liners can result in an increase in the adsorption capacity of the soil and in a decrease in the permeability of the liner. However, excessive increments can promote the appearance of uncontrolled expansive processes in the liner (Amadi & Odedede, 2019). Therefore, identifying the ideal bentonite increment value in the soil mixture is a fundamental factor for the technical performance of the liners.

The efficiency of these base liners also depends on several geotechnical factors, among which it can be highlighted, in a more evident and easily controllable way in the execution, the water content and the compaction energy used to obtain the liner (Bressan Jr. et al., 2022). Commonly, these factors are studied in isolation, through compaction and water permeability tests (Daniel & Benson, 1990; Daniel & Wu, 1993; Yeo et al., 2005; Kang & Shackelford, 2010; Morandini & Leite, 2015; Falamaki et al., 2018; Rashid et al., 2021). Often, tests are carried out without prior statistical planning, following the sensitivity and experience of researchers in conducting experiments, isolating a certain parameter and seeking to understand the bio-physical-chemical processes involved in the processes.

One way to plan the experiments and obtain the results, in an optimized way, with a minimum number of tests and high statistical reliability, is through the Factorial Design technique. This method uses the spatialization of data from controlled experimental variables, with defined limits, and allows analyzing the significance of the effects of factors on a response variable. This technique can help in understanding the causes and effects between the variables of a problem (Salerno et al., 2018; Raychaudhuri & Behera, 2020). In this way, the use of analyzes, with statistical reliability, that take into account the effects of geotechnical factors and the interactions between them in the permeability of the soil liners, has become a challenge, mainly due to the enormous variability of characteristics of Brazilian soils.

The main contribution of this study lies in the optimization and concomitant analysis of several factors that influence the behavior of the permeability of this soil liner, enabling speed, economy and safety in the execution of waterproofing works in sanitary landfills. With experimental data, it is possible to quickly predict the water permeability of soils with similar characteristics and analyze whether a new deposit is viable for use as CCL. Furthermore, the models obtained can assist in manipulating the controlled variables to achieve the required waterproofing.

Therefore, the objective of this research is to evaluate the reliability of the use of factor analysis in the water permeability performance of compacted sand-bentonite layers used as base liner for landfills.

2. Methodology

2.1. Materials used

Mixtures of two types of soils were used, which are used in the execution of the base liner of a Landfill located in the municipality of Campina Grande (ASCG), State of Paraíba (Brazil). This landfill is located in a region with a semi-arid climate, with high average temperatures and low precipitation throughout the year. Drill holes carried out in the region demonstrated the absence of a water table at least 30 meters deep, demonstrating a thick layer of unsaturated soil, typical of Brazilian semi-arid regions.

The first soil is obtained from deposits in the area of the ASCG enterprise itself. This soil was classified by the Unified Soil Classification System (USCS) as poorly graded clayey sand, with a grain density of 26.9 kN/m³ and hygroscopic content of 0.56%. It is a sandy soil typical of the region, with permeability of the order of 10^{-7} m/s, low liquid retention capacity, mainly due to the mineralogical composition predominantly composed of quartz grains.

The second soil used in the mixture was collected from a deposit in the municipality of Boa Vista – Paraiba (Brazil). It is predominantly clayey and was identified as calcium bentonite, with a plasticity index (PI) of 124.00%, grain density of 27.5 kN/m³ and hygroscopic humidity of 7.78%. This soil demonstrates a high capacity for expansion and liquid retention, justifying the presence of montmorillonite clay minerals, with high waterproofing capacity.

Then, from an experimental planning, specimens with mixtures of the two types of soils and variations of geotechnical parameters were made, with the objective to analyze how the interaction between the geotechnical parameters of the layers can interfere with the performance of base layers of landfills.

2.2. Planning of experiments

The experiments were carried out based on a 2k factorial design. Two types of procedures were performed: the Composite Design with Central Point (CDCP) and the Composite Central Rotational Design (CCRD). The CDCP allowed varying the data on a flat behavior surface, with flexibility in different experimental situations, obeying a minimum number of necessary experiments and a high degree of statistical reliability. The CCRD, in addition to complying with reliability criteria and a minimum number of tests, allows verifying the behavior of the data with the inclusion of curvature (axial points) in the model. For this purpose, central and axial points were inserted in the designs, as described by Rodrigues and Iemma (2009), obtaining the constant number of experiments in Equations (1) and (2):

$$N_{CDCP} = 2^k + n_c; \quad (1)$$

$$N_{CCRD} = 2^k + n_c + 2 \times k, \quad (2)$$

where: N_{CDCP} = number of tests for CDCP; N_{CCRD} = number of trials for the CCRD; k = number of test factors planned; n_c = number of center points.

The experiments were planned with two levels (minimum and maximum), three factors were used, which are Compaction Energy (EC), Water content (U) and Bentonite increment percentage (B). These factors are considered controllable or independent variables, as they can be easily manipulated when carrying out experiments. Furthermore, they were inserted 3 central points (n_c), which are important to reduce the pure error, present in the design, as indicated by Raychaudhuri and Behera (2020). The response variable of the proposed variations was the water permeability coefficient in the saturated condition (k_w). According to the number of tests in the factorial design, the planning matrix is obtained (Table 1).

Table 1. Experiment planning matrix

Experiments	EC (MN.m/m³)	U (%)	B (%)	k_w (m/s)
1	0.47	8.24	10.00	R1
2	0.70	8.24	10.00	R2
3	0.47	18.24	10.00	R3
4	0.70	18.24	10.00	R4
5	0.47	8.24	30.00	R5
6	0.70	8.24	30.00	R6
7	0.47	18.24	30.00	R7
8	0.70	18.24	30.00	R8
9 (C)	0.59	13.24	20.00	R9
10 (C)	0.59	13.24	20.00	R10
11 (C)	0.59	13.24	20.00	R11
12 (A)	0.39	13.24	20.00	R12
13 (A)	0.77	13.24	20.00	R13
14 (A)	0.59	4.83	20.00	R14
15 (A)	0.59	21.65	20.00	R15
16 (A)	0.59	13.24	3.18	R16
17 (A)	0.59	13.24	36.82	R17

Note: (C) = central points; (A) = axial points.

The EC, U and B values were based on the central point (average values) of what has been carried out in the field when implementing this base liner. The central compaction energy was Proctor Normal, varying more and less depending on each model. The CDCP design varied the EC value by ±20% in relation to the central energy. For CCRD, this energy varied around ±32%. The central water content was obtained using the Proctor Normal Compaction Test on the sample with medium bentonite content, the latter being 20%. The variation of these values promotes a sweep between the minimum and maximum, making it possible to obtain appropriate models. It is worth mentioning that the different variations between the CDCP and CCRD models are justified by the need for greater coverage of values to obtain the curvature of the second model.

Experiments numbered 1 to 11 are used for CDCP and experiments 1 to 17 are for CCRD. The 17 specimens were compacted according to the indicated factors and levels. The results (R1 to R17) were obtained through tests of permeability to variable load in a rigid wall permeameter, following the recommendations of ABNT (2000), with non-prehydrated samples.

2.3. Analysis of water permeability behavior in base liners of compacted soil

After obtaining the results of water permeability for each of the tests, factor analysis was carried out with the aid of the Statistica® 12.0 Software, obtaining statistical tests of analysis of variance, Pareto chart, models of permeability behavior and response surfaces for each designed model.

The permeability coefficient standards, established for the base layer configuration of this study, followed values of the order of 10^{-9} m/s (USEPA, 1993) or 10^{-8} m/s (ABNT, 1997). The value established by ABNT (1997) is valid for regions with a thick unsaturated zone of soil, with no detection of water level at least 3 meters deep, such as the case under study.

The response surfaces obtained by the designs indicated in the factorial design show the behavior of soil water permeability by varying the levels of the proposed factors, whether for trends of flat or curved surfaces. An analysis of variance was performed, with a significance level of 5%, and, through the pvalue, it is possible to verify the variables that have a significant influence on the behavior of the model. The studied designs provide a 95% reliability in the model.

For the knowledge of water permeability in the base liner, the CDCP and CCRD present different behaviors, mainly due to the inclusion of quadratic terms in the latter. So, it was necessary to select the model that best fits the experimental data, in view of the predictive knowledge of the presented soil.

In the analysis of the models for the case under study, 2 tests were used: Coefficient of determination (R^2) and Mean Squared Error (MSE). The R^2 and EQM values are calculated by Equations (3) and (4), respectively.

$$R^2 = \frac{\sum_{i=1}^{n}\left(X_e - \bar{X}\right)^2}{\sum_{i=1}^{n}\left(X_0 - \bar{X}\right)^2}; \quad (3)$$

$$MSE = \frac{1}{n} \times \sum_{i=1}^{n}\left(X_0 - X_e\right)^2, \quad (4)$$

where: n = number of observations; X_0 = observed variables; X_e = estimated variables.

The R^2 varies between 0 and 1, and the closest to 1 indicates that the observed values are close to the behavior estimated in the model, that is, the best explained is the variability. The smaller the MSE value, the better the fit of the data obtained to the retention curve equation, that is, the smaller the residuals generated by the difference between the observed and estimated values (Montgomery, 2009). With the results of these tests, it was possible to select the model that presented the best fit, being able to represent the behavior of water permeability in saturated condition for the soil according to the studied factors.

3. Results and discussions

3.1. Responses from the design of experiments

Table 2 shows the results obtained in the water permeability test for the tested samples. With variations in the proposed factors, the values of the water permeability responses vary from $1.90.10^{-6}$ to $8.00.10^{-9}$ m/s. This study was carried out on samples with saturation levels greater than 95%. The water permeability values presented for the soils, when compared with typical values presented by Das (2010), show that the mixtures varied between silts (10^{-6} to 10^{-8} m/s) and clays ($<10^{-8}$ m/s). Such results are acceptable, considering that sand and bentonite clays are being mixed in varying proportions. However, it must be taken into account that, in addition to the type of soil, other factors also influence the permeability behavior of compacted soils, such as compaction energy and humidity.

It should be made clear that permeability values in the order of 10^{-6} and 10^{-7} m/s are high for use in the base liner, which can cause serious environmental problems, such as leakage of leachate through this liner (Gonçalves & Sturaro, 2010). However, in regions with a thick unsaturated zone without the presence of a water table close to the surface, such as the case under study, Silva et al. (2022) stated that the value of this permeability can be reduced by 100 to 1000 times, making this layer low permeability. Furthermore, adjustments to compression factors can correct this permeability.

Figure 1 shows the Pareto Chart for the CDCP (Figure 1a) and for the CCRD (Figure 1b). In the CDCP, it is verified that all the studied factors have influence in obtaining this permeability, exceeding the significance level of 5%. It appears that the combined effect of compaction energy and bentonite increment (EC + B) have a greater influence on the permeability result, followed by B (alone). All factors are significant for the process, with a less expressive effect for the interaction between water content and the increased percentage of bentonite (U + B).

In Figure 1b, EC (square plot), EC + B and B (square plot) show the most influential effects in obtaining the permeability result for the CCRD. The graphs indicate that increasing humidity has an increasing effect on kw values. The opposite behavior is verified from the increase in the percentage of bentonite and in the compaction energy, which produce a reduction in permeability. These typical behaviors are verified in studies by Daniel and Benson (1990), Kenney et al. (1992), Stewart et al. (2003), Morandini and Leite (2015) and Middelhoff et al. (2020). The coefficient of determination (R^2) for the CDCP was 0.7, which demonstrates that approximately 70% of the process variability can be explained by the generated model. For the CCRD, this value was 80%.

As the pvalue of all studied parameters for the two designs were lower than the significance level ($p_{value} < 0.05$), it can be stated that all studied parameters have influence on water permeability (Montgomery, 2009), suggesting that the choice of variables was correctly selected for the case, which does not prevent the inclusion of new factors in future studies.

3.2. Analysis of water permeability behavior

The behavior of water permeability in the base liner, delineated by means of CDCP and CCRD, are described by Equations (5) and (6), respectively.

$$k_{wCDCP} = 33.98 - 36.60.EC + 1.65.U - 2.10.B - 2.64.EC.U + 2.88.EC.B + 0.01.U.B; \quad (5)$$

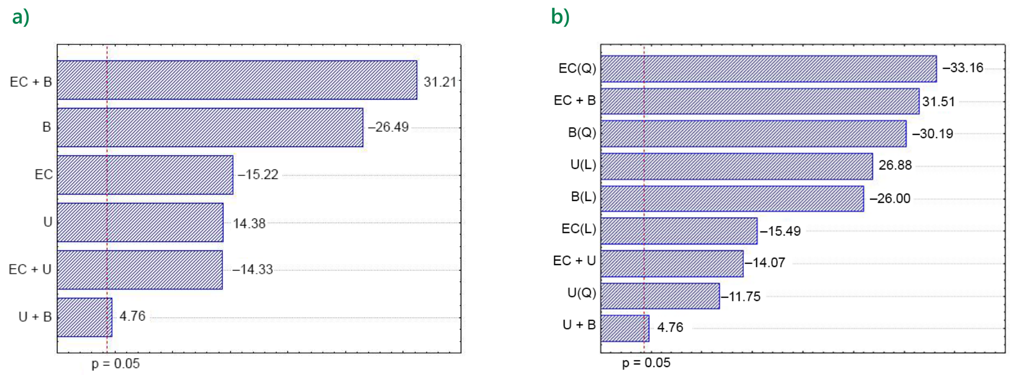
$$k_{w_{CCRD}} = -64.00 + 234.89.EC - 230.49.EC^2 + 2.86.U - 0.04.U^2 - 0.97.B - 0.03.B^2 - 2.59 \times EC.U + 2.90.EC.B + 0.01.U.B, \quad (6)$$

where: EC = Compaction Energy; U = water content; B = Bentonite.

These permeability equations are illustrated in response surfaces, with variation of two factors and the third fixed, in this work established in the central point of each

Table 2. Results of water permeabilities, in m/s, for the proposed designs

R1	R2	R3	R4	R5	R6	R7	R8	R9
$9.03.10^{-7}$	$6.98.10^{-7}$	$1.90.10^{-6}$	$1.09.10^{-7}$	$6.70.10^{-8}$	$2.08.10^{-7}$	$2.88.10^{-7}$	$7.99.10^{-7}$	$1.20.10^{-6}$
R10	R11	R12	R13	R14	R15	R16	R17	
$1.17.10^{-6}$	$1.14.10^{-6}$	$1.73.10^{-7}$	$4.90.10^{-8}$	$1.25.10^{-7}$	$1.15.10^{-6}$	$3.37.10^{-7}$	$8.00.10^{-9}$	



Note: Q = quadratic portion of the model; L = linear portion of the model.

Figure 1. Pareto chart of standardized effects: a) for CDCP; b) for CCRD

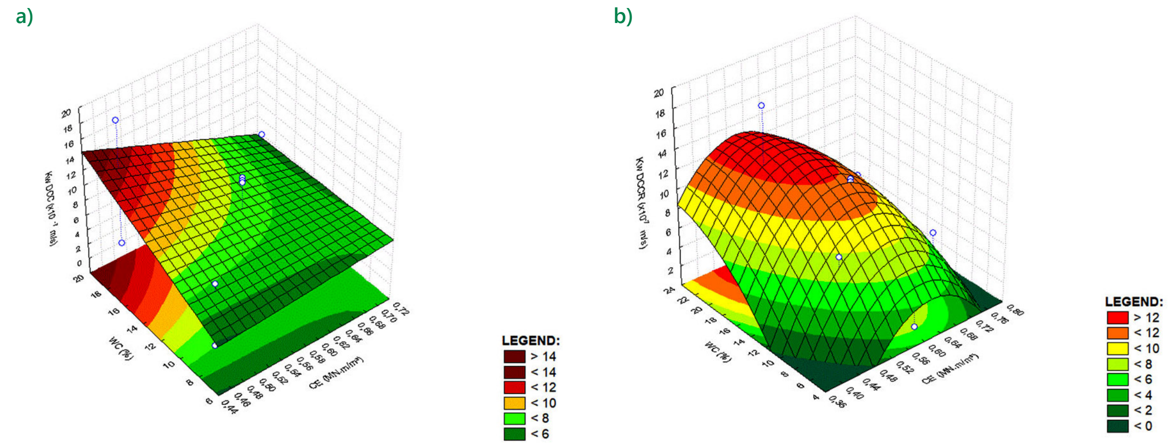


Figure 2. Response surface for Water content x Compression energy: a) for CDCP; b) for the CCRD

factor. The models' responses (water permeability) are on the axis orthogonal to the independent factors.

Figures 2a and 2b show, respectively, the response surfaces obtained for the CDCP models (flat model) and CCRD (model with curvature) involving the Compaction Energy and Compaction Water content factors, with a Bentonite percentage set at 20% (point central).

The EC x U response surface confirms that the higher the humidity, the more compaction energy must be applied to obtain a low permeability coefficient. The increase in compaction energy makes possible greater accommodation of the particles. However, excess energy does not always promote a decrease in permeability, as there may be breakage or rearrangement of particles, allowing interference in the mixture configurations. Since the soil of the mixture is predominantly sandy, in the indicated range of values, there may have been a breakdown of particles for accommodation to occur, allowing the appearance of new preferential flow paths (Watabe et al., 2011; Nasir et al., 2017).

Figures 3a and 3b show the response surfaces for the variables compaction energy and percentage of Bentonite in the mixture, with average Water content fixed at 13.24% (average value). According to the CDCP model (Figure 3a), the increase in compaction energy and Bentonite decreases the water permeability variable. In the CCRD model (Figure 3b) it is possible to verify what was exposed for Figure 3a. The increase in energy and percentage of Bentonite also provides a decrease in water permeability. For high energies, the breaking of the particles becomes beneficial, because, with the humidity fixed at the central point, the sandy soil starts to have a new granulometric configuration, allowing the grains of the bentonite soil to settle more easily in the voids of the liner, allowing sudden decrease in permeability (Nasir et al., 2017).

As Bentonite has a high water retention capacity, fixing the humidity at a central value can allow this soil to expand and further waterproof the liner. The curvature shows that there is an increase in permeability for the range of energy values between 0.44 and 0.56 MN.m/m^3 and percentage of bentonite in the mixture between 8 and 24%. For the indicated energy range, an increase in the percentage of Bentonite is necessary in order to reach low permeability values.

Figures 4a and 4b show the response surfaces for obtaining the permeability variable through the interaction

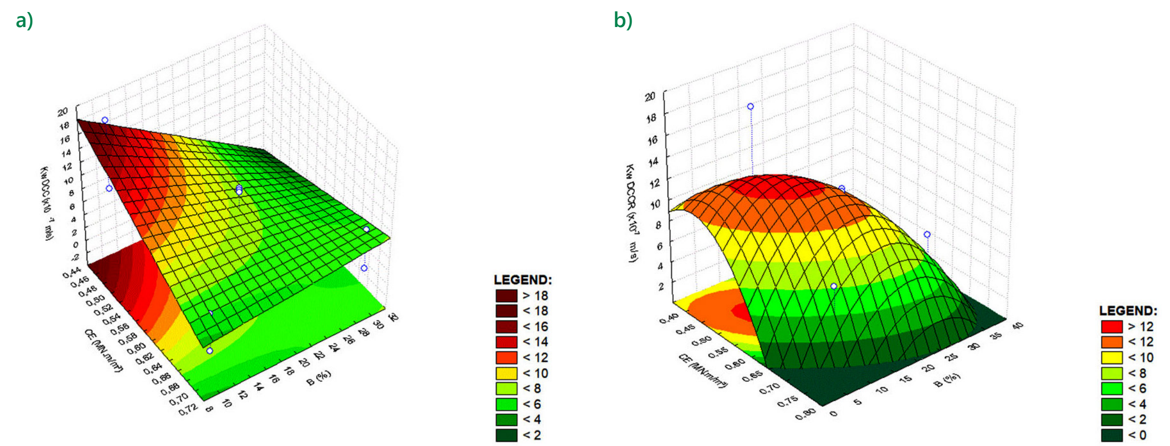


Figure 3. Response surface for Compaction Energy x Bentonite: a) for CDCP; b) for the CCRD

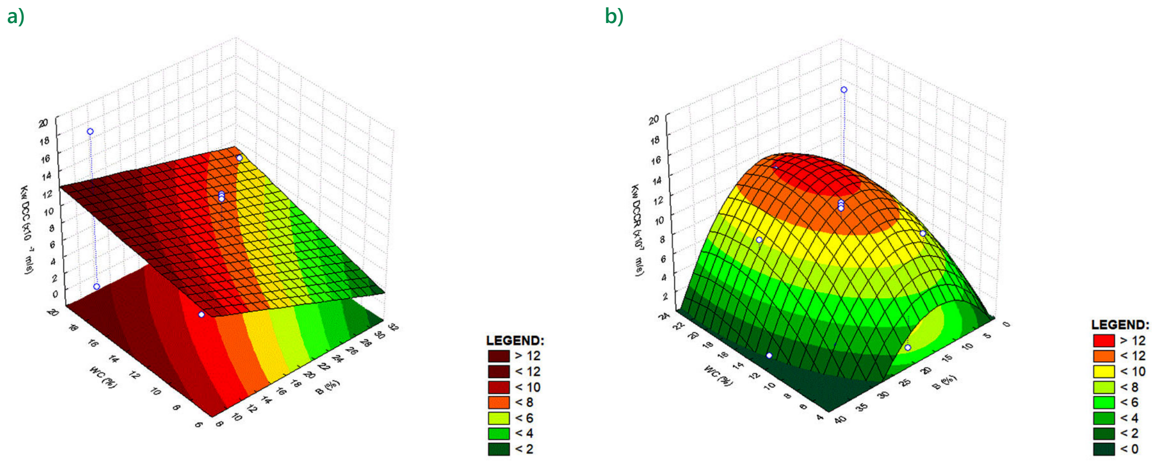


Figure 4. Response surface for Water content x Bentonite: a) for CDCP; b) for the CCRD

between the variables Water content and percentage of Bentonite, with compaction energy fixed at the central point (0.59 MN.m/m³). From the flat model (Figure 4a) it is possible to verify that the increase of Bentonite in the mixture abruptly decreases the permeability to water of the mixture. However, low humidity values do not allow Bentonite to take advantage of its expansion capacity with a view to waterproofing, it is not recommended, for practical purposes, levels below the water content of the central point.

The overall soil behavior is controlled by electrochemical forces existing between clay particles. This soil, which has smectite characteristics (montmorillonite), initially receives Water content and adsorbs it, enabling its expansion. The montmorillonites allow greater water retention in their interior and have a high cation exchange capacity. As soils with a predominance of clay minerals have a high specific surface. Water content is adhered to the particle, becoming adsorbed water (Murray et al., 1997; Azam, 2003; Camapum, 2015).

For the CCRD response surface (Figure 4b), a sharp change in the trend of decreasing permeability can be seen in relation to the model in Figure 5a. It is possible to verify that there is a tendency of increase of the permeability to the water in the range of values of humidity of 14 to 22% and of percentage of Bentonita between 12 and 22%. For high humidities, this percentage of B around the indicated range may be expanding, giving the mixture the appearance of preferential flow paths, increasing permeability in this range.

The experimental (observed) and predicted water permeability values can be seen in Figure 5, for the CDCP (Figure 5a) and CCRD (Figure 5b) designs. It is noticed that the experimental results of the CCRD in relation to the line of predicted values presented better approximations. The increase in the number of tests associated with the use of modeling with curvature may have approximated the results and allowed better comparisons between the approaches.

Table 3 shows the test results for assessing the quality of the CDCP and CCRD. The results of the tests carried out show that the model obtained by the CCRD presented a better adjustment, being a predictive model of greater applicability for the case under study. In this way, it can be said that the model with curvature presented a better fit to the experimental data, being more suitable for calculating the permeability to water in this base liner under study.

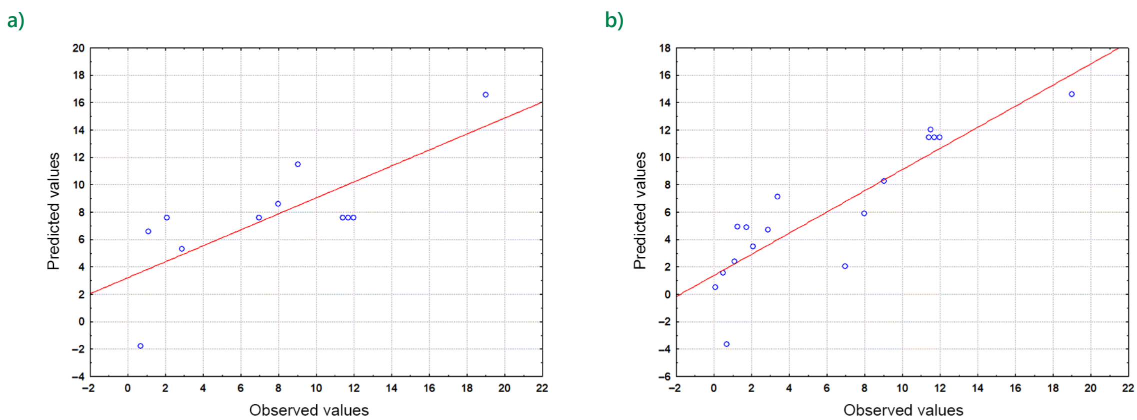


Figure 5. Predicted values x observed values: a) for CDCP; b) for the CCRD

Table 3. Results of criteria for selecting the model with the best fit

Delimitation	Coefficient of determination (R^2)	Mean Squared Error (MSE)
CDCP	0.70	10.82
CCRD	0.80	8.60

In most scientific research, the use of R^2 is the only and predominant factor for choosing the ideal fit. However, as the coefficient of determination concerns only the variability of the results in the model, other tests must be performed to confirm or refute such findings (Montgomery, 2009). In this case, MSE was used as an additional criterion. Such criteria reinforce the reliability of the results, thus allowing greater environmental safety in the project for the execution of base liners of sanitary landfills. The R^2 value for the CCRD model shows that approximately 80% of the phenomena involving water permeability in soil liners can be explained by design.

As the variables studied were Water content, compaction energy and bentonite increment, future studies suggest the inclusion of other variables that may be significant in obtaining the response variable in question, such soil compaction densitity, fluid temperature control, saturation of the specimen, among others, as indicated by Najjar and Basheer (1996), Fattah et al. (2016, 2017, 2022). It is also suggested to analyze characteristics of the percolating fluid and its possible impacts on the permeability of compacted soil layers (Mohammed et al., 2024).

4. Conclusions

From the planning and factorial analysis, it was possible to obtain the permeability of the CCL using the variables compaction energy, mixture Water content and percentage of Bentonite, with a minimum number of tests and a high degree of statistical reliability, thus optimizing the experimental procedure and data analysis.

From the experiments and models carried out in this study, the following conclusions were obtained:

- adequate compaction energy promoted better fit and accommodation between particles. The addition of Bentonite to a predominantly sandy soil made it possible to fill in the pores and consequently reduce the voids in the mixture. The increment this type of clay, when in the presence of water content, presents a significant degree of expansion due to the presence of smectite clay minerals, promoting reduction of porosity and consequent decrease in permeability. This made it possible to meet permeability criteria for base liners in sanitary landfill works.
- the designs were significant and predictive and described, numerically and graphically, the behavior of water permeability in a base liner of a sanitary landfill, with a confidence level of 95%. According to the CCRD it was possible to obtain a better fit of the permeability to the experimental data. This indicates that this design can be used to verify the behavior of this permeability with variations of the studied parameters.
- however, it is noticed that this design can be improved by including other experimental variables in the experiments, such as soil consistency, other compaction methods and energies, partial saturation of the specimens or characteristics of the permeating fluid, which can be controlled in the laboratory, for later application in the field.

Therefore, it is stated that knowledge of the water permeability of these liners is essential to ensure environmental safety around the landfill. Statistical studies applied in this study aim to assist in this guarantee and in decision-making, with a controlled level of reliability.

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Authors contributions

All authors contributed to the conception and design of the study. Material preparation, data collection and analysis were carried out by Silva, T. F., Lyra, M. V. M., Silva, I. F. and Paiva, W. The first version of the manuscript was written by Silva, T. F. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Disclosure statement

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available in the PPGECA/UFCG repository, link: http://www.ppgeca.ufcg.edu.br/dissertacoes-menu/dissertacoes-2017/send/17-dissertations-2017/34-study-of-soil-mixture-for-efficient-waterproofing-of-base-layer-of-sanitary-landfill

References

Amadi, A., & Odedede, O. (2019). Attenuation of contaminants in landfill leachate by lateritic soil enhanced with bentonite. *Geomechanics and Geoengineering*, *14*(6), 348–358. https://doi.org/10.1080/17486025.2019.1670872

Arifin, Y. F., & Sambelum. (2019). Bentonite enhanced soil as an alternative landfill liner in Rikut Jawu, South Barito. *IOP Conference Series: Earth and Environmental Science*, *239*(1), Article 012003. https://doi.org/10.1088/1755-1315/239/1/012003

Azam, S. (2003). Influence of mineralogy on swelling and consolidation of soils in eastern Saudi Arabia. *Canadian Geotechnical Journal*, *40*(5), 964–975. https://doi.org/10.1139/t03-047

Brazilian Association of Technical Standards. (1997). *NBR 13.896: Non-hazardous waste landfills – Criteria for design, implementation and operation*. Rio de Janeiro.

Brazilian Association of Technical Standards. (2000). *NBR 14545: Soil – Determination of the permeability coefficient of clayey soils at variable load*. Rio de Janeiro.

Bressan Jr, J. C., Zampieri, L. Q., Nienov, F. A., Luvizão, G., & Pedroso, M. J. (2022). Evaluating hydraulic conductivity of soil-waste mixtures for use in sanitary landfill waterproof barriers. *Built Environment*, *22*(4), 77–90. https://doi.org/10.1590/s1678-86212022000400629

Camapum, J. C. [orgs]. (2015). *Unsaturated soils in the geotechnical context*. Brazilian Association of Soil Mechanics.

Daniel, D. E. (1993). *Geotechnical practice for waste disposal*. Chapmann & Hall. https://doi.org/10.1007/978-1-4615-3070-1

Daniel, D. E., & Benson, C. H. (1990). Water content-density criteria for compacted soil liners. *Journal of Geotechnical Engineering*, *116*(12), 1811–1830. https://doi.org/10.1061/(ASCE)0733-9410(1990)116:12(1811)

Daniel, D. E., & Wu, Y. K. (1993). Compacted clay liners and cover for arid sites. *Journal of Geotechnical Engineering*, *119*(2), 223–237. https://doi.org/10.1061/(ASCE)0733-9410(1993)119:2(223)

Das, B. M. (2010). *Principles of geotechnical engineering* (7 ed.). Cengage Learning.

Falamaki, A., Eskandari, M., & Homaee, M. (2018). An improved multilayer compacted clay liner by adding bentonite and phosphate compound to sandy soil. *KSCE Journal of Civil Engineering*, *22*, 3852–3859. https://doi.org/10.1007/s12205-018-1554-9

Fattah, M. Y., Salim, N. M., & Irshayvid, E. J. (2016). Experimental study on compressibility, volume changes, strength and permeability characteristics of unsaturated bentonite-sand mixtures. *Engineering and Technology Journal*, *34*(7), 1308–1323. https://doi.org/10.30684/etj.34.7A.5

Fattah, M. Y., Salim, N. M., & Irshayvid, E. J. (2017). Determination of the soil–water characteristic curve of unsaturated bentonite–sand mixtures. *Environmental Earth Sciences*, *76*, Article 201, https://doi.org/10.1007/s12665-017-6511-2

Fattah, M. Y., Salim, N. M., & Irshayvid, E. J. (2022). Influence of soil suction on swelling pressure of bentonite-sand mixtures. *European Journal of Environmental and Civil Engineering*, *26*(7), 2554–2568. https://doi.org/10.1080/19648189.2017.1320236

Fu, X. L., Zhang, R., Reddy, K. R., Li, Y. C., Yang, Y. L., & Du, Y. J. (2021). Membrane behavior and diffusion properties of sand/SHMP-amended bentonite vertical cutoff wall backfill exposed to lead contamination. *Engineering Geology*, *284*, 1–16. https://doi.org/10.1016/j.enggeo.2021.106037

Gleason, M. H., Daniel, D. E., & Eykholt, G. R. (1997). Calcium and sodium bentonite for hydraulic containment applications. *Journal of Geotechnical Engineering*, *123*(5), 438–445. https://doi.org/10.1061/(ASCE)1090-0241(1997)123:5(438)

Gonçalves, R. H., & Sturaro, J. R. (2010). Application of the response surface methodology in the remediation of a sandy soil artificially contaminated with copper. *Geociências*, *29*(1), 59–70.

Gupt, C. B., Bordoloi, S., Sekharan, S., & Sarmah, A. K. (2020). A feasibility study of Indian fly ash-bentonite as an alternative adsorbent composite to sand-bentonite mixes in landfill liner. *Environmental Pollution*, *265,* Article 114811. https://doi.org/10.1016/j.envpol.2020.114811

Kang, J. B., & Shackelford, C. D. (2010). Membrane behavior of compacted clay liners. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*(10), 1368–1382. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000358

Kenney, T. C., Van Veen, W. A., Swallow, M. A., & Sungaila, M. A. (1992). Hydraulic conductivity of compacted bentonite-sand mixtures. *Canadian Geotechinical Journal*, *29*, 364–374. https://doi.org/10.1139/t92-042

Meier, A. J., & Shackelford, C. D. (2017). Membrane behavior of compacted sand-bentonite mixture. *Canadian Geotechnical Journal*, *54*(9), 1284–1299. https://doi.org/10.1139/cgj-2016-0708

Middelhoff, M., Cuisinier, O., Masrouri, F., Talandier, J., & Conil, N. (2020). Combined impact of selected material properties and environmental conditions on the swelling pressure of compacted claystone/bentonite mixtures. *Applied Clay Science*, *184*, 1–10. https://doi.org/10.1016/j.clay.2019.105389

Mohammed, Z. B., Fattah, M. Y., & Shehab, E. Q. (2024). Effect of leachate contamination in municipal solid waste on clay liner characteristics. *Journal of Engineering Research*, *12*(2), 34–43. https://doi.org/10.1016/j.jer.2023.10.025

Montgomery, D. C. (2009). *Design and analysis of experiments*. John Wiley & Sons.

Morandini, T. L. C., & Leite, A. L. (2015). Characterization and hydraulic conductivity of tropical soils and bentonite mixtures for CCL purposes. *Engineering Geology, 196*, 251–267. https://doi.org/10.1016/j.enggeo.2015.07.011

Murray, E. J., Jones, R. H., & Rix, D. W. (1997). Relative importance of factors influencing the permeability of clay soils. *Geoenvironmental Engineering*, 229–239.

Nasir, O., Nguyen, T. S., Barnichon, J. D., & Millard, A. (2017). Simulation of hydromechanical behavior of bentonite seals for containment of radioactive wastes. *Canadian Geotechnical Journal*, *54*(8), 1055–1070. https://doi.org/10.1139/cgj-2016-0102

Najjar, Y. M., & Basheer, I. A. (1996). Utilizing computational neural networks for evaluating the permeability of compacted clay liners. *Geotechnical and Geological Engineering*, *14*, 193–212. https://doi.org/10.1007/BF00452947

Rashid, H. M. A., Sardar, A., & Ismail, A. (2021). Geotechnical characterization of bentonite-fly ash mixtures for their application as landfill liner in Pakistan. *Arabian Journal of Geosciences*, *14*, Article 1307. https://doi.org/10.1007/s12517-021-07663-6

Raychaudhuri, A., & Behera, M. (2020). Review of the process optimization in microbial fuel cell using design of experiment methodology. *Journal of Hazardous, Toxic, and Radioactive Waste*, *24*(3). https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000503

Rodrigues, M. I., & Iemma, A. F. (2009). *Design of experiments and process optimization* (2nd ed.). House of the Spirit Friend Fraternity Faith and Love.

Salerno, D., Jordan, H., La Marca, F., & Carvalho, M. T. (2018). Using factorial experimental design to evaluate the separation of plastics by froth flotation. *Waste Management*, *73*, 62–68. https://doi.org/10.1016/j.wasman.2017.12.001

Silva, T. F., Santos, J. J. N., Souza, J. C. M., Araujo, P. S., & Paiva, W. (2022). Estimation of unsaturated permeability in a sanitary landfill cover layer in the Brazilian semiarid region. *Sanitary and Environmental Engineering*, *27*(5), 1049–1057. https://doi.org/10.1590/S1413-415220220108

Stewart, D. I., Studds, P. G., & Cousens, T. W. (2003). The factors controlling the engineering properties of bentonite-enhanced sand. *Applied Clay Science*, *23*, 97–110. https://doi.org/10.1016/S0169-1317(03)00092-9

United States Environmental Protection Agency. (1993). *Solid waste disposal facility criteria technical manual*. Washington DC.

Watabe, Y., Yamada, K., Saitoh, K., & Millard, A. (2011). Hydraulic conductivity and compressibility of mixtures of Nagoya clay with sand or bentonite. *Geotechnique*, *61*(3), 211–219. https://doi.org/10.1680/geot.8.P.087

Wu, H., Wen, Q., Hu, L., Gong, M., & Tang, Z. (2017). Feasibility study on the application of coal gang as landfill liner material. *Waste Management*, *63*, 161–171. https://doi.org/10.1016/j.wasman.2017.01.016

Yeo, S. S., Shackelford, C. D., & Evans, J. C. (2005). Membrane behavior of model soil–bentonite backfills. *Journal of Geotechnical and Geoenvironmental Engineering*, *131*(4), 418–429. https://doi.org/10.1061/(ASCE)1090-0241(2005)131:4(418)