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Stiffness, compressibility, and hydraulic conductivity of compacted soil mixtures submitted to acidic percolation

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Technical Note

Keywords
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Long-term hydraulic conductivity
Bender element test

Abstract

The inadequate disposal of hazardous solid waste has become a potential issue, mainly because of the impacts on the environment and human health. This occurs mainly through the contamination of subsurface soil and groundwater by leachates, which are often of the acidic constitution. To prevent such situations, the study of more efficient waste containment techniques has become opportune. In this way, this work was aimed to investigate the mechanical and hydraulic behavior of compacted clayey soil, with and without the addition of Portland cement (0 and 2%), submitted to the action of a sulfuric acid solution (2% volume concentration) and to a constant static vertical load (280 kN/m^2), aiming at its prospective application as containment barrier. The experimental program comprised a few tests performed in an instrumented rigid-wall permeameter, during which the variations in hydraulic conductivity, shear modulus, and settlements were measured. The results showed that the hydraulic conductivity increased with cement addition when only water was percolated. During the acidic percolation, however, a reduction was observed only for the cemented soil. The acidic attack caused, almost instantaneously, an increase in the settlement rate and a reduction in stiffness, although a trend of stabilization was observed afterward.

1. Introduction

Industrial landfills and tailing dams generate leachates, which potentially impact the environment, sometimes due to their strong acidic nature and the presence of toxic inorganic substances, as in the leaching of corrosive wastes from metallurgical industrial processes and the acid mine drainage from metal or coal mining operations.

The construction of engineered waste disposal systems is one of the ways to avoid the problem. Particularly, impervious barrier systems have been used to minimize the migration of contaminants into the soil and the groundwater (e.g., Daniel, 1993; Rowe et al., 1995).

However, an aggressive contaminant can modify the physical-chemical characteristics of barriers, affecting their mechanical and hydraulic behavior (Knop et al., 2008; Hamoi & Srasra, 2012; Gratchev & Towhata, 2013, 2016; Bakhshipour et al., 2016, 2017; Agbenyeku et al., 2016; Chavali & Ponnapureddy, 2018a, b; Chavali et al., 2017; Lui & Gao, 2018; Ferrazzo et al., 2020; Korf et al., 2020). Strong acids can dissolve materials in the soil and form preferential flow channels (Daniel, 1993). Also, the vertical load from the waste deposited above the barrier might favor the migration of contaminants due to structural changes.

In recent years, efforts have been made to develop optimized barriers to simultaneously provide low permeability and structural durability. In this sense, physical-chemical stabilization through the addition of Portland cement or other cementing agents has been studied (Morandini & Leite, 2015; Gueddouda et al., 2016), given its potential to preserve the barrier structure, without compromising the hydraulic conductivity (Knop et al., 2008). Therefore, the generation of useful knowledge for the design of more efficient and durable soil barriers is necessary, minimizing their impacts and guaranteeing their applicability as a waterproofing system.

In this context, the objective of the present study was to investigate the hydraulic and mechanical behavior of a compacted clayey soil, with and without the addition of Portland cement, subjected to an acidic solution percolation.

2. Materials and methods

The experimental program included permeability tests under constant load lasting more than 30 days, in which saturated specimens were percolated by distilled water followed by a sulfuric acid solution. During the tests, the stiffness and the settlements were continuously measured.

2.1 Experimental variables

The variables investigated were the type of percolating liquid (water and sulfuric acid solution) and the cement content (0 and 2%). Other variables were kept fixed: hydraulic gradient; static vertical load; curing period; water content and

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specific weight of the specimens. The response variables were the hydraulic conductivity coefficient, the shear deformation modulus (stiffness), and the settlement (compressibility).

2.2 Soil

The residual basalt clayey soil comes from the Experimental Geotechnical Field of the University of Passo Fundo, located in Passo Fundo - RS. The sample was collected at a depth of 1.2 meters and is classified (Streck et al., 2008), as a humic dystrophic red latosol. This soil is predominant in the north of Rio Grande do Sul and is suitable for use as a compacted barrier. It is 68% clay, 5% silt, and 27% sand, presenting a plasticity index of 11% (liquid limit of 53 and plasticity limit of 42%), specific gravity of 26.7 kN/m^3, and organic matter content lesser than 0.8%.

2.3 Cement and contaminant solution

Portland cement CP-V was used to mold the cemented specimens. Its average composition comprises 0-5% of mineral additions and 95-100% of clinker, with a nominal compression strength of 40 MPa at 28 days.

For the acidic percolation, a solution of 2% by volume of sulfuric acid (H_2SO_4) (Merck® 95-97%), diluted in distilled water was prepared. The average pH of the solution was 1.31.

2.4 Testing apparatus

The testing apparatus was developed by Santos (2012) at the Environmental Geotechnical Laboratory of the University of Passo Fundo. It has six independent test cells, in which the application of static vertical loads is made, independently, through a system of pneumatic cylinders powered by an air compressor and controlled by pressure regulators and transducers connected to a data acquisition system. The vertical displacements are measured by LVDT transducers. Each of the six cells functions as a downward-flow rigid wall permeameter. In the present work, one of the cells was adapted with piezoceramic bender elements, which allowed to continuously evaluate the stiffness of the tested specimens.

The use of bender elements is one of the most popular non-destructive techniques for the determination of maximum shear modulus (G_{max}) in soils at the small strain range (Viggiani & Atkinson, 1995; Lee & Santamarina, 2005).

The bender elements were adapted in such a way that the free portions of the transducers (approx. 7mm) are completely inserted into the test specimen at its ends (top and base). The G_{max} value can be measured at any stage of the test by applying an electrical signal to one of the transducers (transmitter), which emits a mechanical shear wave (S wave) through the specimen, and by determining the time of arrival of the wave at the other end of the specimen, using the electrical signal produced by the second transducer (receiver).

2.5 Molding of specimens

The specimens were compacted in three layers, directly on the cell pedestal, in which the receiving bender element was adapted. The specimens, with 6 cm in height and 7 cm in diameter, were molded with a dry specific weight of 14.5 KN/m^3 and water content of 26%, defined from the compaction curves of the soil. After compaction, it was necessary to carve a groove at the top of the specimen to insert the transmitting bender element. For the transducer to be in complete contact with the specimen material, a filling paste was used.

To ensure a uniform distribution of the percolating liquid and prevent preferential paths, separating filter papers were placed at the top and bottom interfaces between the specimen and the perforated metal plates.

After molding, the test cell was filled with distilled water, and the specimen was subjected to a 48-hour resting period. The cell was then coupled to the equipment for the application of the vertical static load and the beginning of the saturation/percolation phase. The vertical load applied was 280 kPa, to simulate a constant load over a hypothetical bottom liner in a waste disposal site.

2.6 Saturation, percolation, and hydraulic conductivity determination

The saturation was started by percolating distilled water for approximately 5 days. The minimum volume percolated was 6 void volumes, and the hydraulic gradient used was 33, defined from preliminary tests. The total curing period for the samples with cement addition was approximately 7 days (48 hours at rest plus the time needed for the percolation of distilled water). The degree of saturation obtained was greater than 95%.

After the percolation with water, the acidic solution percolation was started, lasting for approximately 30 days. The variation of the hydraulic conductivity coefficient (k) was determined by the direct application of Darcy's Law and from the continuous monitoring of the percolated volumes.

2.7 Maximum shear modulus determination

The maximum shear module ($G_{máx}$) is obtained by Equation 1 (Viggiani & Atkinson, 1995). The speed of the shear wave (sinusoidal with frequencies from 2 to 10 kHz) is obtained from the division of the distance traveled by the wave between the bender elements, corrected by the settlement value) by the propagation time, which was determined by the procedure proposed by Lee & Santamarina (2005).

$$G_{máx} = \rho . V_s^2 \tag{1}$$

in which:
V_s is the shear wave velocity; and
ρ is the apparent specific mass of the soil.

3. Results and discussion

Figure 1 shows the variation in hydraulic conductivity and the evolution of settlements for the specimens tested with and without cement. The arrows indicate the start of the acidic percolation.

Before the acidic percolation phase, it is observed that the addition of cement resulted in an increase in hydraulic

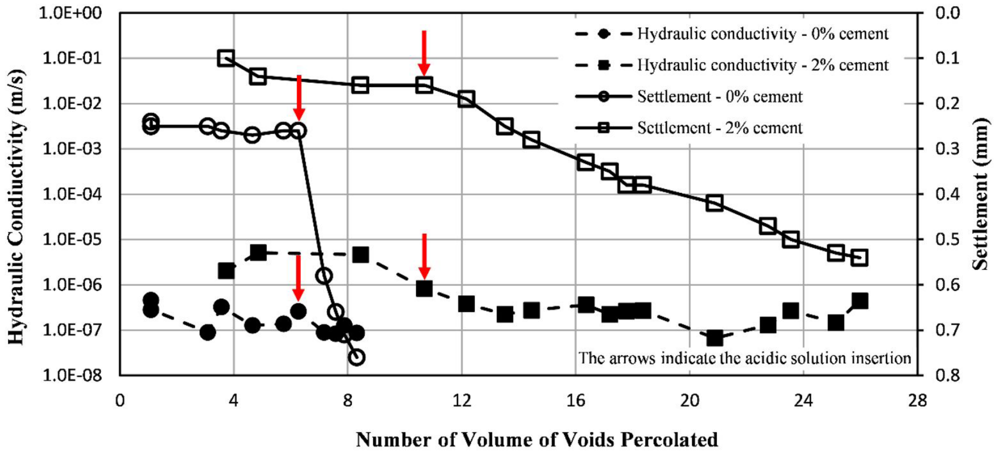

Figure 1. Variation of hydraulic conductivity and settlement.

conductivity of approximately one order of magnitude. It is also observed that the specimens did not show significant settlements under the action of the vertical load. In fact, the addition of Portland cement can increase the hydraulic conductivity of clay soils, due to hydration and solubilization reactions (Sharma & Reddy, 2004; Knop et al., 2008). In addition, it could be attributed to the physical-chemical interaction between the clay particles and the calcium present in the Portland cement solution, which is expected to induce flocculation due to the reduction in the double layer thickness of the clay particles (e.g., Mitchell & Soga, 2005).

Korf et al. (2016), for the same soil of the present study, also observed an initial increase in permeability followed by a reduction after the percolation with a solution of nitric acid.

For the soil without cement, the hydraulic conductivity was apparently not affected by acidic percolation, being around 10^{-7}m/s at the end of the test. For the soil with 2% cement, there is a reduction in hydraulic conductivity, showing the effect of the acidic percolation. The hydraulic conductivity did not show significant variations throughout the test but in the end, it was between 10^{-6} and 10^{-7} m/s, above the value obtained for the soil without cement. These values are high for use in containment barriers since the minimum recommended value is 10^{-9} m/s (Daniel, 1993).

The analysis indicates a remarkable effect of the acid solution insertion. There is a sudden increase in the rate of settlement under the constant load of 280 kN/m^2, characterizing a collapse of the material structure. However, the evolution of settlements should result in a reduction in hydraulic conductivity. As described in the preceding paragraph, this reduction was observed only for the cemented soil.

The observed behavior is possibly related to the different interaction mechanisms between the soil structure, including the cementing bonds and the acid solution, with antagonistic effects on hydraulic conductivity. On the one hand, the reduction in the void ratio, due to the collapse of soil structure. On the other hand, the probable formation of preferential paths at the end of the process (after 21 volumes of voids percolated). The behavior observed would, therefore, be the sum of these antagonistic effects. Timbola (2014), who studied the hydraulic response of the same material, reported a very similar pattern of behavior.

Finally, it appears that the settlement rate was higher for the soil without cementation, indicating that the acidic attack to the soil structure occurred with greater intensity and that the presence of cementation may have helped, at least partially, in preserving soil structure during acidic percolation.

Figure 2 shows the results of the stiffness measurements during the percolation tests with distilled water and sulfuric acid solution. The arrows indicate the insertion of the sulfuric acid solution.

The soil with 2% cement showed values of shear modulus in the range of 60 to 120 MPa, while the soil without cement presented values from 18 to 46 MPa, demonstrating the effect of cement addition on the stiffness of the compacted soil. These ranges are similar to the modules (20 to 251 MPa) obtained for similar clayey materials (e.g., Vardanega & Bolton, 2013).

With the insertion of the acid solution, there was an immediate increase followed by a drop in stiffness, more clearly observed for the cemented soil. However, when comparing the responses before and after the acidic solution insertion, for both uncemented and cemented specimens, the relative impact of the acidic percolation is greater for the soil without cement, which presented a reduction in shear modulus of about 34%, comparing the values at the start and at the end of the test. For the cemented soil, the observed reduction was of about 10%.

The most plausible hypothesis is that the variation in stiffness during acidic percolation results from the superposition of different mechanisms, often with antagonistic effects: the gradual degradation of cementation, the reduction of the average void ratio, and the formation of localized zones of higher hydraulic conductivity.

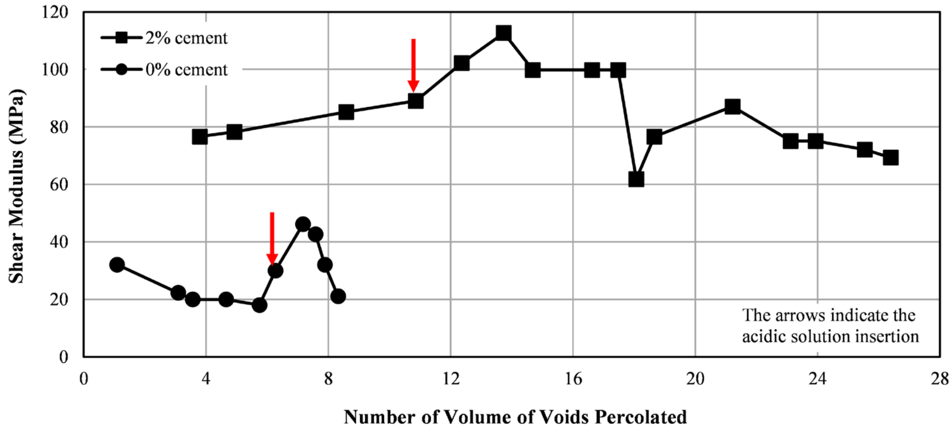

Figure 2. Variation of shear modulus.

In fact, one of the possible outcomes of strong acid percolation is the dissolution of the cementing compounds formed among particles, causing loss of rigidity.

Silva et al. (2009) studied artificially cemented soils and reported a degradation in stiffness with the increase of the confinement stress. Consoli et al. (2000) investigated the usual procedure for obtaining the stiffness of cemented soils in conventional triaxial tests, focusing on the influence of the confining stresses before and after cementation formation. The authors found that the degradation of cementation occurred only in specimens cured without confinement, whereas in samples cured under tension, there was an increase in stiffness with the confining stress.

In the present study, however, cementation degradation is not related to changes in the state of stresses but results from the physical-chemical interaction between the acidic solution and the soil compounds.

The cementation degradation, however, does not explain the immediate increase in stiffness after the insertion of the acidic solution, nor the reduction in stiffness observed for the soil without cement (Figure 2). As for the immediate increase in stiffness, this can be explained by the collapse of the soil structure and reduction of the void's ratio, as indicated by the evolution of settlements in Figure 1. On the other hand, the reduction in stiffness of the non-cemented soil observed during acidic percolation can be credited to structural changes such as the formation of localized areas of higher porosity (preferential paths).

4. Conclusions

The present work evaluated the hydraulic and mechanical behavior of a compacted clayey soil, with and without Portland cement, when percolated with distilled water and sulfuric acid solution, aiming at its use in impermeable barriers to contain hazardous industrial and mining solid waste.

The analysis of the results allowed to infer that the acidic percolation affected more the hydraulic conductivity of the cemented soil, from the occurrence of two antagonistic mechanisms: the collapse of soil structure, evidenced by the sharp increase in the settlement rate, which reduces hydraulic conductivity, and the possible formation of preferential percolation paths, with the opposite effect.

Regarding stiffness, the results showed an immediate increase and a subsequent reduction in the shear modulus with the acidic percolation, again indicating the occurrence of different mechanisms: the gradual degradation of cementation, the reduction of the average void ratio, and the possible formation of preferential percolation paths.

As a final remark, it is expected that the results reported herein contribute to establishing patterns for geotechnical materials under acidic percolation that can serve as a basis for the design of bottom barriers used in landfills and tailing dams, providing experimental evidence that allows the development of prediction models.

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Declaration of interest

The authors declare that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest (such as personal or professional relationships, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

Author's contributions

Franciele Noll da Silva: conceptualization, investigation, writing of the original draft. Pedro Domingos Marques Prietto: project administration, supervision, writing, review and editing. Márcio Felipe Floss: supervision, writing, review and editing.

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List of symbols

k = hydraulic conductivity of the porous media (distance/time)
Gmáx = maximum shear modulus
Vs = seismic wave propagation velocity
ρ = apparent specific mass of the soil