Effects of bio-clogging on leachate exposed geotextiles for filter and drainage layer construction.

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ABSTRACT

Geotextiles are products of uttermost importance for filter and drainage layer construction in landfills barriers systems, they allow to control leachate levels inside dumping cells. The most relevant hydraulic properties considered in the design of these layers are aperture opening size, hydraulic conductivity and hydraulic transmissivity, which can be affected by biological clogging during landfill operation since these layers are in constant contact with fluids that possess high biological activity, like leachate. In this research, the effect of biological clogging on woven and non-woven geotextiles was investigated by immersing geotextiles samples in three different fluids (deionized water, natural leachate and nutrient solution) and determining the change in their hydraulic conductivity after different times of immersion. General trends observed show that hydraulic conductivity decreases with time for specimens immersed in natural leachate and nutrient solution. Finally, the effects of changes in the hydraulic gradient were explored in order to allow an increase in flow rate that might help to remove biofilm from geotextile fibers.

1. INTRODUCTION

Despite reductions in waste generation, landfills facilities are a requirement for safe disposal of municipal solid waste because of the continual increase in its quantities due to population growth and increase in industrial activity. Landfills are accompanied by environmental issues such as the generation of leachate and gases, which must be correctly controlled and treated. Through an engineering point of view, the long-term performance of these facilities depends on a system composed by three main sub-systems: the barrier system below the waste, the landfill operations and the landfill cover and gas collection system (Rowe, 2011). At this stage it is important to highlight that one of the most significant aspects is to guarantee the barrier system hydraulic performance during the lifespan of the landfill.

Typical landfill liner systems are composed of layers with different specific functions. Filtration layers and drainage layers are among those. The main function of these layers is to minimize the leachate head over the low hydraulic conductivity layers in order to limit contaminant migration through the underlying barrier. The correct design of this system is of importance because landfill operations that can affect the performance of the entire system include cleaning and maintenance of leachate collection subsystem.

Filtration and drainage layers can be composed by geosynthetics or granular materials, with the advantage that geosynthetics are more cost-effective, easy to install and transport, and because of their strict quality control during manufacturing (Christopher and Fischer, 1992). Failure of the system mentioned above is said to occur when the hydraulic conductivity drops to the point where the leachate collection system can no longer control the leachate head to the design value. The accumulation of leachate, a complex and heterogeneous fluid, can lead to problems in the stability of the waste mass (Koerner *et al*, 1999), or an increase in the loss of contaminants through the underlying low permeability layer, resulting in a decrease of the expected lifespan of the landfill. Some notable failures attributed to slides as consequences of leachate head inside dumping cells are Central Maine (Reynolds, 1991), Kettleman Hills, California (Byrne et al., 1992) and Cincinnati, Ohio (Kenter et al., 1997).

The increase of the leachate head that results in the failure of these systems can arise from clogging of the drainage layer and/or filter layer due to physical clogging, soil grain or waste particles intrusion, particulate material precipitation and the build-up of biofilm (Colmanetti *et al.*, 2002; Koerner *et al.*, 2015). The objectives of this research are to evaluate and quantify the effects of bio-clogging in the hydraulic performance of woven and non-woven geotextiles that are commonly employed in filter and drainage layers construction.

2. BACKGOUND

2.1 Filter and Drainage layers geotextile design

Geotextiles products have been used as filters and drains due to their successful application in geotechnical engineering and environmental earthworks. Geotextiles as filters allow the flow of leachate across its plane and retain suspended particulate material, whilst as drains they allow the flow within its plane and drive the leachate towards an extraction point outside of the dumping cells (Koerner, 2012). The primary leachate collection system must be designed in order to ensure that an allowable maximum hydraulic head value is not surpassed inside the cells. This liquid head depends on the rate of liquid supply, the leachate collection layer slope, the distance between drain tubes and the hydraulic conductivity and hydraulic transmissivity of the materials (Giroud *et al*., 2000).

Hydraulic conductivity and hydraulic transmissivity are not constant material properties, they depend on the hydraulic gradient and as a consequence on the slope of the leachate collection system. Darcy's law is an empirical relationship for liquid flow through a porous medium, expressed by Equation 1, which proves hydraulic conductivity (k) as a function of the hydraulic gradient (i):

$$q = k.i \qquad [1]$$

Because of what was mentioned above, the determination of the maximum leachate head in the leachate collection system is of uttermost importance. There are several equations available for determining maximum leachate head in drainage layer, among them one of the most applied in practice is the one proposed by Giroud et al. (1992) (Equation 2).

$$t_{max} = j\frac{\sqrt{\tan^2\beta + \frac{4q_h}{k}} - \tan\beta}{2\cos\beta}L \qquad [2]$$

Where β is the slope of the leachate collection layer (assumed to be smaller than 90 degrees), q_h is the rate of liquid supply, L the length of the layer, k the hydraulic conductivity of the layer, and j is a dimensionless correction factor calculated using Equation 3, where ϑ is a dimensionless parameter calculated by Equation 4:

$$j = 1 - 0{,}12\exp\left[-\left[\log\left(\frac{8\vartheta}{5}\right)^{\frac{5}{8}}\right]^2\right] \qquad [3]$$

$$\vartheta = \frac{q_h}{k\ tan^2\beta} \qquad [4]$$

On the other hand, there are numerous empirical methods available for geotextile filter design, most of them include a retention component, a drainage or permeability component and a clogging resistance criteria (Cristopher and Fischer 1992, Luettich *et al*., 1992).

Geotextiles acting as drains and filters have to cope with severe mechanisms of chemical, physical and biological clogging that affect the hydraulic performance of the material.

2.2 Geotextile bio-clogging

The reduction in hydraulic conductivity of geosynthetics caused by bio-clogging mechanisms is the result of pore-level phenomena such as bacterial transport and attachment, bacterial growth, multiplication, biomass accumulation, and the development of micro-colonies and biofilms on the surface of geosynthetics, with the consequent reduction in pore space. This process self-regulates through different mechanisms such as the rate of biomass generation and the rate of removal, which is larger as the hydraulic gradient increases through the obstruction zone. (Mitchell *et al.* 2005). Koerner and Koerner (1990) performed ninety-six test columns with leachates from six domestic landfills to evaluate the tendency to clog of both geotextile and natural soil filters; 36% of the tests showed major clogging with a 75% to 95% flow reduction, and 15% of the tests showed severe clogging with a 95% to 100% flow reduction.

Bio-clogging mechanisms affect the long term hydraulic performance of geotextiles acting as filters and drains. A way to quantify the consequences of bio-clogging is through the impregnation ratio proposed by Palmeira and Gardoni (2000), λ, calculated as the relationship between the total mass of particles in the geotextile and the total mass of fibers of the geotextile. While clogging increases, hydraulic conductivity and hydraulic transmissivity are affected, Equation 5 allows to calculate the change in the hydraulic conductivity of partially clogged geotextiles:

$$k^* = \frac{\beta \rho_w g}{\eta_w} \cdot \frac{\left[n - \lambda \cdot \frac{\rho_f}{\rho_s} \cdot (1-n)\right]^3}{\left(\frac{4}{d_f} + \lambda \cdot \frac{\rho_f}{\rho_s} \cdot \frac{6}{d_s}\right)^2 (1-n)^2} \qquad [5]$$

Where, η_w is the fluid dynamic viscosity, ρ_w is the specific gravity of the fluid, g is the acceleration of gravity, d_f is the fiber diameter, β is the shape factor, d_s is the diameter of the soil particles inside the geotextile, ρ_f is the density of the geotextile fibers, ρ_s is the density of the soil particles and n is the porosity of the geotextile. Palmeira *et al.* (2008) presented relevant results for long-term permittivity tests using leachate to evaluate biological clogging of nonwoven geotextiles.

3. MATERIALS AND METHODS

3.1 Geotextiles products tested

This research analyzes two types of geotextiles products: a woven geotextile (WG) and a non-woven geotextile (NWG). The WG consists of loops of polypropylene straps having an opening size (O_{90}) of 250 µm, a mass per unit area of 0.027 g/cm^2 and a thickness of 0.75 mm. The NWG consists in a needle-punched geotextile manufactured by continuous filaments of polyester with an opening size of 18000 µm, a mass per unit area of 0.027 g/cm^2 and a thickness of 1.53 mm. The geotextile samples were carefully cut into circles with of 10 cm diameter in order to fit into the flexible wall permeameter cell. Figure 1 shows pictures of both geotextile types analyzed.

3.2 Main characteristics of fluids employed

Three different fluids were used for the hydraulic conductivity test: deionized water (DIW), natural landfill leachate (NL) and a nutrient solution (NS). The NS was prepared with 2% glucose, 0.1% NaCl, 0.1% yeast extract, 0.1% $MgSO_4.7H_2O$, 0.08% K_2HPO_4, 0.02% KH_2PO_4 and 7.5×10^{-4}% $FeCl_3$ (Glatstein and Francisca, 2014).Table 1 summarizes the main chemical and biological properties of the natural leachate used.

Employed fluids were selected in order to have data that allowed a correct analysis of bio-clogging impact on geotextile hydraulic properties. DIW test results were considered as the reference situation where no biological activity was expected, NL tests intended to represent as best as possible operational landfill conditions. The nutrient solution was prepared in order to analyze what occurs and the impact of bio-clogging under the best conditions for microbiological growth.

Table 1: Chemical and biological properties of leachate

Property	Value
Lead	15.9 µg/L
Chrome	92 µg/L
Heterotrophic aerobic bacteria	71400 UFC/ml
Total coliform bacteria	16000 NMP/100ml
Fecal coliform bacteria	1700 NMP/100ml
Escherichia coli	Present
Pseudomonas aeruginosa	Present

3.3 Bio-clogging batch tests

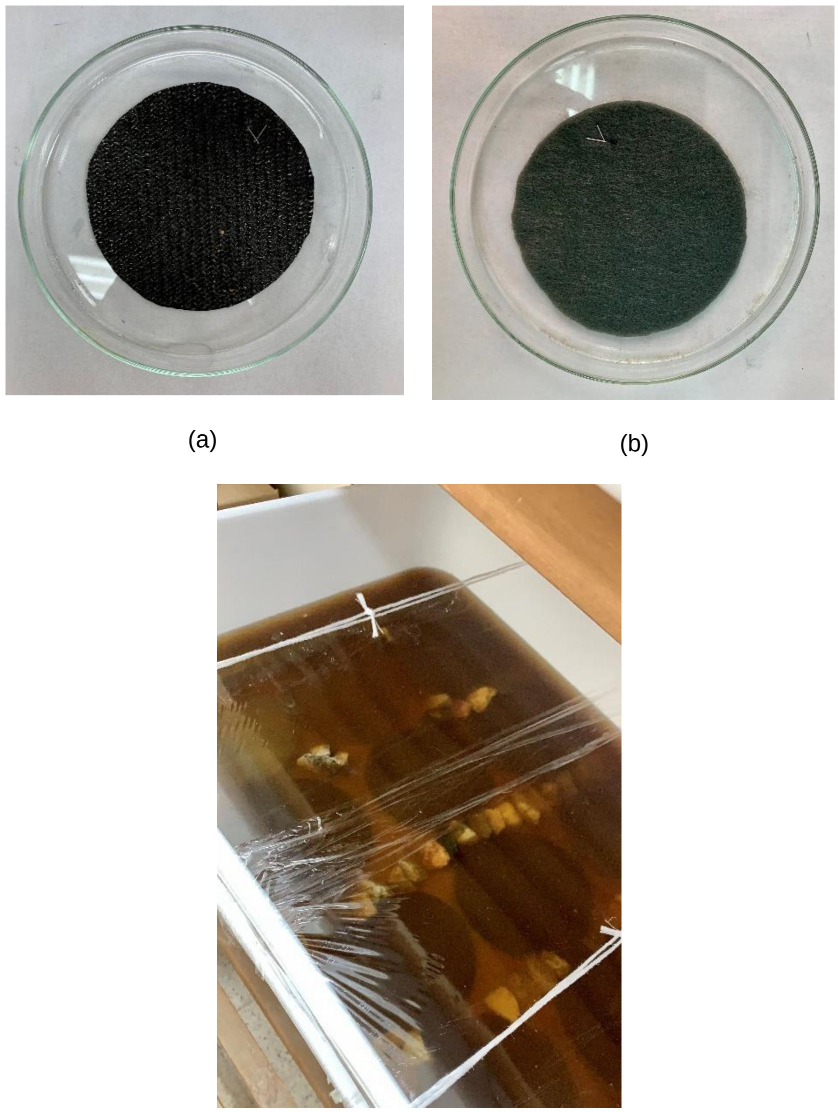
The research program described in this paper involved bio-clogging batch tests on both types of geotextiles using the three different fluids mentioned above, impregnation ratio tests and microscopic observations of geotextile specimens at different stages during the research program.

Bio-clogging batch test consisted in immersing 54 disks of each type of geotextile in recipients containing the three different fluids mentioned in the previous section. These 54 disks involved 27 duplicated samples that were used one for impregnation ratio tests and microscopic observation, and the other for the corresponding hydraulic conductivity test. All disks were weighted in a 0.0001 g precision balance in order to determine their dry weight. After that, disks were immersed in 15 different recipients that contained the three different fluids. Immersion time ranged for a period that varied between seven and 98 days. Each recipient contained five liters of fluid and was carefully covered with a plastic film to prevent impurities intrusion inside the recipients. In order to ensure that geotextile specimens were submerged all the time, a fiberglass net was placed in each recipient with counterweights in its lateral ends. Figure 1 shows a picture of the geotextiles disks placed in the recipient. Biological activity in the recipients containing NL and NS were monitored by measuring the chemical oxygen demand (COD) and the pH of the fluids every week.

At predetermined time intervals duplicated specimens of geotextiles were removed from the recipients for impregnation ratio tests and hydraulic conductivity tests. Right before testing any of the samples, their weight was measured in wet condition.

For the impregnation ratio tests, after weighting the samples, they were placed in an automatic oven for drying at 50 ºC during 48 hours. After that, their dry weight was determined in order to obtain the impregnation ratio.

Each geotextile disk was observed under an optical microscope in wet and dry conditions which allowed evaluating the formation of biofilms at the surface of the specimens.



(a) (b)

(c)

Figure 1: (a) picture of the WG disk, (b) picture of the NWG disk, (c) picture of disks submerged in leachate.

3.4 Hydraulic conductivity test

Hydraulic conductivity tests were performed in a flexible wall permeameter using the constant head technique following the general guidelines of the ASTM D5887 standard procedure (ASTM 2014).

The test assembly started with the preparation of the porous stones and filter paper sheets, which were submerged in tap water overnight to guarantee their full saturation before testing. For the assembly of the cell, a porous stone and a filter paper sheet were placed on top of the bottom cap; after this the geotextile specimen was placed and on top of it a superior filter paper sheet, a superior porous stone and finally the top cap.

A flexible membrane was placed over the totality of the lateral surface of the assemblage that contains the specimen, and was fixed using four O-rings (two in each cap). After that, all necessary tubing was connected, and the cell was adequately closed. The cell was filled with water, taking care that no air bubbles remained trapped inside that could affect the measurements. Then, valves were connected to a Mariotte bottle, the confining water column and the graduated effluent flask respectively. Confinement of the cell was achieved by a 112 cm height water column. The geotextile specimen was subjected to an upward water flow in order to facilitate the removal of air bubbles during the system saturation.

Once the system was completely saturated and visually checked for the absence of air bubbles occluded in the conducts, the hydraulic conductivity test was performed by measuring the time required to collect 100 cm^3 volume of water in the effluent flask. Measurements were repeated three times, in a consecutive way, in order to obtain an average value.

For the specimens submerged 98 days, the hydraulic conductivity was determined at three different hydraulic gradients, increasing it in a gradual and incremental form in three steps, in order to evaluate the effects of an increase in flow rate for removing biofilms from geotextile fibers.

4. TEST RESULTS AND ANALYSIS

4.1 Impregnation ratio

Filters and drainage layer materials clogging can be quantified by determining mass increase of the material after being placed in the corresponding barrier layer for a period of time. For the particular situation of geotextiles clogging, it can be quantified by determining the impregnation ratio. Figure 2 presents the variation of the impregnation ratio with time for woven and non-woven geotextile specimens submerged in deionized water, natural landfill leachate and nutrient solution.

The impregnation ratio is a parameter directly proportional to the total mass of microorganisms attached to the fibers of the corresponding geotextile specimens. Therefore, the general tendency observed in the figure indicates that the ratio increases with time for the specimens immersed in NL and NS as the biological activity is more severe than for the specimens immersed in DIW. Furthermore, impregnation ratio values for NWG specimens immersed in NL and NS are higher than the ones corresponding to WG specimens. This trend can be explained given that NWG specimens possess a bigger aperture opening size, hence the more available space for the development of biofilms in comparison to WG. As mentioned above, the tests performed using DIW present the baseline for comparison, showing a constant impregnation ratio and approximately equal to zero during the testing period, highlighting in this way the importance of the magnitude of pore clogging due to the biological activity on the other fluids.

As indicated in the preceding section, chemical properties changes due to biological activity in the NL and NS were monitored with time by measuring pH and COD. Variations in these two parameters for both fluids are expected due to oxygen consumption by bacterial growth. Figure 3 and Figure 4 show the variation of COD and pH with time during the testing period. Figure 3 presents a general tendency for the pH of NL and NS samples, whereas time passes values tend to a neutral pH or slightly basic, close to 8. The most important variation occurs for the nutrient solution due to higher biological changes in time than for leachate. At this stage it is important to highlight that microbiological growth was not the same, or constant, for all recipients containing NS or NL. This observation is supported by the difference in values of pH measured in the same day for the different recipients. In regards to the COD variation, values increase as time passes for NL while for the NS, COD decreases until day 71, and then increases until it reaches values similar to the ones at the beginning of the testing time. This trend is because samples for the analyses were taken from different recipients, and, as mentioned above, the microbiological development seems not to be the same in all recipients, mostly for the case of NS.

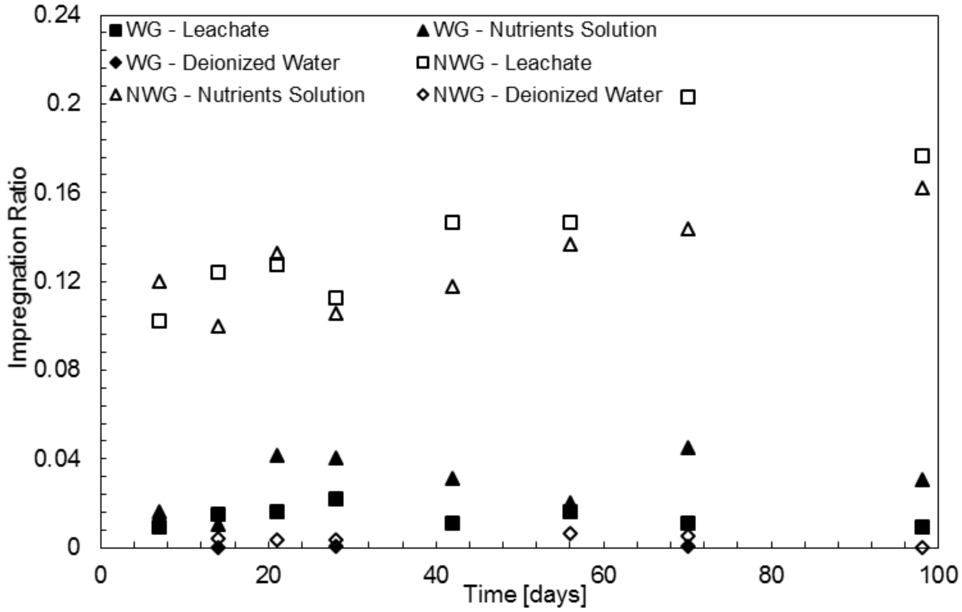


Figure 2: Variation of the impregnation ratio in time for woven and non-woven geotextile specimens submerged in deionized water, natural landfill leachate and nutrient solution.

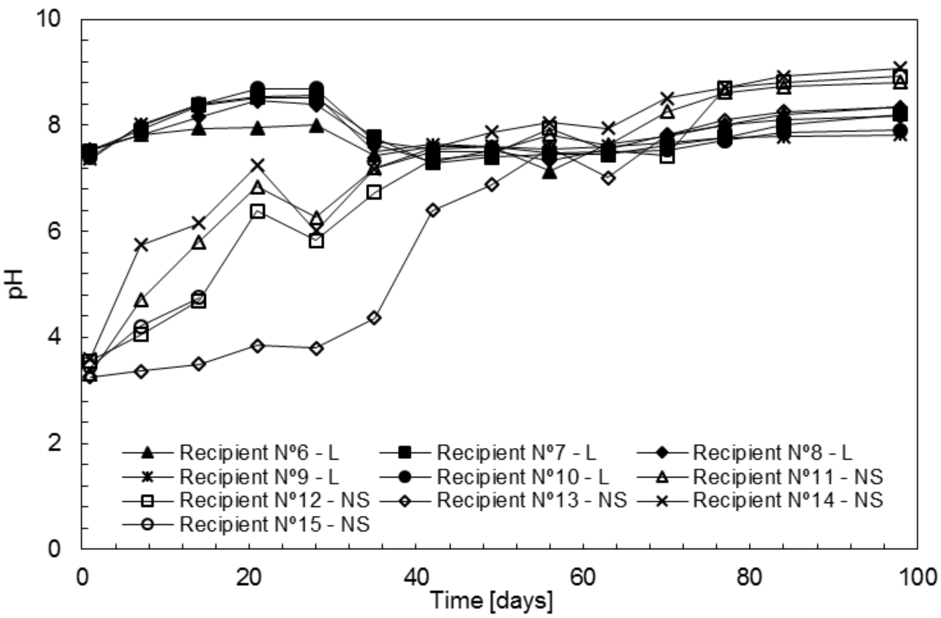
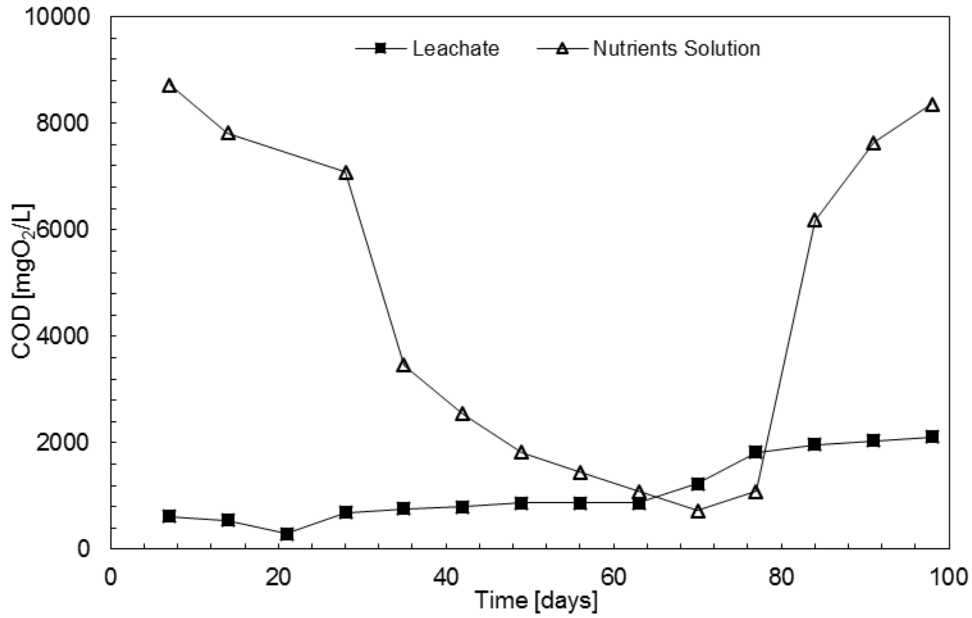


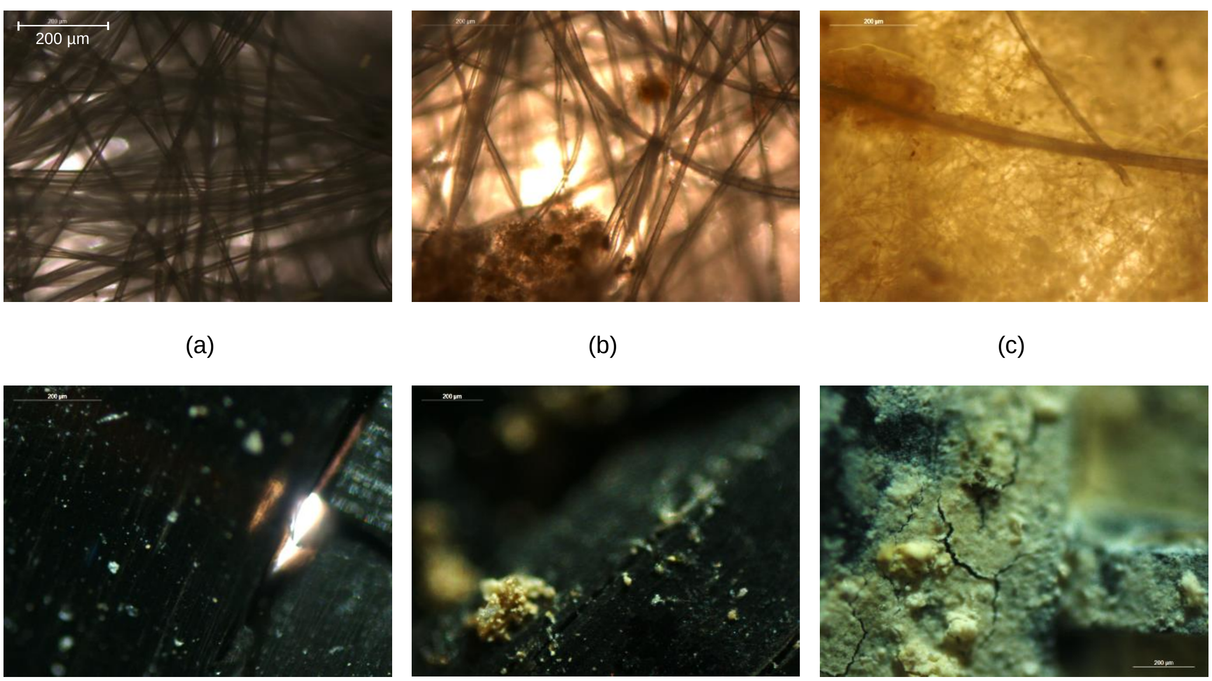
Figure 3: Variation of pH with time for natural landfill leachate and nutrient solution.

These trends were also verified by qualitative analysis from optical microscopy images. Figure 5 presents microscopic images of WG and NWG samples in wet and dry conditions, immersed in DIW, NL and NS taken after 21 days of immersion. All images were acquired with the same optical magnification. Figures 5 (a), (b) and (c) are images of NWG immersed in DIW, NL and NS respectively. It can be observed a clear contrast between the microbiological growths for the three different fluids. As can be seen, fibers immersed in DIW were clean, whereas a biofilm surrounding the fibers can be observed for the other two fluids. The analysis of the complete set of microscopic pictures allowed to determine that for NWG, the microorganisms first adhered to the individual fibers and then developed the biofilm over the surface of the material. Figures 5 (d), (e) and (f) are images of WG immersed in DIW, NL and NS, respectively. The same contrast between the microbiological growths was observed than that for the WG, but in this case, the microorganisms first developed between the fibers crossing and then formed the biofilm over the surface of the specimen. For both types of geotextiles, it is evident an increase in the presence of bacterial colonies over time.



(b)

Figure 4: Variation of COD with time for natural landfill leachate and nutrient solution.



(a) (b) (c)

(d) (e) (f)

Figure 5: Microscopic images after 21 days of immersion, (a) NWG immersed in DIW (wet condition), (b) NWG immersed in NL (wet condition), (c) NWG immersed in NS (wet condition), (d) WG immersed in DIW (dry condition), (e) WG immersed in NL (dry condition), (f) WG immersed in NS (dry condition).

4.2 Hydraulic conductivity

Figure 6 shows the variation on hydraulic conductivity with time for WG and NWG exposed to natural leachate and nutrient solution. The values for hydraulic conductivity are of uttermost importance because this parameter allows optimizing the filter and drainage layer's design by calculating maximum leachate head using for example Giroud's equation. Independently on the type of geotextile considered, results show a decreasing tendency of hydraulic conductivity with time, proving that bio-clogging mechanisms affect the hydraulic performance of the specimens. Furthermore, the decrease in hydraulic conductivity for WG is more affected due to the smaller geotextile opening size, so even though the developed biofilm mass was less, the consequences were higher because a smaller mass was required to clog the pores and affect the flow rate.

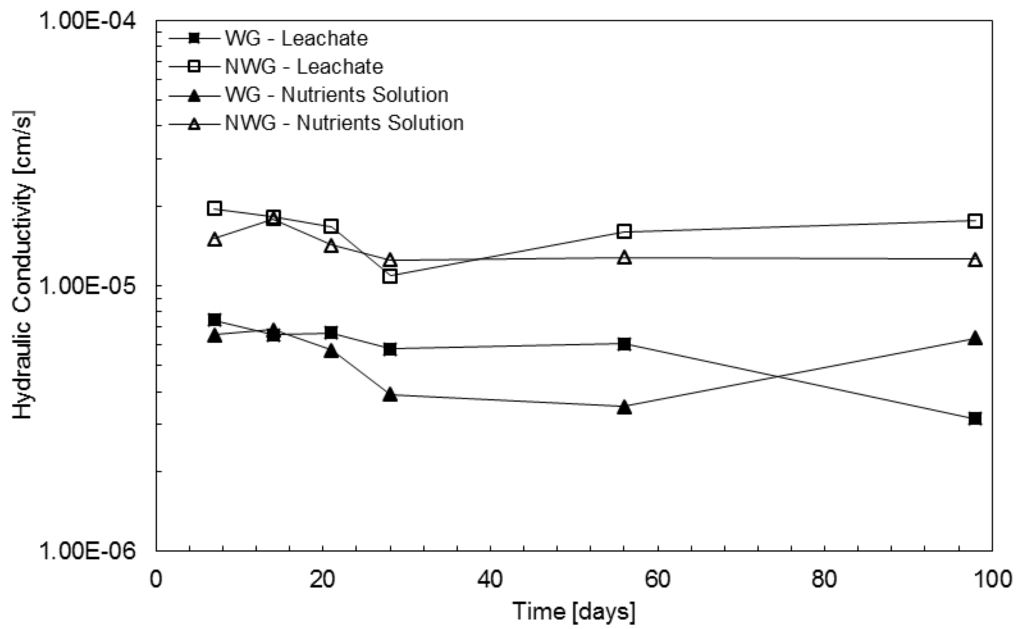
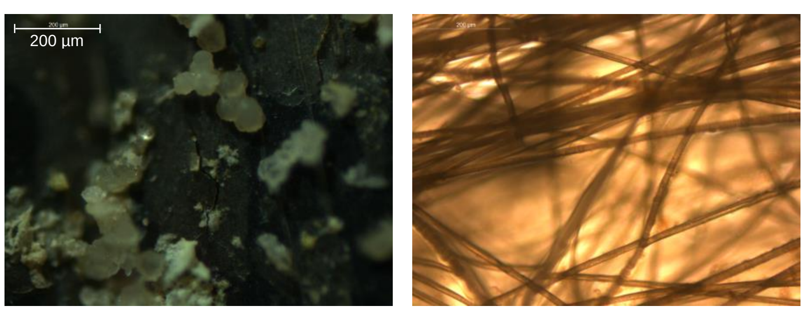


Figure 6: Variation of hydraulic conductivity with time of woven and non-woven geotextiles exposed to natural landfill leachate and nutrient solution.

Not all the values obtained for day 98 coped the general tendency observed because, as it was mentioned before, the biological activity for the different recipients was not the same, resulting in geotextile specimens less affected by bio-clogging and higher hydraulic conductivity values. The observation was supported by the images obtained by optical microscopy. Figure 7 (a) shows the image of the woven geotextile immersed 98 days in nutrient solution and (b) shows the image of a non-woven geotextile immersed the same period of time in leachate. Although bacteria colonies formed in the specimens, the level of development was not the expected compared to previous values.



(a) (b)

Figure 7: (a) Woven geotextile immersed 98 days in nutrient solution, (b) non-woven geotextile immersed 98 days in leachate.

The values of the normalized hydraulic conductivity coefficient are presented in Figure 8 for geotextile specimens in natural landfill leachate and nutrient solution. Hydraulic conductivity values are normalized considering the initial value for specimens of each type of geotextile tested after one day of immersion in deionized water. After the first two weeks, changes in the coefficient between fluids were not significant, indicating that bio-clogging mechanisms produced a significant change from the third week. The general tendency was the same as the observed for Figure 5. The maximum percentage of change for the normalized hydraulic conductivity coefficient was calculated for WG and NWG immersed in natural leachate. The NWG suffered a 44.3% decrease and the WG a 57.5% decrease.

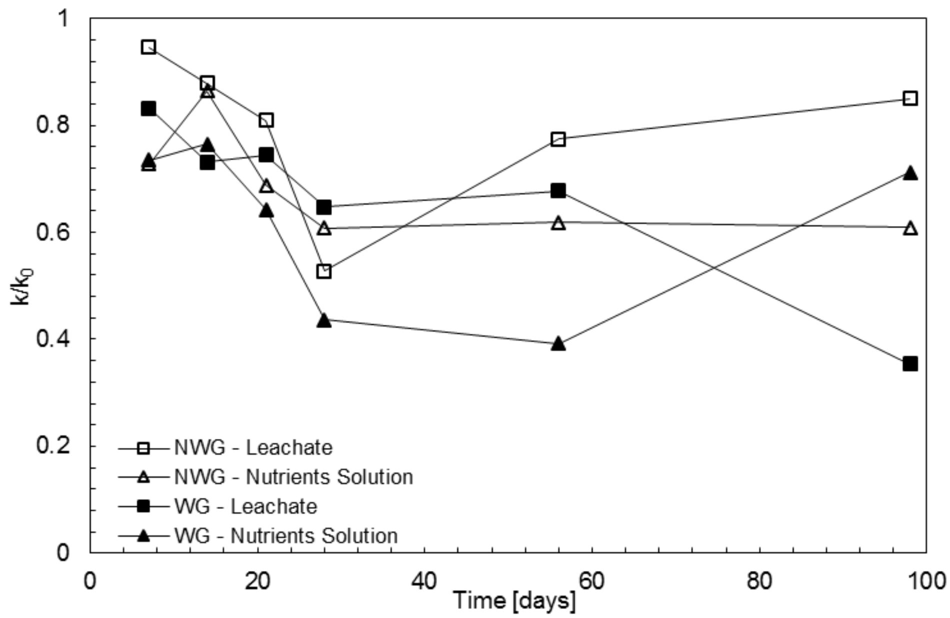


Figure 8: Normalized hydraulic conductivity coefficient variations with time for NWG and WG immersed in natural landfill leachate and nutrient solution.

One of the common strategies suggested for cleaning up clogged filters and drains was to prepare the drainage system in order of being able to invert flow direction increasing the hydraulic gradient (Koerner and Koerner 1992). This increase in hydraulic gradient allows an increase in flow velocity and its drag force that might contribute in removing bio-films that clog the permeable layers.

In order to evaluate the effect of hydraulic gradient on the removal of biofilm, disks immersed in NL and NS during 98 days were tested at three different hydraulic gradients. Figure 9 shows the change in flow rate with the change in hydraulic gradient for WG and NWG. As it can be observed there is a clear increase in flow rate with the increase in hydraulic gradient, however that increase can be closely fitted by a straight line, highlighting that the hydraulic conductivity, which according to Darcy's law is the proportionality constant between hydraulic gradient and flow, remains constant for each geotextile type. Therefore, only the increase in hydraulic gradient wasn't enough to remove the biofilms and to allow the increase of hydraulic conductivities of filter and drainage layer. Hence, other hydraulic gradients magnitudes should be considered, having in mind that those hydraulic gradients magnitudes must be possible to achieve in the field or a different maintenance methods should be explored.

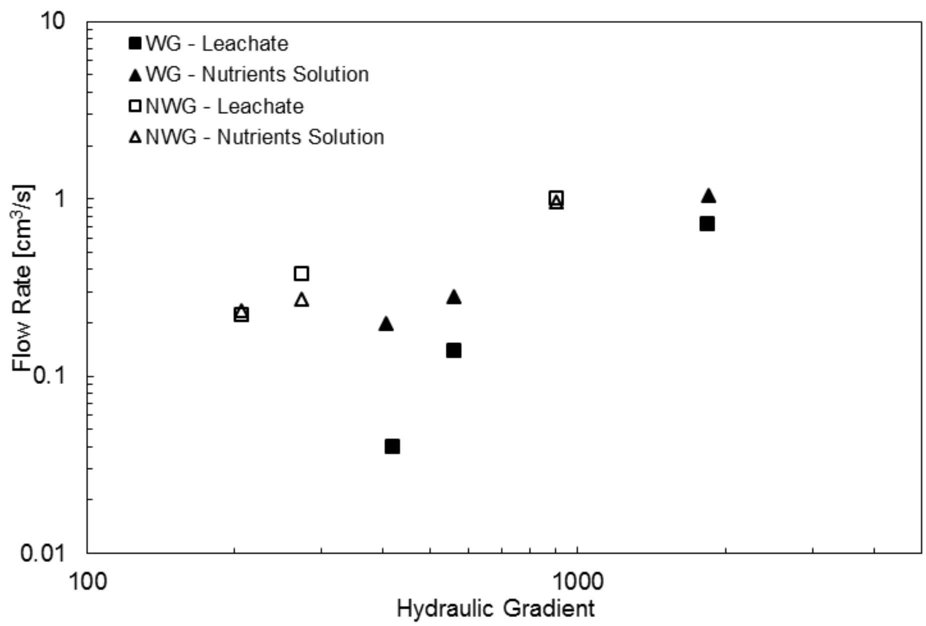


Figure 9: Change in flow rate with hydraulic gradients for WG and NWG immersed in natural landfill leachate and nutrient solution.

5. CONCLUSIONS

This research analyzed the effects of bio-clogging mechanisms on the filter and drainage layers in landfill barrier systems. This was accomplished by performing a variety of test that included bio-clogging batch tests, hydraulic conductivity and impregnation ratio tests. Chemical analysis of natural leachate and nutrient solution were carried in order to determine the changes in pH and COD of these fluids, and optical microscopy observations of geotextile specimens were carried out to understand and evaluate the magnitude of the biological clogging. The main conclusions can be summarized as follows:

- The impregnation ratio for both types of geotextiles showed an increase over time for those immersed in natural leachate and nutrient solution. However, the values were higher for non-woven geotextiles.
- Because of the formation of biofilms on geotextile specimens immersed in natural leachate and nutrient solution, the geotextile opening size of the materials decreased, resulting in a decrease in hydraulic conductivity.
- The increase of 5 times the hydraulic gradient in order to remove the biofilms adhered to the geotextile specimens was not successful. Higher hydraulic gradients should be analyzed to maintain a high hydraulic conductivity to guarantee the filter and drainage layers performance, taking into consideration that the values must be reproducible in the field.

From the results obtained from different tests and the analyses performed in this research, it is evident that bio-clogging should be addressed as a key phenomenon to consider in the design of the filter and drainage layers. Overlooking this factor could lead to the accumulation of a leachate head higher than the allowed by design criteria, resulting in the malfunction of the landfill barrier system and a reduction in its lifespan.

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