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Saturated Hydraulic Conductivity of Municipal Solid Waste Considering the Influence of Biodegradation

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Abstract: Municipal solid waste (MSW) permeability is influenced mainly by compaction, unit weight, overburden pressure, composition, and biodegradation of the waste. However, the variation of hydraulic conductivity with MSW biodegrading over time has not yet been sufficiently studied, and consequently not fully understood. This study aimed to present the saturated hydraulic conductivity (K_{sat}) of the MSW, considering the influence of anaerobic biodegradation, by using two large-scale rigid wall permeameters (P1 and P2) in two experimental groups. The leachate produced was subjected to physicochemical analysis. The MSW confined in both permeameters presented similar gravimetric composition and total mass but diverse initial unit weight, ranging from 4.9 to 7.2 $\mathrm{kN \cdot m^{-3}}$. Maximum and minimum values of K_{sat} obtained for the confined MSW were $2.0 \times 10^{-2}\ \mathrm{ms^{-1}}$ and $7.4 \times 10^{-6}\ \mathrm{ms^{-1}}$, respectively. Physicochemical analysis indicated that MSW biodegradation in permeameters remained in the anaerobic acid phase. The methodology adopted for the permeability tests influenced the MSW biodegradation, and consequently its hydraulic behavior. It is believed that, during 7 days before the permeability tests, the drained gas changed the MSW mass structure into the permeameters and the K_{sat} values over time. Within the permeameters with higher unit weight MSW, the K_{sat} values increased for up to 3 months, tending to stabilization. **DOI: 10.1061/(ASCE)EE.1943-7870.0001432.** *© 2018 American Society of Civil Engineers.*

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Introduction

Brazil produced about 78.6 million tons of municipal solid waste (MSW) in 2014, which represents an increase of 2.9% compared with 2013. In the same year, about 58.4% of the MSW collected was sent to sanitary landfills. In the state of São Paulo, the southeastern region of the country, 76.8% of MSW collected in 2014 was disposed in sanitary landfills (ABRELPE 2015).

The construction of sanitary landfills in Brazil has increased in the last 15 years, as well as the interest in understanding the MSW hydro-geomechanical behavior, such as compressibility, permeability, and shear strength, aiming at safer and economically viable landfill designs. MSW has specific characteristics such as higher heterogeneity and biodegradation that make its behavior very complex. Consequently, the use of large-scale prototypes in the laboratory to study MSW behavior has been used with reasonable success (Chen and Chynoweth 1995; Wall and Zeiss 1995; Powrie et al. 2005; Durmusoglu et al. 2006; Powrie et al. 2008; Reddy et al. 2009a, b; Jie et al. 2013; Mortatti et al. 2013; Benatti et al. 2014).

MSW permeability is an important parameter for the overall performance of the sanitary landfill, as much as, for example, stability and settlements. Several researchers have shown that MSW permeability is influenced by its compaction, overburden pressure, waste composition, and particle-size distribution (Chen and Chynoweth 1995; Powrie et al. 2005; Durmusoglu et al. 2006; Hossain et al. 2008; Reddy et al. 2008, 2009a, b; Jie et al. 2013; Siddiqui 2014; Reddy et al. 2015; Gavelyte et al. 2016; Fei and Zekkos 2016).

The MSW showed at least four biodegradation phases when disposed into a sanitary landfill: aerobic phase, anaerobic acid phase, initial methanogenic phase, and stable methanogenic phase (Kjeldsen et al. 2002). Nonetheless, few researchers have associated permeability to MSW biodegradation. Hossain et al. (2008) prepared MSW at different biodegradation phases and determined that MSW permeability is a function of the decomposition degree. Reddy et al. (2011) studied changes in the geotechnical properties of synthetic MSW samples at various phases of biodegradation and under highly controlled conditions in customized test reactors. Several studies concluded that the MSW degradation produced more fines and higher unit weight, which resulted in lower hydraulic conductivity (Xie et al. 2006; Hossain et al. 2008; Reddy et al. 2011). Moreover, Powrie et al. (2008) reported the effect of gas generation on the hydraulic conductivity of fresh MSW due to biodegradation, decreasing the permeability and saturated area. However, the variation of hydraulic conductivity in association with the MSW biodegradation over time has not yet been sufficiently studied, and consequently is not fully understood.

Hydraulic conductivity is a parameter used to quantify the MSW permeability, which can be obtained by tests in the laboratory or

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field, using several apparatuses, such as permeameters. Reddy et al. (2009a) demonstrated the wide variation in MSW hydraulic conductivity values (from 10^{-4} to 10^{-10} ms^{-1}) determined through much research.

Thus, this study aimed to contribute to this issue by presenting the variation of the fresh MSW hydraulic conductivity over time, using two large-scale rigid wall permeameters. The biodegradation phases of the MSW were defined by physicochemical analysis of the leachate produced during the permeability tests. The fresh MSW samples were inserted into the permeameters and remained throughout the study time, thus being subjected to the biodegradation processes while the permeability tests were performed.

Materials and Methods

Construction and Installation of the Permeameters

Two large-scale rigid-wall permeameters (P1 and P2) have been developed from a cylindrical piece of PVC with 30-cm diameter and 1-cm wall thickness. One was 80 cm high (P1) and the other was 100 cm high (P2). Two acrylic covers with rubber rings were used for sealing each permeameter on the top and at the bottom, both with a square section of 40 × 40 cm and 2.5-cm thickness. PVC ball regulator valves were installed in the center of each acrylic cover. A high-density polyethylene (HDPE) tank with 200-L capacity was placed on a level above the permeameters' top and connected by silicone hoses to the ball valves in the top acrylic cover. Five PVC fittings were distributed along the permeameters' height (spaced 15 cm in P1 and 20 cm in P2) and connected by silicone hoses, which were fixed to a millimeter-scale panel to act as piezometers, thus enabling the reading of hydraulic heads at different heights (Fig. 1). These silicone hoses allow the release of the gas produced by MSW in the permeameters before the permeability tests.

Two fresh MSW samples from the Delta A municipal landfill, which is in the city of Campinas, São Paulo, southeastern Brazil, were acquired and properly characterized in place, using the methodology described in Associação Brasileira de Normas Técnicas (ABNT 2004), and then transported to the laboratory to fill the permeameters. The sample characterization was divided into the following categories: organic matter, paper and cardboard, hard and soft plastics, metal, glass, Tetra Pak (all long life packaging), diaper, construction waste, wood, textiles, toilet waste, miscellaneous (rubber, foam, shoes, mixed material with more than one category, and hazardous waste, such as paint cans, light bulbs, and batteries), and pruning. Each category was weighed to obtain the gravimetric composition of the MSW samples.

The permeameters were filled out by depositing the fresh MSW in layers and pressing them with a manual socket until the desired unit weight value was reached. Two 10-cm layers of crushed stone (diameter between 19 and 25 mm) were inserted on the top and at the base of the permeameters. Thus, the initial heights of MSW samples in the permeameters were 60 and 80 cm for P1 and P2, respectively (Fig. 1).

Permeability Tests

Four permeability tests were performed in two groups: two in Group 1 (P1-1 and P2-1) and two in Group 2 (P2-1 and P2-2), after approximately 6 months. In Group 1, one of the MSW samples was used in both permeameters (P1 and P2), and then later used in the same procedure for the other MSW sample in Group 2. The two fresh MSW samples were collected at different times (about 6 months apart) and were stacked in the permeameters, reaching different unit weight values.

In the first group, the unit weight values for the MSW confined in P1 and P2 were 7.1 and 6.2 kN · m^{-3}, respectively. In the second group, these values were 7.2 and 4.9 kN · m^{-3} for P1 and P2,

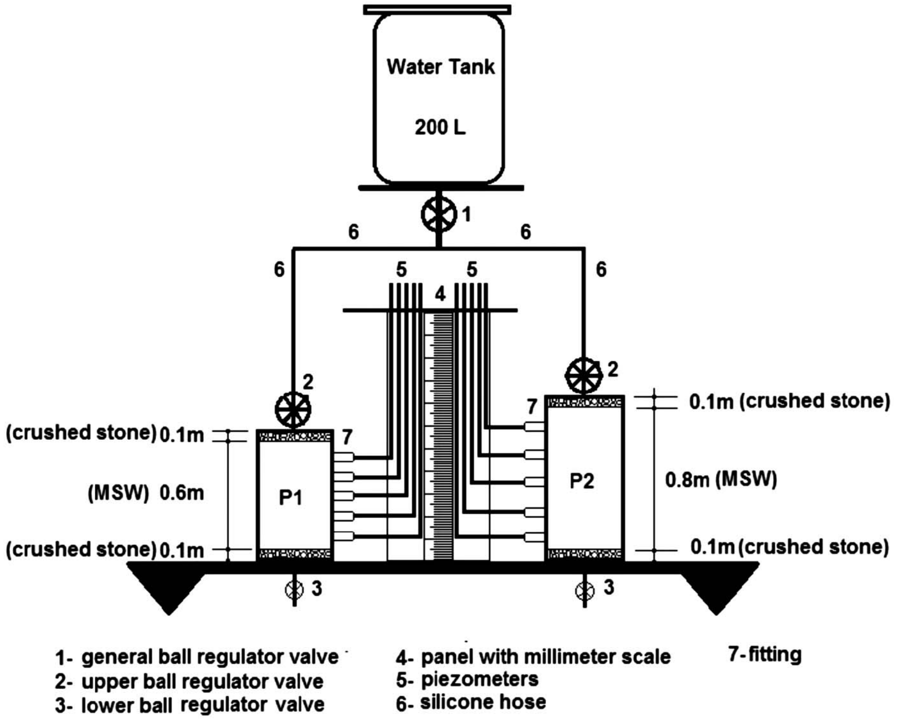

Fig. 1. Permeameters used in the determination of saturated hydraulic conductivity of MSW.

respectively. In both groups, the permeability tests were performed with the saturated MSW and under constant hydraulic head as follows:

1. First, MSW was saturated within the permeameters by back-pressure, guaranteed by the stabilization of the piezometric levels. After this, the valves were closed and the MSW saturation was maintained for 7 days. Gases produced inside the permeameters were drained through the piezometers.
2. After 7 days, the leachate produced by the MSW within the permeameters was drained through lower ball regulator valves. The drainage was complete when the leachate reached the field capacity.
3. A second saturation of the MSW inside permeameters by downflow and stabilization of piezometric levels was performed.
4. Five liters of leachate from each permeameter and the measurement of the time required to do it were collected for posterior flow-rate calculation.
5. A third saturation of the MSW within the permeameters through downflow and stabilization of piezometric levels was performed.
6. Five liters of leachate samples were collected for physicochemical analysis. During this collection, the hydraulic heads were measured in the piezometric panel and the corresponding time was read to determine saturated hydraulic conductivity (K_{sat}).

The saturated hydraulic conductivity (K_{sat}) was determined by Darcy's law, according to Eq. (1), for each variation in hydraulic head between the piezometers installed along the permeameters height (Fig. 1)

$$K_{\text{sat}} = \frac{\Delta V}{\Delta t \times i \times A} \tag{1}$$

where $\Delta V/\Delta t$ = volume change in a given time interval (L^3T^{-1}); K_{sat} = saturated hydraulic conductivity (LT^{-1}), in this case, the MSW saturated hydraulic conductivity was calculated; i = hydraulic gradient (LL^{-1}) represented by the $\Delta H/\Delta L$ ratio, in which ΔH is the variation in hydraulic head between the piezometers, while ΔL refers to the vertical distance between the piezometers; and A = cross-sectional area (L^2) of the permeameter.

The permeability tests were performed weekly and without interruption up to 92 days (about 3 months) for the two permeameters (P1 and P2) in Group 1, and for up to 196 days (about 6.5 months) for P1 and 89 days (about 3 months) for P2 in Group 2. Therefore, there was a total of 17 permeability tests performed for P1 and P2 in Group 1, in addition to 26 tests for P1 and P2 in Group 2, respectively.

Physicochemical Analysis of the Leachate

The physicochemical variables of the leachate samples generated by the MSW during the two groups were determined after testing hydrogen potential (pH), total alkalinity, volatile fatty acids (VFA), oxidation-reduction potential (ORP), electric conductivity, chemical oxygen demand (COD), and ammonia nitrogen. Tests were conducted in accordance with *Standard Methods for the Examination of Water and Wastewater* (APHA 1998), except for total alkalinity [adapted from Ripley et al. (1986)] and volatile fatty acids [adapted from DiLallo and Albertson (1961)].

Results and Discussion

Characterization of MSW

The gravimetric composition, based on the wet weight of MSW samples inserted in Permeameters P1 and P2, is shown in Table 1. The average percentage of organic matter presented in the MSW sample in Group 1 was about 6% greater than the average percentage presented in Group 2, as well as the percentage of plastic, which was about 16% greater. In Group 1, the average percentage of diapers was 2.7 times greater than the percentage in Group 2. In general, both MSW samples presented a high biodegradable fraction (organic matter, wood, paper, and pruning) compared with MSW in developed countries. According to Münnich et al. (2006), developing countries have a high concentration of organic waste in MSW.

Gavelyte et al. (2016) verified that the permeability is incremented because the waste particle size increases and decreases considerably when the particle size diminishes. This is due to the greater free space between large particles, as well as the larger specific surface area and the absorptive nature of the smaller particles such as paper, cardboard, and textiles. Xie et al. (2006) reported that the presence of impermeable plastic fragments decreases the hydraulic conductivity.

Table 1. Gravimetric composition of the MSW samples in the permeameters

	Group 1			Group 2		
	Wet weight (kg)		Average (%)	Wet weight (kg)		Average (%)
Category	P1-1	P2-1	P1-1 and P2-1	P1-2	P2-2	P1-2 and P2-2
Organic matter	14.2	16.5	45.5	13.4	12.1	42.9
Plastic (hard and soft)	4.8	5.5	15.3	4.0	3.6	12.8
Diaper	4.4	5.1	14.1	1.6	1.5	5.2
Paper and cardboard	4.0	4.7	12.9	4.0	3.6	12.8
Tetra Pak	0.5	0.6	1.6	0.4	0.4	1.4
Metal	0.4	0.4	1.2	0.4	0.4	1.4
Glass	0.4	0.4	1.2	0.6	0.5	1.8
Wood	0.03	0.03	0.1	0.3	0.2	0.8
Textiles	—	—	—	1.2	1.1	3.9
Pruning	—	—	—	1.4	1.3	4.5
Construction waste	—	—	—	0.6	0.5	1.8
Toilet waste	—	—	—	1.4	1.3	4.5
Miscellaneous[a]	3.1	2.4	8.1	1.9	1.7	6.1
Total	31.83	35.63	100	31.20	28.20	100

[a] Products such as rubber, foam, shoes, mixed material with more than one category, and hazardous waste such as paint cans, light bulbs, and batteries.

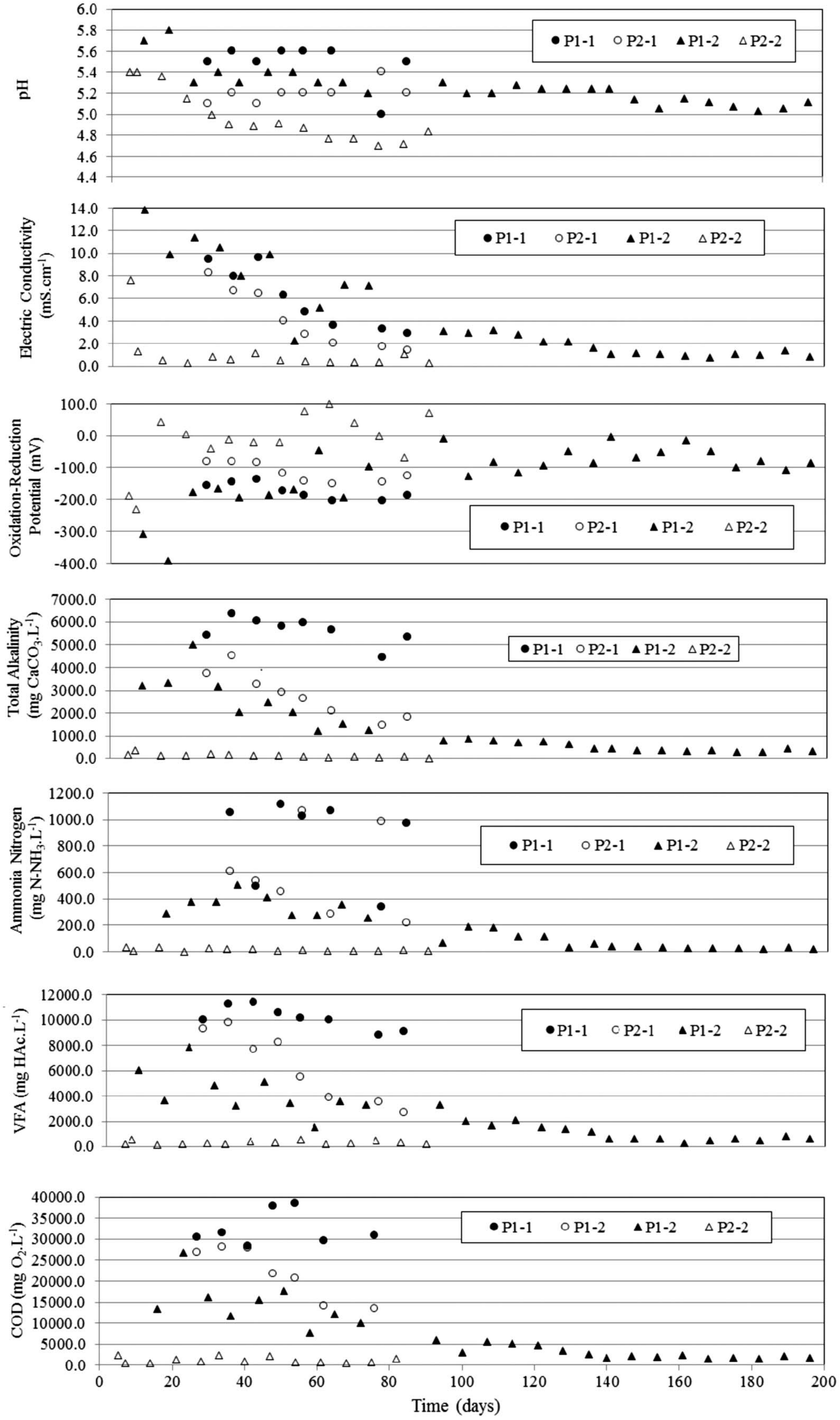

Fig. 2. Physicochemical variables of leachate collected over time.

Table 2. Values of the variables obtained for leachate from P1-1, P2-1, P1-2, and P2-2

	Maximum and minimum values			
Variable	P1-1	P2-1	P1-2	P2-2
Hydrogen potential (pH)	5.0–5.6	5.1–5.4	5.1–5.8	4.7–5.4
ORP (mV)	−205.3 to −138.9	−146.9 to −62.0	−392 to −5.0	−231 to +99
Electric conductivity (mS cm^{-1})	2.9–9.6	1.4–8.2	0.8–13.8	0.3–1.3
Total alkalinity (mg $CaCO_3L^{-1}$)	4,441.1–6,337.3	1,447.1–4,491.0	271–500	14–366
Ammonia nitrogen (mg $N\text{-}NH_3L^{-1}$)	337.7–1,111.5	215.0–1,069.3	19–508	0–36
VFA (mg HAc L^{-1})	8,802.0–11,384.0	2,699.3–9,740.9	260–7,849	147–575
COD (mg O_2L^{-1})	28,291.0–38,466.0	13,401.0–28,043.0	1,477–26,699	422–2,333

Physicochemical Characterization of the Leachate

The results of physicochemical analyses of leachate samples collected in the permeameters are shown in Fig. 2. Variations of the values obtained are presented in Table 2. All variables analyzed showed a decrease over time for the two permeameters (P1 and P2) in both groups, except for the oxidation-reduction potential.

Both MSW samples remained in acid conditions into the permeameters, with pH values ranging from 4.7 to 5.8 (Table 2). The frequent saturation of the MSW, performed as part of the permeability tests, led to an intense leaching of the nutrients required for complete the MSW anaerobic biodegradation. This leaching was more intense in P2-2 because of its lower unit weight value and higher void ratio, and therefore greater volume of water for saturation.

According to Ko et al. (2015), increasing the contact area between waste particles enhances the mass transfer process, which can promote the MSW biodegradation. Nonetheless, this increased contact at the beginning of anaerobic biodegradation increases acidic inhibition for methanogenic microorganisms. The leachates generated in P1-1, P2-1, and P1-2, with the higher MSW unit weight, and thus greater contact area between the waste particles, had virtually the same behavior for up to 3 months of operation time. Variable values decreased (except for the oxidation-reduction potential), but the values of COD and VFA remained high, indicating little activity of microorganisms; moreover the low pH values suggest that MSW within these permeameters was in the anaerobic acid phase (Kjeldsen et al. 2002). The anaerobic acid phase is characterized by the accumulation of short-chain carboxylic acids because of the imbalance between the activity of the hydrolytic and fermentative microorganisms and the acetogenic and methanogenic microorganisms (Barlaz et al. 2010). As a result, the pH decreases. Liu et al. (2013) reported that low values of pH inhibit the ability of methanogenic microorganisms and affect the gas production. The aerobic phase did not occur because the MSW remained saturated from the beginning of the permeability tests.

On the other hand, the variable values of the leachate generated from P2-2, which had the lowest MSW unit weight, showed different behavior. The pH values remained low, as did the values of COD and VFA from the beginning of the tests. This fact suggests that the MSW confined in P2-2 had reached the methanogenic phase in 1 week, and this phase was predominant over time. The methanogenic phase is characterized by the consumption of the acids accumulated in the anaerobic acid phase and converted to methane (CH_4) and carbon dioxide (CO_2) by the methanogenic microorganism (Kjeldsen et al. 2002). As a result, COD and VFA concentrations decrease and the pH increases, which did not occur in this research.

Fei et al. (2015) observed that MSW saturation and leachate recirculation accelerated the initiation of the methanogenic phase, resulting in rapid MSW biodegradation and methane generation. Although the leachate recirculation was not performed in this research, the MSW confined in the permeameters was subjected to the leaching processes weekly, and it was more intense in P2-2. These processes eliminated the nutrients necessary for the activity of microorganisms, so MSW remained in the anaerobic acid phase.

After 3 months, the MSW confined in P1-2 presented the same behavior as the MSW in P2-2, with low values of COD and VFA concentrations under acid conditions. The leaching processes that occurred in the MSW samples were less intense because of the lower void ratio and therefore smaller volume of water for saturation. Then the nutrients for the activity of microorganisms were leaching gradually, and consequently the COD and VAF concentrations were also decreasing.

Saturated Hydraulic Conductivity of MSW

The values of saturated hydraulic conductivity of the MSW confined into P1 and P2 permeameters in Groups 1 and 2 versus time are shown in Fig. 3. The average and the maximum and minimum values are presented in Table 3.

The influence of unit weight in saturated hydraulic conductivity values (K_{sat}) was duly noted, as it has already been by Chen and Chynoweth (1995), Powrie et al. (2005), and Jie et al. (2013), among other authors. The MSW with higher unit weight presented lower saturated hydraulic conductivity values.

Considering the variation of saturated hydraulic conductivity (K_{sat}) values of MSW over time, there are different behaviors at P1 and P2 in both stages. The K_{sat} decreased over time for the MSW confined in P2-2. However, in P1-1, P2-1, and P1-2, K_{sat} values increased for up 3 months, with P1-2 tending to stabilize after this time. Chen and Chynoweth (1995) observed that in each permeability test performed in MSW columns, the hydraulic conductivity declined sharply during the first few days, followed by an increase. In this research, there was a strong relation between the K_{sat} behavior and the behavior of the leachate variables (Figs. 2 and 3).

Hossain et al. (2008) and Reddy et al. (2011) had already commented on the reduction of MSW permeability according to its biodegradation process, in which the matrix structure of MSW particles is broken into smaller particles. In this study, physicochemical analysis of the leachate over time indicated that the MSW confined in permeameters experienced biodegradation, but remained in the anaerobic acid phase. Therefore, an increase of the percentage of the fine fraction (passing US Sieve No. 200) should occur. Nonetheless, the decrease in K_{sat} in P2-2 could not be related only by increasing the percentage of the fine fraction.

Gases were generated inside the permeameters by the MSW biodegradation and were drained through the piezometers (Fig. 1) for a week before the permeability tests performed in saturated conditions. Chen and Chynoweth (1995) observed the gas generation inside MSW columns even after being soaked for several days. In

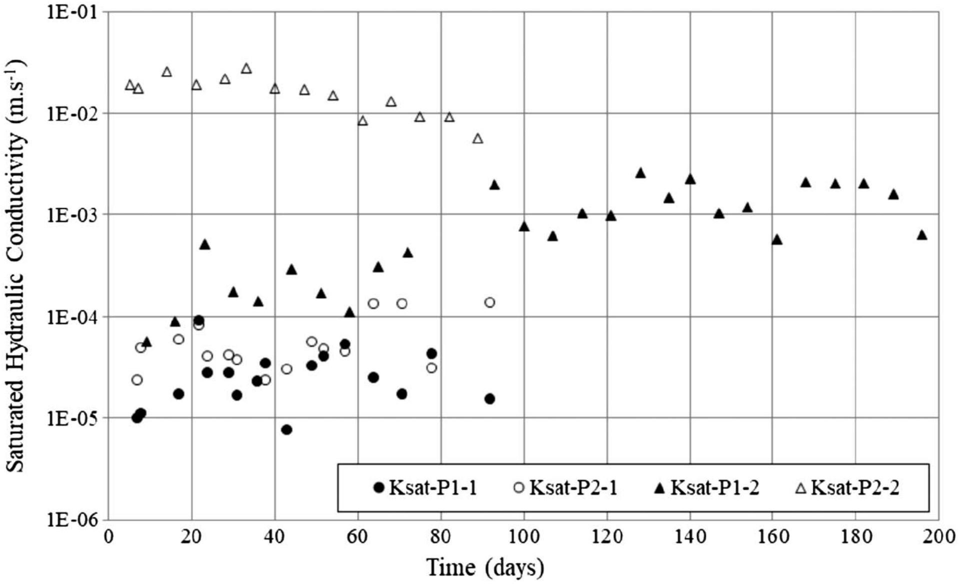

Fig. 3. Saturated hydraulic conductivity over time.

Table 3. Results of the permeability tests

Hydraulic parameter	Permeameter and group			
	P1-1	P2-1	P1-2	P2-2
Average saturated hydraulic conductivity $(m \cdot s^{-1})$	2.8×10^{-5}	5.7×10^{-5}	1.0×10^{-3}	2.0×10^{-2}
Maximum saturated hydraulic conductivity $(m \cdot s^{-1})$	9.0×10^{-5}	1.3×10^{-4}	3.0×10^{-3}	1.0×10^{-2}
Minimum saturated hydraulic conductivity $(m \cdot s^{-1})$	7.4×10^{-6}	2.3×10^{-5}	6.0×10^{-5}	6.0×10^{-3}

P2-2, the gas drainage was facilitated due to the sample's higher porosity, and consequently its higher number of intercommunicating pores. Powrie et al. (2008) reported that gas accumulation could occur very quickly inside a compression cell filled with saturated MSW. Liu et al. (2013) reported that the pore gas pressure was not the same throughout the whole section of a MSW sample; the values increased as the depth increased. Thus, it is reasonable to consider that the gas flowed toward the piezometers under different pressures.

The space formerly occupied by the gas is then invaded by the MSW particles, leading to a decrease in the volume of voids, and consequently in the permeability of the sample (Fig. 3). Thus, the K_{sat} of the MSW confined in P2-2 probably decreased due to the increase in the fine particles percentage, a function of the MSW biodegradation, associated with the decrease in the volume of voids due to the free drainage of internal gases during the 7 days before the permeability tests. Ke et al. (2017) observed that compression has a much greater influence on the reduction of K_{sat} than degradation because it exerts influence on the geometric properties of the waste particles and pores. Chen and Chynoweth (1995) presented the possibility the declined hydraulic conductivity is associated with the relative movement of fine particles, creating a denser matrix. In this research, the reduction of the MSW samples was not measured, but was clearly observed.

In the case of the MSW confined to P1-1, P2-1, and P1-2, the unit weight was higher, and therefore the number of intercommunicating pores and porosity was smaller. During the 7 days before the permeability tests in saturated conditions, it is believed that the gases generated were more difficult to drain and went out through the piezometers. Depending on the gas pressure, the gas can carry smaller particles and change the MSW mass structure. As a result, there was an increase in the volume of voids without immediate accommodation of the particles. As a consequence, the permeability tests were performed in an MSW with greater porosity, resulting in increased K_{sat} (in one order of magnitude for P2-1, and two orders for P1-2) (Fig. 3).

After 3 months, considering only P1-2, K_{sat} values stabilized (Fig. 3) until the end of this test (196 days), while the values of physicochemical variables of the leachate generated also began to stabilize (Fig. 2), but remained in acid conditions. The explanation for this behavior was based on a hypothesis. The increase volume of voids (3 months before) allowed the multiplication in the intercommunicating pores, and consequently the drainage of gas was facilitated during the 7 days before the permeability tests. After 3 months, the MSW remained a structure that could maintain a stable flow as well as permeability (Fig. 3) until 196 days.

Conclusion

The procedure adopted for the permeability tests influenced the fresh MSW biodegradation, and consequently the hydraulic behavior of the MSW samples. The physicochemical analysis in the leachates generated by the MSW within the permeameters indicated that the biodegradation occurred and remained in the anaerobic acid phase. The leachate generated by MSW remained inside the permeameters for 7 days before being drained. This procedure was performed weekly, which resulted in intense leaching of the MSW, leading to changes in the biodegradation process.

A strong relation was observed between the MSW samples' hydraulic behavior and the behavior of the leachate variables over time. The gases generated by MSW samples before the permeability tests were drained through piezometers and this flow caused changes in MSW structures, which influenced the values of hydraulic conductivity, while the permeability tests were performed in saturated conditions (without gas).

In the permeameter containing MSW with lower unit weight and higher number of intercommunicating pores, the K_{sat} values decreased over time (about 3 months) because of increase in fine fractions, a consequence of the biodegradation process, and from the accommodation of the MSW because of the facilitated drainage of gases generated before the permeability tests. Moreover, the values of physicochemical variables of the generated leachates remained low, indicating little microbial activity as a result of nutrient leaching.

In permeameters containing MSW with higher unit weight and lower number of intercommunicating pores, the K_{sat} values increased for up to 3 months and then tended to stabilization. Values of physicochemical variables of the generated leachates gradually decreased for up to 3 months and then stabilized at lower values after this time. The increase in K_{sat} until almost 3 months was interpreted as resulting from the increased volume of voids in the confined MSW samples. The 7-day gas drainage before the permeability tests was more difficult to perform without an immediate accommodation because of the high unit weight and movement of the MSW particles. After 3 months, the samples' permeability tended to stabilization, as well as the values of the leachate's physicochemical variables produced.

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