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Use of a flexible wall permeameter to study the hydraulic properties of tropical soils from a municipal solid waste disposal site

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ABSTRACT

The inadequate disposal of municipal solid waste (MSW) is a global problem, particularly in developing countries. This scenario can lead to soil and water contamination by leachate, such as the Bauru MSW landfill in Brazil, which has an identified contamination plume and may reach possible water supply sources in Bauru. In this context, the direction of the contamination plume depends on the hydraulic characteristics of the soil and rock. The hydraulic conductivity (k) of a tropical sandy soil profile representative of the Bauru MSW landfill was studied together with the bedrock (sandstone) using a flexible wall permeameter at average effective stresses close to the in situ values, i.e., 20, 40, 80, 160 and 320 kPa. The unsaturated hydraulic conductivity was estimated by the soil water retention curve (SWRC). Disturbed and undisturbed soil samples were collected at 1, 4, 7, 11, 13, and 16 m depth at the experimental research site of Unesp-Bauru. The sandstone samples were collected from a rock outcrop at the Bauru MSW landfill. The results indicated a decrease of hydraulic conductivity by 43% for 1 m depth, 29% for 4 m depth, 46% for 7 and 11 m depth, 61% for 13 and 16 m depth, and 96% for sandstone under 320 kPa of confinement pressure. Based on SWRC, the soil and sandstone results suggest using the saturated hydraulic conductivity for further analyses concerning the Bauru MSW landfill.

Keywords: Bauru MSW landfill, tropical soils, sandstone, flexible wall permeameter, hydraulic conductivity

1 INTRODUCTION

The continuous increase in waste generation represents a logistical, financial, and environmental challenge, especially in developing countries (Ayomoh et al., 2008; Alfaia et al., 2017; Guerrero et al., 2013; El-Mathana et al., 2021). Landfills have been widely used as a final MSW destination. The implementation of these landfills occurs in sites that do not necessarily result in practical solutions to receive a large amount of waste generated, as well as the use often above the capacity of the initial project, configuring one of the primary sources of environmental pollution and risk to human health (Teh et al., 2016; Ozelim et al., 2021). At the Bauru MSW landfill, a contamination plume was identified in previous works and reached the groundwater (Mondelli et al., 2007, 2012; Faria & Mondelli, 2017). The knowledge of the direction of the contamination plume is essential to define the adequate treatment along with the medium monitoring. Thereby, hydraulic conductivity is one of the most critical parameters to be determined. The influence of confinement and unsaturated conditions in a tropical environment is highly relevant to understanding plume migration, mainly because most works are concentrated in developed countries where soil genesis differs. Likewise, the studies of the hydraulic proprieties of sandstones are concentrated in temperate areas with predominant physical weathering (Silva et al., 2019).

The permeability is quantified by hydraulic conductivity, which could be determined by Darcy's law using in situ or laboratory tests. Experimental programs in situ are more representative, while laboratory tests can simulate different conditions in a controlled environment. A rigid wall permeameter is commonly used in laboratories. However, the aforementioned equipment cannot control boundary conditions, such as confinement pressure and high gradients. In this case, a flexible wall permeameter allows more realistic representation in the laboratory (Daniel et al., 1984; Wang et al., 2020).

Aside from that, seepage behavior in a vadose zone is essential since it exists in different soil profiles, including the Bauru MSW landfill. Thus, the main objective of this work is to study the hydraulic conductivity of tropical sandy soil and its bedrock (sandstone) widely found in Brazil using a flexible wall permeameter to further understand their hydraulic behavior and the contamination plume migration.

2 MATERIALS AND METHODS

2.1 Study sites and sampling

The Bauru MSW landfill (22°15’S 49°08’W) and the experimental research site at the Unesp Bauru campus (22º21’S 49º 02’W) are located in the Midwest of São Paulo State. The first is managed by Bauru Municipal Urban and Rural Development Company (EMDURB), in which rock samples were collected from a rock outcrop. Disturbed and undisturbed soil samples were collected at 1, 4, 7, 11, 13, and 16 m depth in the Unesp Bauru experimental site. Both areas are shown in Figure 1. The sites have similar geological formations and are composed of Marília and Adamantina with Sandstones, Argillites, and Conglomerates (Ferreira et al., 1993; De Mio, 2005).

The soil has been widely studied and corresponds to the middle profile found in the city of Bauru, thereby, red fine clayey sand with lateritic behavior up to 13 m depth (Giacheti, 2001). The grain size distribution, dry unit mass (ρ_d), void ratio (e), and average water content (W) along the soil profile are shown in Figure 2, and a typical Bauru MSW cross-sectional is shown in Figure 3.

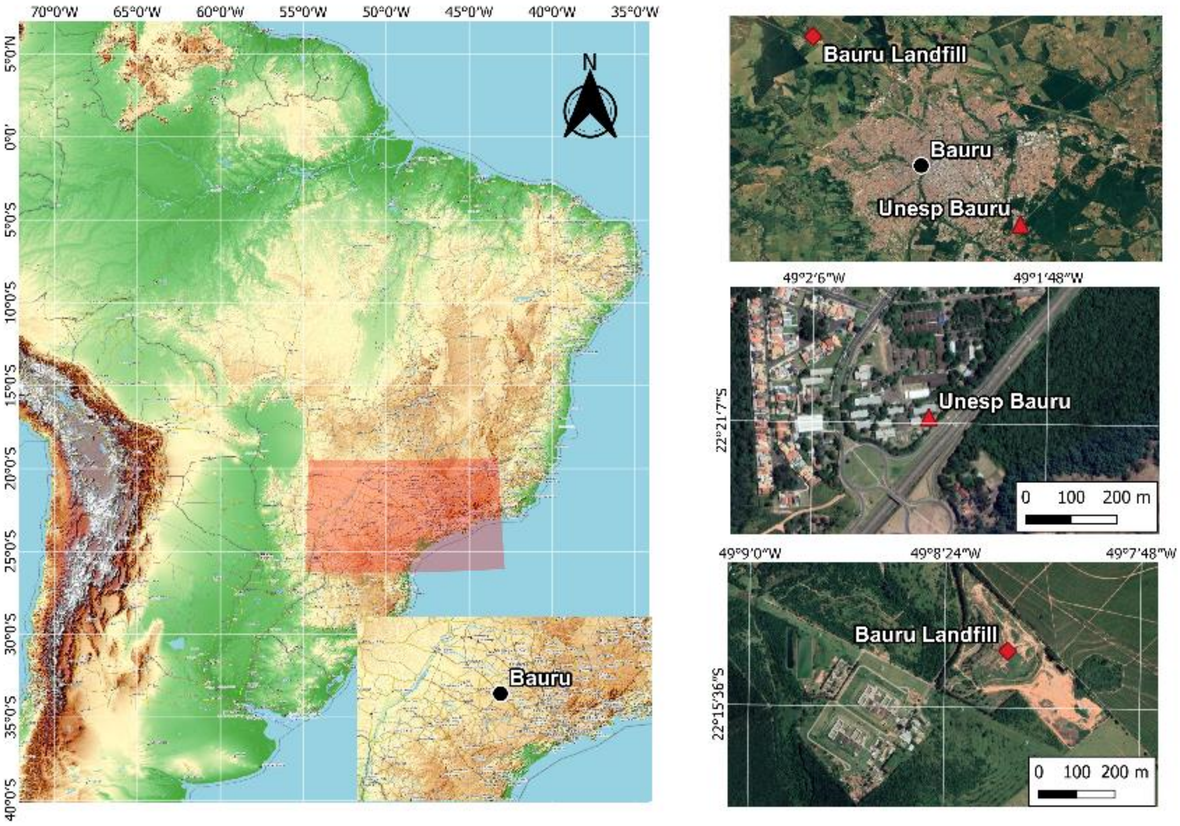


***Figure 1**. Unesp Bauru and Bauru MSW landfill sampling areas*

2.2 Hydraulic conductivity

Tests were conducted to determine the saturated hydraulic conductivity as ASTM D5084 (2016) recommended, using the constant head method. Cylindrical core samples with a height and diameter of about 70 mm (H/D=1), represented by the sandstone specimen shown in Figure 4, were tested using a flexible wall permeameter (Figure 5). This device allows the application of different boundary conditions, such as gradient and confinement pressure, allowing measuring the volume variation. The soil samples were performed with a gradient of 10 and average effective stress close to the in situ condition, i.e., 20, 40, 80, 160, 320 kPa, since the assumed effective stresses for 1, 4, 7, 11, 13, and 16 m depth are respectively 17, 65, 120, 193, 230, and 290 kPa. The sandstone specimens were tested with a gradient of 10 for confinement pressures up to 80 kPa, 20 for 160 kPa, and 25 for 360 kPa. The unsaturated hydraulic conductivity was estimated through the Soil Water Retention Curve (SWRC) determined by Fernandes et al. (2022), and for the sandstone in the herein work, both of them by the drying process using filter paper and Haines' funnel as shown in Figure 6. It was assumed that the SWRC for the soil from 3 and 11 m depth could be applied for estimating the unsaturated hydraulic conductivity for the soil from 4 and 13 m depth. To fit the SWRC and estimate the unsaturated hydraulic conductivity, Equation 1 and Equation 2 were used, respectively (van Genuchten, 1980).

$$W(s)=W_r+(W_s-W_r)\left\{\frac{1}{[1+(\alpha s)^n]^m}\right\} \tag{1}$$

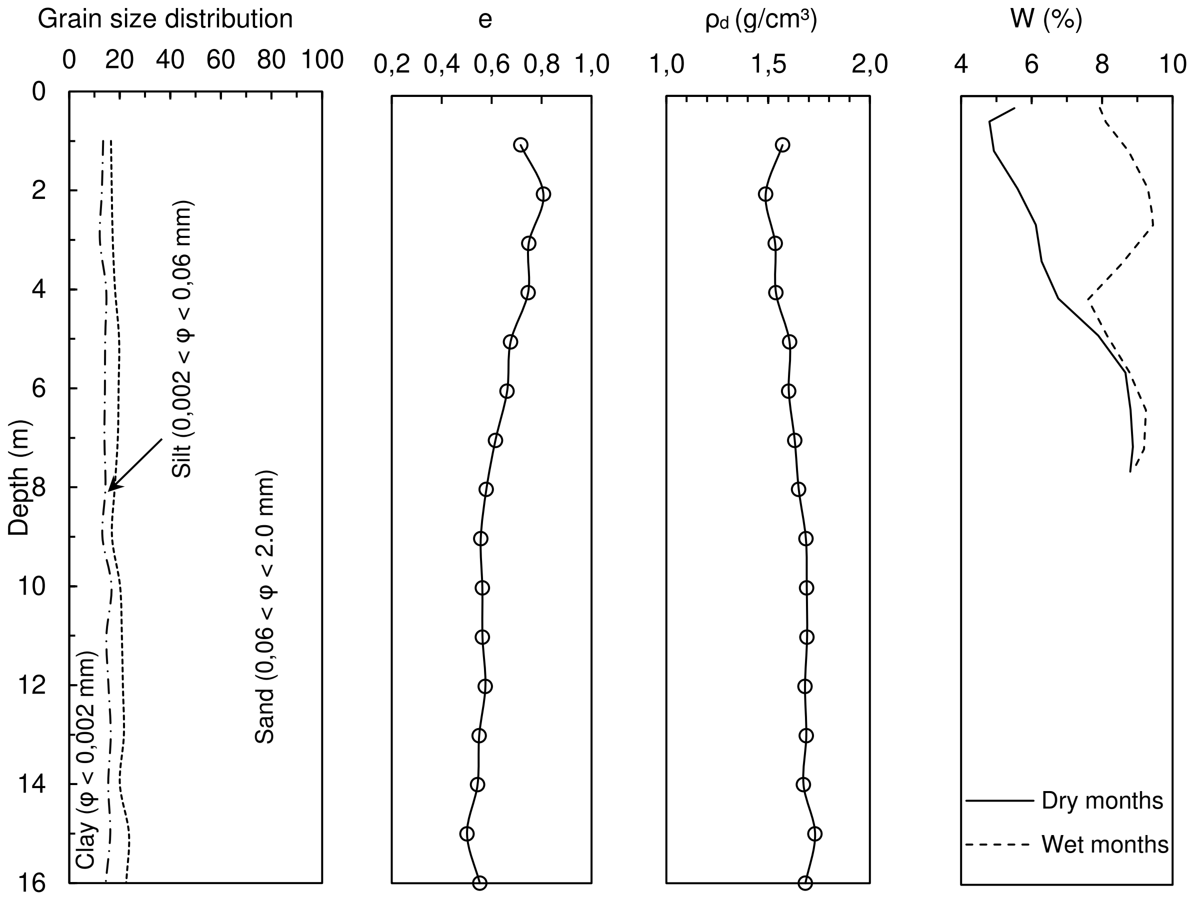


__Figure 2__. Grain size distribution and soil index properties for the Unesp Bauru site (adapted from Fernandes et al., 2022)

where W(s) is the water content in the suction function, W_r is the residual water content, W_s is the saturation water content, α, n, and m are the fitting parameters.

$$k(s)=k_s\sqrt{\frac{W(s)-W_r}{W_s-W_r}}\left\{1-\left[1-\left(\frac{W-W_r}{W_s-W_r}\right)^{\frac{1}{m}}\right]^m\right\}^2 \tag{2}$$

where k(s) is the unsaturated hydraulic conductivity, and k_s is the saturated hydraulic conductivity

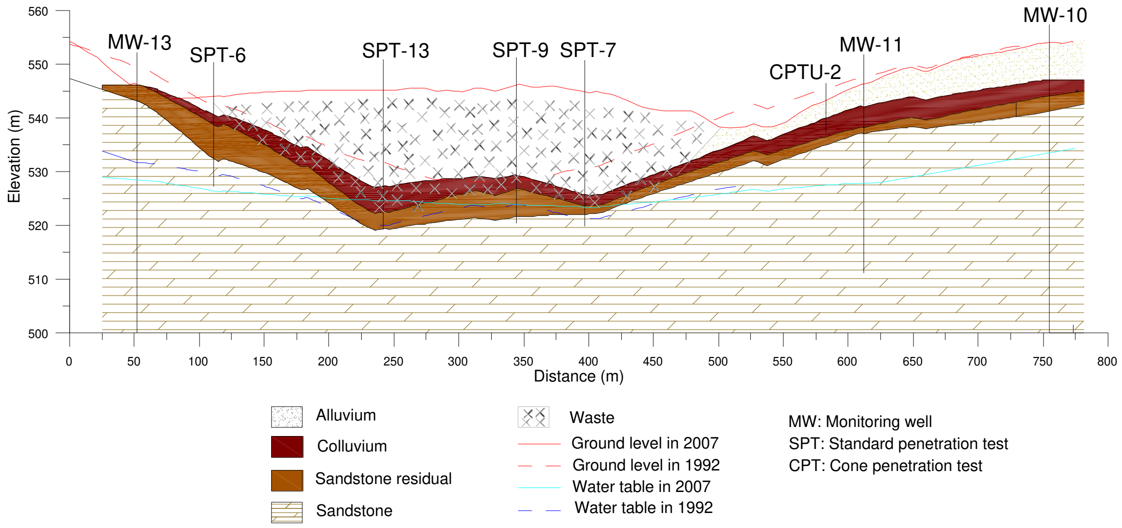


***Figure 3**. Geological-geotechnical North-South profile from Bauru MSW landfill (adapted from Mondelli, 2008)*

***Figure 4**. Rock outcrop (left). Sample preparation (center). Specimen in the test chamber (right)*

***Figure 5**. Flexible wall permeameter*

Figure 6. *Filter paper (left). Haines' funnel (right)*

3 RESULTS

The hydraulic conductivity for the soil and the sandstone samples are respectively shown in Figure 7 and Figure 8. As seen in these figures, the influence of confinement pressure is more relevant for values higher than 100 kPa. Such an effect can be related to the overconsolidation stress, in which the porous medium is in plastic deformation, resulting in a relevant decrease in the void ratio and, consequently, in the hydraulic conductivity values.

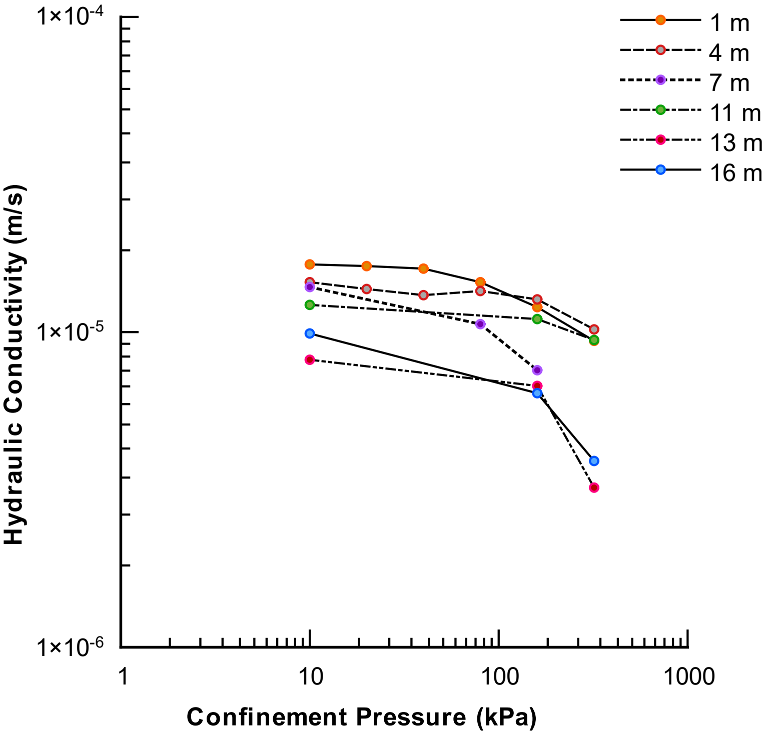


Figure 7. *Variation of soil hydraulic conductivity with confinement*

The percentual variation of hydraulic conductivity increases with the increment of confinement pressure. Therefore, the hydraulic conductivity is a function of the confinement and the void ratio. The hydraulic conductivity decreases by 43% for 1 m, 29% for 4 m, 46% for 7 and 11 m, 61% for 13 and 16 m depth, and 96% for sandstone for the 320 kPa of confinement pressure.

Similarly, the void ratio decreases by 26%, 17%, and 14% for 1, 4, and 7 m, 8% for 11, 13 m depth and sandstone, and 7% for 16 m depth. The values were compatible with granular soil (Kandalai et al., 2018) and sandstone (Chen et al., 2009; Gong et al., 2019).

Even though the shallow soil samples (1 and 4 m depth) had a considerable decrease in void ratio after consolidation, the decrease in hydraulic conductivity was perceptible for all samples. However, the sandstone and soil at 13 and 16 m depth had a more notable decrease in hydraulic conductivity, which can be related to interconnected voids.

Once sandstone and the deeper soil samples have few voids, therefore, fewer connected pores, a small reduction of voids leads to a noteworthy reduction in hydraulic conductivity. In other words, the permeability depends on how the voids are connected (Horn et al., 1994). The presented results suggest that the decrease of void ratio on the consolidation process in soil samples above 13 m depth was not able to change the flow path between interconnected pores as it was able to shift in sandstone, and the soil samples collected at 13 and 16 m depth. Thereby, the magnitude of k values for the soil samples collected between 1 and 11 m depth were somewhat affected, as observed by Ng & Pang (2000).

Huo & Benson (2016) and Cheng et al. (2019) noticed that the effect of different stresses could lead to different preferred flow paths with little contribution of isolated pores to the flow.

Phueakphum & Fuenkajorn (2014) and Bohnsack et al. (2021) comment on the sensitivity of hydraulic conductivity with increasing stress in fractured rock. The authors observed an exponential decrease, mainly when the hydraulic conductivity depended on a few flow paths.

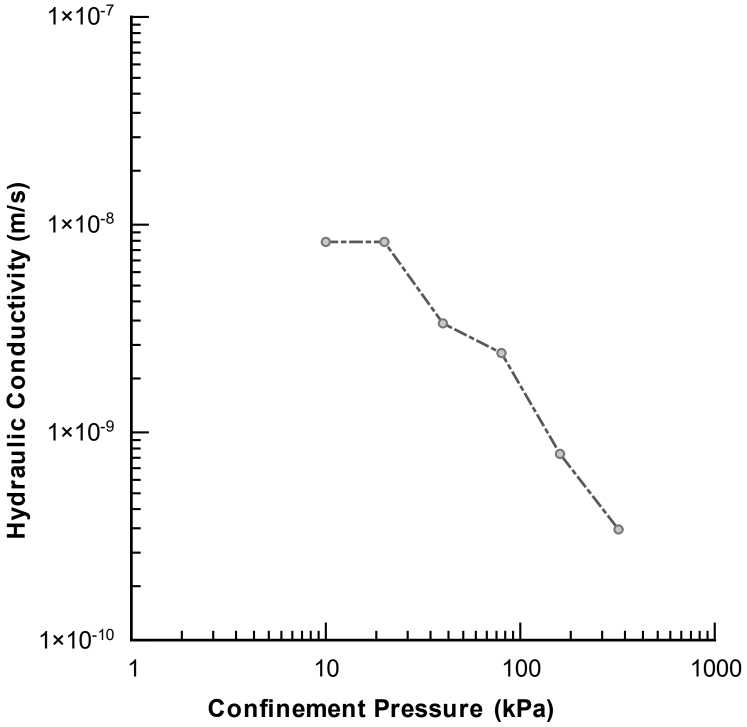


***Figure 8**. Variation of sandstone hydraulic conductivity with confinement pressure*

Although the relationships between void ratio, grain size distribution, mineralogical composition, and hydraulic conductivity are well established by means of classical studies (Hazen, 1911; Terzaghi, 1925; Taylor, 1948; Kozeny, 1953), it is difficult to make an inference about it for tropical, since they are non-textbook geomaterials. Furthermore, seepage in pores medium is complex, and a detailed explanation of fluid motion in weathered tropical medium needs further studies (Chapuis, 2012). Rhino et al. (2021) observed that it is complex to relate the variation in effective stresses to strain and change in flow paths. Well-connected pores were shown to be less influenced by stress increase.

In addition to the previous observations, the sandstone presents clay minerals kaolinite, montmorillonite, smectite, and palygorskite (Silva et al., 2019), which may also have influenced the more significant reduction in hydraulic conductivity, as shown by Zhang et al. (2001).

Moreover, the tests were performed in a laboratory setting, and such observations must be considered when making inferences, as explained. The same occurs to the weathered sandstone under tropical conditions.

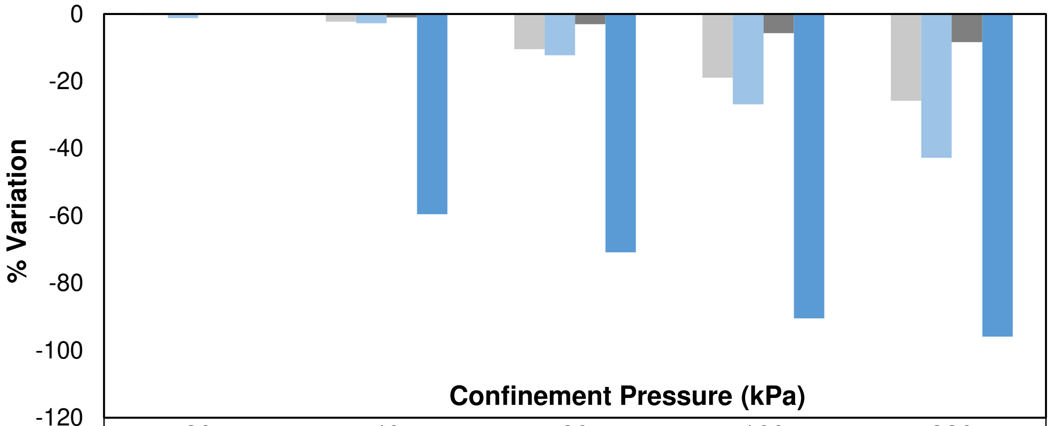
Therefore, further investigations are recommended to evaluate pore size, distribution, and mineralogy to help better understand the hydraulic behavior of the studied soil and rock.

Figure 9 illustrates the reduction of void ratio and hydraulic conductivity from a 1 m depth soil sample and the sandstone.

The SWRC from the soil and the sandstone were determined to estimate the unsaturated hydraulic conductivity condition, as shown in Figure 10, and the van Genuchten parameters in Table 1, which was used to fit the experimental data to the van Genuchten analytical curve.

The estimated unsaturated hydraulic conductivity is present in Figure 11, wherein could be noticed the similar behavior between the SWRC and the unsaturated hydraulic conductivity since the last one was determined by the first one. It means the desaturated behavior got underway for suction higher than 2 kPa until 10 kPa (range of soil air-entry) for the soil sample. Suction values between 10 and 50 kPa reduced hydraulic conductivity to 10^{-12} m/s. Thereby, the hydraulic conductivity was too low, and the medium was more permeable to the gas phase than the water phase.
The definition of the value of air-entry for the sandstone was challenging, with the desaturation occurring between 0.1 and 7 kPa, therefore a short-saturated behavior. It implied that the hydraulic conductivity reached 10^{-12} m/s for 7 kPa suction.

The Soil Water Retention Curves differ. The sandstone has a slower desaturation, which may be associated with a fewer porosity and the previously mentioned clay minerals capable of retaining water. Similar conclusions were presented by Moazeni-Noghondar et al. (2021) and Chen et al. (2019). As previously discussed, the hydraulic conductivity determination may also reflect such aspects.



	20	40	80	160	320
■ e 1 m	0	-2	-11	-19	-26
■ k 1 m	-1	-3	-12	-27	-43
■ e Sandstone	0	-1	-3	-6	-8
■ k Sandstone	0	-60	-71	-90	-96

Figure 9. *Variation of void ratio and hydraulic conductivity for 1 m depth soil and sandstone*

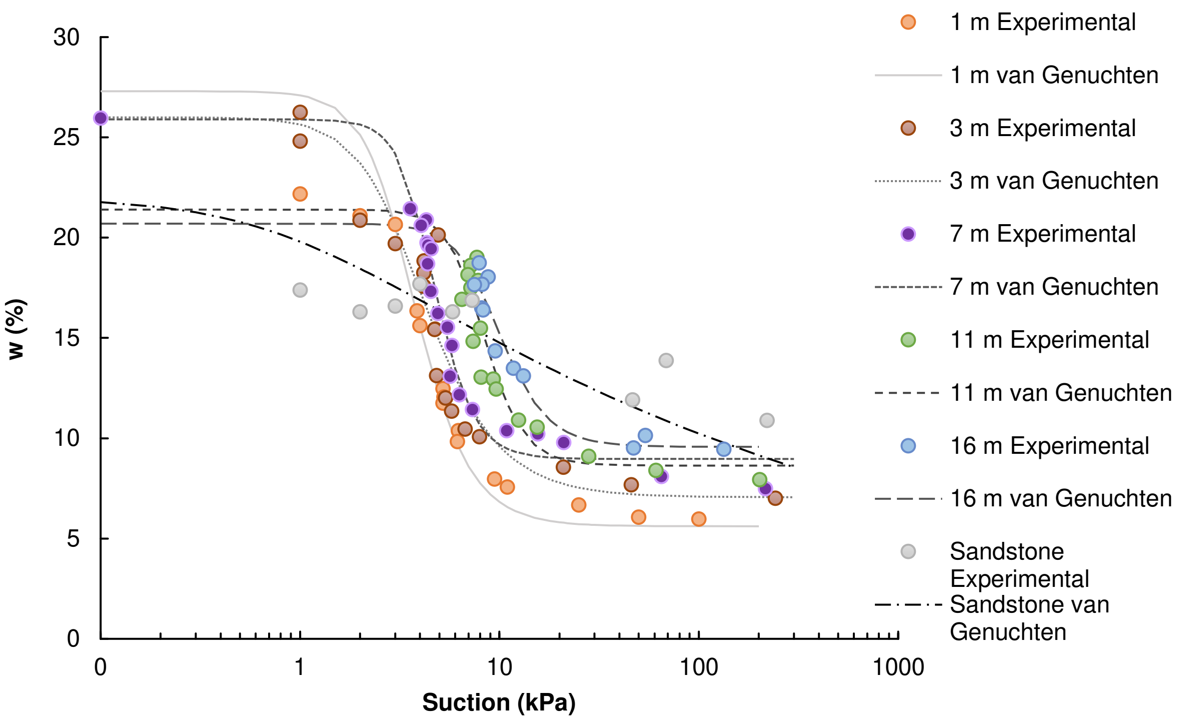


Figure 10. *SWRC for the soil and sandstone samples (adapted from Fernandes et al., 2022)*

Table 1. *Estimated van Genuchten parameters for the soil collected from different depths and the sandstone (adapted from Fernandes et al., 2022)*

Depth (m)	Wr	Ws	α	m	n	R²
1	0.056	0.273	0.30	0.72	3.61	0.969
3	0.071	0.260	0.29	0.65	2.84	0.896
7	0.090	0.259	0.22	0.80	4.88	0.970
11	0.089	0.196	0.12	0.84	6.13	0.869
16	0.096	0.207	0.11	0.76	4.08	0.943
Sandstone	0.000	0.220	1.10	0.14	1.16	0.938

The hydraulic conductivity of the soil and the sandstone can vary as a function of the in situ effective stress and average moisture content (suction). Therefore, the advection and the contaminant plume have different flows throughout the year, depending on the soil layer and wet or dry season.

The shift in the position of the groundwater table, as shown in Figure 3, may be due to natural causes, such as variation between dry and wet seasons, and changes in the environment, such as the construction of the landfill that may have affected local recharge and evapotranspiration (Kellner, 2007; Petersen & Stringham, 2008; Woodward et al., 2016).

Even though the soil hydraulic conductivity of 10^{-12} m/s is considered a natural barrier, achieving suction values higher than 20 kPa at the Bauru MSW landfill site is challenging since the waste is near the groundwater table. Likewise, the moisture due to MSW degradation (leachate) influences SWRC (Dang et al., 2020). However, the sandstone could be a natural barrier as its saturated hydraulic conductivity is 10^{-9} m/s. Nevertheless, the such value was obtained in the laboratory, which can differ from the in situ conditions due to site variability and fractures.

Based on what has been presented and discussed for the site where the Bauru MSW landfill is installed, continuous soil and water quality monitoring is necessary to prevent leachate from reaching water supply sources.

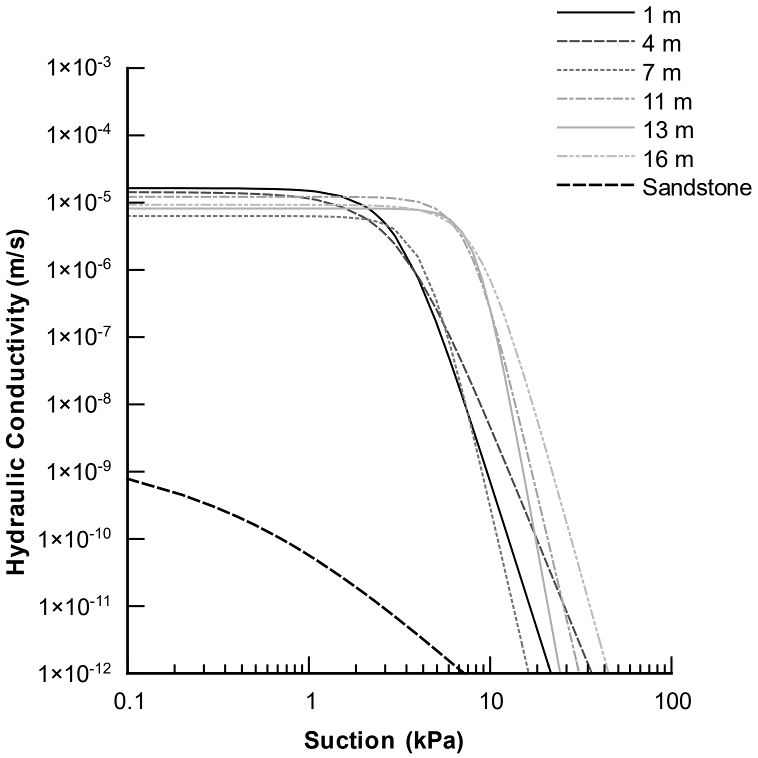


***Figure 11**. Estimate unsaturated hydraulic conductivity for the soil collected from different depths and the sandstone*

4 CONCLUSIONS

- The confinement pressures higher than 100 kPa significantly decreased the hydraulic conductivity for both the soil and the sandstone. This behavior stands out for the sandstone that achieved a 96% reduction at 320 kPa confining pressure and dropped 8% void ratio, versus a 43% reduction for the soi collected at 1 m depth at 26% void ratio;
- The results suggest that the increase in confinement altered the interconnected pores, and the effective flow path was affected, resulting, in a more expressive decrease in the hydraulic conductivity for the samples with few void ratio, i.e., sandstone and soil samples collected at 13 and 16 m depth.
- The air-entry values between 2 and 10 kPa for the soil samples implied that saturated condition is expected at the Bauru MSW landfill site because it surrounds the groundwater table and for it is a leachate source. Then, the soil and rock tend to have high water content and low suction;
- It is a critical situation for contaminant flow due to the position of MSW. Therefore, the saturated hydraulic conductivity values are recommended to be assumed as representative for further analyses.

5 ACKNOWLEDGEMENTS

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