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Hydraulic conductivity of compacted soils controlled by microbial activity

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The hydraulic conductivity defines the displacement of liquids inside porous media and affects the fate and transport of contaminants in the environment. In this research the influence of microbial growth and decay inside soil pores on hydraulic conductivity is analysed. Long-term tests performed in silt–bentonite mixtures permeated with distilled water and a nutrients solution demonstrated that hydraulic conductivity of compacted silt–bentonite samples decreases with time of permeation as a bioclogging mechanism develops. The injection of antibiotics and antifungals in the specimens produces a rebound in the hydraulic conductivity associated with the decay of microbial activity. These results show that biomediated reactions can be used to control the flow rate through compacted soil liners.

Keywords: earthen liners; hydraulic conductivity; microbes; landfills; barriers; organic mater

Introduction

Displacement of liquids inside soil pores has been extensively studied in the past.[1–3] Hydraulic conductivity of soils depends on porosity, soil fabric, particle size distribution, specific surface area, spatial variability of porosity, presence of swelling clay minerals, and permeating liquid density, viscosity and ionic strength.[4–9]

Soil microstructure and bentonite content are the most fundamental soil properties considered in the construction of earthen liners to restrict the displacement of contaminated water or groundwater.[10,11] The hydraulic conductivity of soil liners must be as low as possible in order to prevent fluid displacement and contaminant transport. Therefore, fine particle soils, usually with more than 5–7% bentonite content, are frequently used as construction material for earthen liners.

Soils are often considered to be abiotic, thus the biological activity therein is often overlooked. However, the microbiological aspect of a soil affects hydraulic conductivity, stiffness, compressibility and shear strength of soils, promoting changes up to two or three order of magnitude in these soil properties during bioremediation, biomineralization (calcite precipitation), organic precipitation (biofilms) or gas generation.[12–14] On these matters, most efforts have addressed the increase in stiffness and shear strength by biomediated carbonate precipitation in soils [15–17] and construction materials [18]; the detrimental effects of bioclogging in drainage systems [19,20]; or the decrease in

hydraulic conductivity of compacted soil liners permeated with leachate due to bioclogging mechanisms.[21]

The purpose of this research is to evaluate the relative importance of bentonite content, biomass accumulation in soil pores and permeating liquid properties on the long-term hydraulic conductivity of compacted silt–bentonite mixtures. The results obtained show the utility of biological control of soils, where the impact of microorganisms is understood in terms of potential increases or decreases in soil hydraulic conductivity.

Bioclogging and hydraulic conductivity

The presence of microorganisms within pores can obstruct flow paths and decrease soil hydraulic conductivity.[22] This behaviour is widely thought to be the mechanism for bioclogging.[23] Bacteria, fungi and yeast live in the pore voids and consequently pore and throat sizes can affect the growth of microorganisms.[24]

Hydraulic properties of soil are frequently related to porosity, soil fabric, grain shape and mineralogy, and representative grain size diameter. While hydraulic conductivity (k) of saturated soils can be affected by liquid properties, absolute permeability (K) is assumed to be a porous media property, and they are related with each other as follows:

$$K = k \left(\frac{\mu}{\rho g} \right), \quad (1)$$

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where g is the gravitational constant, ρ is the fluid density and μ is the fluid viscosity. In addition, the hydraulic conductivity k is theoretically related with soil and liquid properties by means of the Kozeny–Carman equation [25]:

$$k = \left(\frac{\rho g}{\mu} \right) \frac{1}{k^* T^2 S_0^2} \left(\frac{e^3}{1+e} \right) S^3, \quad (2)$$

where T is the tortuosity, k^* is the pore shape factor, S_0 is the wetted surface area per unit volume of particles, e is the void ratio and S is the degree of saturation.

Equation (2) shows that any change in void ratio affects hydraulic conductivity. Then, microorganism growth in the pore space reduces the effective porosity, which is the porosity available for liquid displacement.[26–28] Thus, when the initial void ratio e_0 reduces to e_f due to the biomass that accumulates in the pores, the reduction in hydraulic conductivity from k_0 to k_f can be computed as follows:

$$k_r = \frac{k_f}{k_0} = \frac{1+e_0}{1+e_f} \left(\frac{e_f}{e_0} \right)^3, \quad (3)$$

where k_r is the relative hydraulic conductivity. Equation (3) assumes negligible changes in fluid density and viscosity, tortuosity and specific surface or pore shape factor. Reduction of pore space due to biomass accumulation is frequently presented in terms of either void ratio (e) or porosity (n) which are related with each other as follows:

$$n = \frac{e}{1+e}, \quad (4)$$

$$e = \frac{n}{1-n}. \quad (5)$$

Table 1 summarizes accepted theoretical and empirical models frequently used to evaluate the influence of a

decrease in porosity (or void ratio) on k caused by bacteria and yeast growth. Accepted models consider different mechanisms affecting hydraulic conductivity, which are associated with the presence of uniform biofilm formation, cell aggregation and colony growth. The presence of occluded gas bubbles generated by bacteria and fungi respiration may also be responsible for hydraulic conductivity and effective porosity reductions.

Materials and methods

The hydraulic conductivity of compacted silt–bentonite mixtures was evaluated by following the ASTM D5856 standard procedure.[31] Table 2 summarizes the relevant properties of the two soils that were used as components for the soil specimens studied in this research. Microscopic properties of soils were identified by means of scanning electron microscopy (SEM) images. Figure 1 shows an SEM image of the silt–bentonite mixture before compaction and permeation.

Particle size analysis showed that the silty soil was formed by fine sand (4%), silt (92%) and clay (4%) particles (ASTM D422 [31]). The main minerals constituting the silt fraction are quartz, feldspar and calcite, as identified by X-ray diffraction. By means of polarized light petrography it was also possible to identify volcanic glass, biotite, altered fragments and ferrous aggregates. The clay fraction was mainly constituted by illite (81%) and kaolinite (12%). The specific surface of the soil was 2500 m²/kg and the cation exchange capacity (CEC) was 3.2 meq/kg.

The clay was a natural bentonite consisting of more than 92% of sodium montmorillonite, with a specific surface area of 731,000 m²/kg and CEC = 934 meq/kg.

Table 1. Influence of pore volume changes on hydraulic conductivity.

| Main mechanism | Equation | References |
|--|---|------------|
| Volume occupied by colonies or bulk colloids. | $k_r = (n_r)^{3-2p}$ $k_r = F(B) (1-B)^2 + [1-F(B)] \left(\frac{a}{a+B-aB} \right)$ | [22] |
| Uniform biofilms accumulation and cell aggregates. | $F(B) = \exp \left[-0.5 \left(\frac{B}{B_c} \right)^2 \right]; B = \left[1 - \left(\frac{n_f}{n_0} \right) \right]$ | [23] |
| Bacterial growth. | $k_r = (n_r)^{19/6}$ | [29] |
| Bacteria growing in a colony-enveloping space | $k_r = \left[1 - \frac{[(n_0 - n_f)/(\beta_e(1 - n_0)) + 1]^{1/3} - 1}{[\tau/(1 - n_0)]^{1/3} - 1} \right]^3$ | [30] |
| Bacteria growing in colonies | $k_r(n_r) = d \left(\frac{n_r - n_0^*}{1 - n_0^*} \right)^3 + (1+d) \left(\frac{n_r - n_0^*}{1 - n_0^*} \right)^2$ | [26] |
| Presence of biofilms | $k_r(n_r) = \left[\left(\frac{n_r - n_0^*}{1 - n_0^*} \right)^b + k_{rel}^{min} \right] \left(\frac{1}{1 + k_{rel}^{min}} \right)$ | [26] |

Note: n_r = relative porosity (n_f/n_0); n_0 = initial porosity; n_f = final porosity; p = fitting parameter; B = biovolume fraction; a = model parameter (average 2.5×10^{-4}); B_c = fitting parameter; β_e = enveloping factor ($\beta_e = 1$ for a real biofilm); τ = shape factor; d = fitting parameter ($-2 < d < -0.5$); n_0^* = relative porosity at which there is no flow; b = fitting parameter and k_{rel}^{min} = minimum relative hydraulic conductivity when all porosity is filled with microorganisms.

Table 2. Main physical properties of tested soils.

| Property | Silt | Bentonite | Standard |
|--|---------|-----------|------------------|
| Specific gravity | 2.63 | 2.71 | ASTM D 854 [31] |
| Particles < 7.4×10^{-5} m (%) | 96.0 | 100 | ASTM D 422 [31] |
| Particles < 2×10^{-6} m (%) | 4.0 | 80.1 | ASTM D 422 [31] |
| Liquid limit, LL (%) | 27.0 | 285.0 | ASTM D 4318 [31] |
| Plasticity Index, PI (%) | 2.8 | 240.0 | ASTM D 4318 [31] |
| Specific surface, SS, (m^2/kg) | 2,500 | 731,000 | [32] |
| Cation exchange capacity (meq/kg) | 3.2 | 934 | [33] |
| Soil classification | CL – ML | CH | ASTM D 2487 [31] |

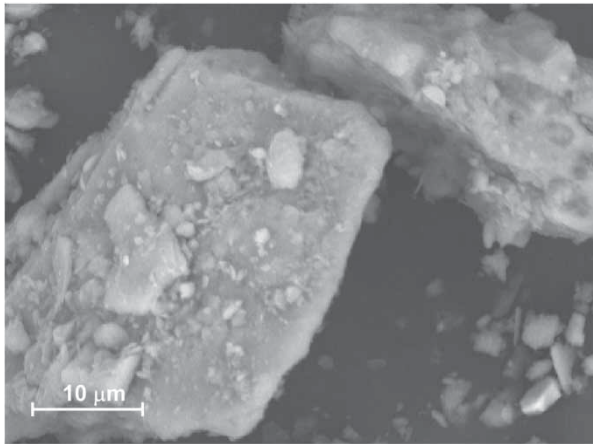


Figure 1. SEM image of the silt-bentonite mixture.

The permeating liquids were (a) distilled water (DW), (b) a nutrients solution (NS), and (c) an antibiotics and antifungal solution (AAS). The NS was prepared with 2% glucose, 0.1% NaCl, 0.1% yeast, 0.05% $MgSO_4$, 0.08% K_2HPO_4 , 0.02% KH_2PO_4 and 7.5×10^{-4} % $FeCl_3$, [34] while the AAS had the same composition as NS but with the addition of chloramphenicol (2000 kg/m^3), gentamicin sulphate (50 kg/m^3) and nystatin (50 kg/m^3). [35,36] The presence of biomass in the soil specimens is assumed to be associated with the presence and growth of bacteria and yeast in the NS.

The soils were oven dried at 105°C for 24 h and thereafter the silt was mixed with 0%, 5% and 10% of Na-bentonite. Silt and bentonite were thoroughly mixed until a homogeneous sample was obtained. The compaction moisture content was 20% in order to achieve a dispersed fabric given that the optimum moisture content determined by using the standard proctor energy (ASTM D698 [31]), ranged from 17.6% to 19.6%. Therefore, the

expected hydraulic conductivity is lower than for specimens with the same void ratio but compacted in the dry side of the compaction curve where a flocculated fabric is expected. [37]

The wet soils were compacted in rigid-wall compaction-moulds using the standard proctor energy. Initial porosities of compacted specimens varied from 0.40 to 0.45. Hydraulic conductivity tests were performed by following the falling head technique during 25 months. Hydraulic gradients ranged from 5.6 to 2.1. No significant influence of the hydraulic gradient on hydraulic conductivity was observed within this range.

Different specimens were permeated with DW and NS. For selected specimens permeated with the NS, the permeating liquid was changed to the AAS after 18 months of testing. This change in the permeating liquid allows for the determination of the relevance of bioactivity on flow rate.

The presence of biomass was determined analysing the effluent after permeation by means of the heterotrophic plate count technique, following the American Standard Methods for the Examination of Water and Wastewater, [38] and by the SEM analysis of selected specimens after permeation. The amount of biomass could not be determined given the extremely low hydraulic conductivity of the tested specimens and therefore long time was required to collect a significant amount of effluent.

Results

The hydraulic conductivity of silt-bentonite mixtures permeated with DW experienced negligible changes over time (Figure 2). However, the specimens permeated with the NS showed a decrease in the hydraulic conductivity with time of permeation (Figure 3). At the beginning of permeability tests ($t = 0$), the hydraulic conductivity of the samples compacted with NS was higher than those tested with DW for each bentonite contents. These results highlight the relevance of ionic concentration of the compacted and permeation liquid on soil fabric. The presence of ions

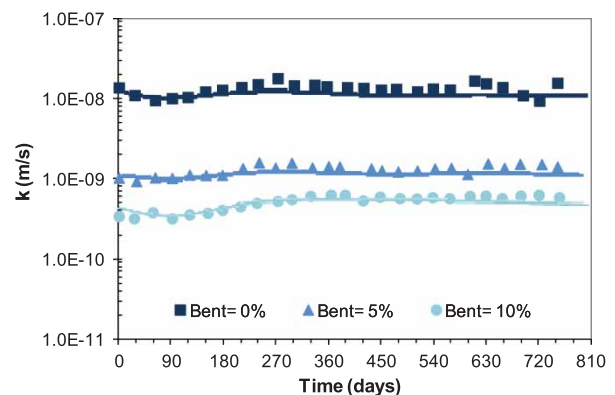


Figure 2. Long-term hydraulic conductivity of compacted silt-bentonite specimens permeated with DW. Bentonite contents, Bent = 0%, 5% and 10%.

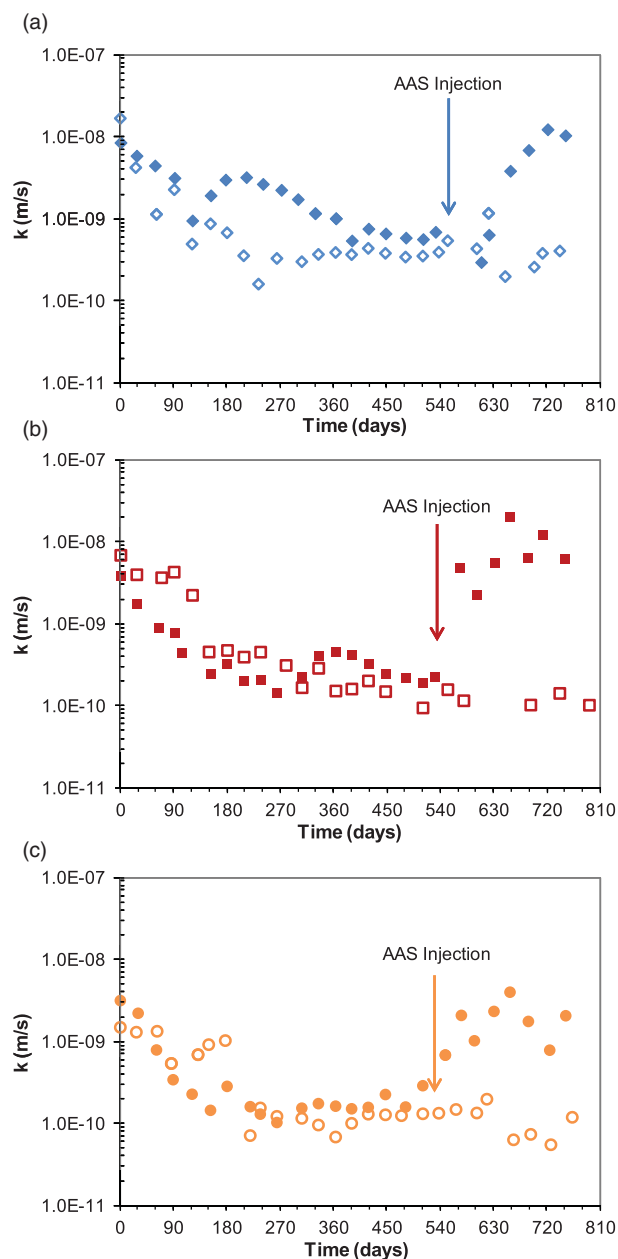


Figure 3. Long-term hydraulic conductivity of compacted silt-bentonite mixtures permeated with NS; (a) 0% bentonite, (b) 5% bentonite and (c) 10% bentonite.

Note: Filled symbols represent the specimens that were injected with the AAS.

in the NS favours the formation of a more flocculated and permeable soil fabric.[39]

Regardless of the amount of bentonite, the hydraulic conductivity of samples permeated with NS decreased more than one order of magnitude during the first 6–12 months of testing. This time-dependent hydraulic conductivity was observed even when the permeating liquid properties remained constant during the test.

Figure 3 shows the experimental results obtained in two identical samples prepared with 0%, 5% and 10% of bentonite. In one of these twin specimens (filled symbols), the

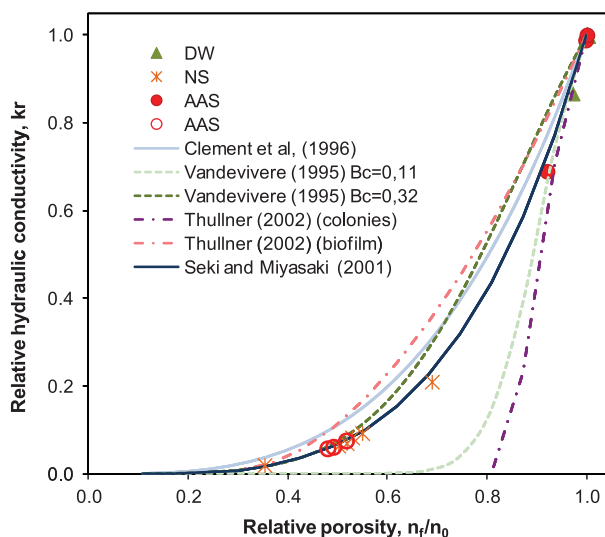


Figure 4. Influence of relative porosity on relative hydraulic conductivity.

Note: DW = distilled water, NS = nutrient solution, empty circles before AAS injection and filled circles after AAS injection.

permeating liquid was changed after 18 months of permeation, replacing the NS by the AAS. As result, the hydraulic conductivity of the specimens showed a clear rebound effect by approaching the values determined during the first 30 days of permeation. Then, in these specimens the initial and final hydraulic conductivities had similar values. The change in ionic concentration between the NS and AAS was negligible, and therefore, observed fluctuations in hydraulic conductivity were attributed to changes in the amount of biomass.

The observed decreases in hydraulic conductivity were associated with bioclogging mechanisms. The physical and empirical models presented in Table 1 were calibrated in order to confirm the relevance of biomass accumulation in the pore space on hydraulic conductivity.

The increase in the amount of biomass over the long-term tests clearly reduced the effective porosity, partially blocking flow paths initially occupied by bulk water. Figure 4 shows the obtained relationship between the relative hydraulic conductivity defined in Equation (3) and the change in soil porosity defined as the ratio between final and initial porosities (n_f/n_0).

All specimens had initial porosities that fell in a very narrow range given that they were prepared and compacted identically. The initial conditions cannot be responsible for any significant difference in void ratio (Equation (5)), or hydraulic conductivity according to Equation (2) [$k \propto (e^3/1 + e)$]. Bentonite content also had a very small influence on the relative hydraulic conductivity in long-term tests. In all cases, k_r values close to one are observed when the permeating liquid is DW, given that $k_0 \cong k_f$ (Figure 2). However, k_r ranged from 10^{-3} to 10^{-1} when specimens were permeated with the NS.

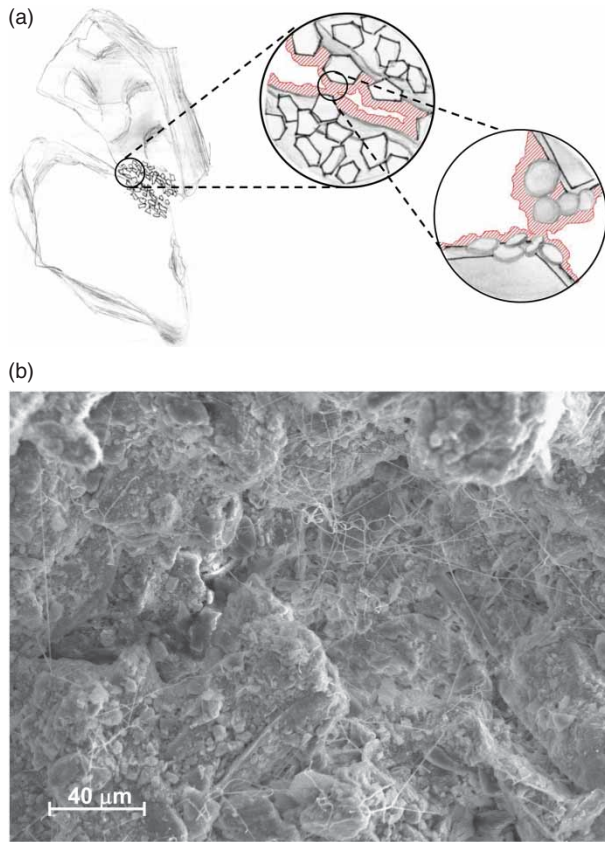


Figure 5. (a) Schematic representation of microbial growth in pores; (b) SEM image showing microbial exopolysaccharides in the pores of a specimen with time-dependent hydraulic conductivity (filament-like structures).

Figure 5 shows a schematic representation of the main mechanisms responsible for pore clogging and consequent decrease of k . Coarse particles are held together by means of interconnecting groups of fine particles that are surrounded by biomass as shown in Figure 5(a). All pores are available for liquid displacement before biomass forms, but effective porosity decreases due to the presence of colonies and biofilms. Figure 5(b) shows the SEM image with the presence of microbial exopolysaccharides (EPS) in the bulk of pores which confirms the presence of microorganisms in the soil pores during the test.

Discussion

Changes in void ratio affect the hydraulic conductivity of compacted soils, which can be used for the development of new bio-stimulated liners and porous media filters. Figure 6 compares the initial and final void ratios of tested samples. Initial void ratio e_0 was obtained from mass–volume relationships, while final void ratio e_f is computed from k_r , e_0 and Equation (3). All final void ratios were close to 10–30% of e_0 . However, void ratio changes were negligible in the case of the specimens permeated with DW and in those injected with the AAS. This effect was attributed to the

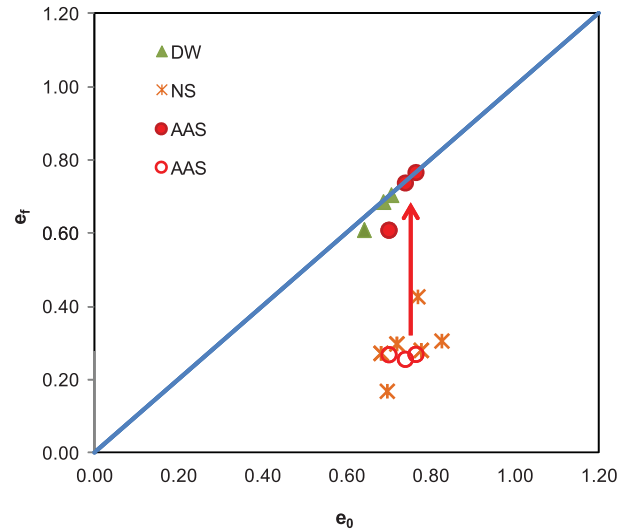


Figure 6. Comparison between initial void ratio, e_0 , and final void ratio, e_f , of tested specimens.

Note: DW = distilled water, NS = nutrient solution, empty circles before AAS injection and filled circles after AAS injection.

biomass reduction produced by the injection of antibiotics and antifungals.

Figure 7 shows the simultaneous effect of bentonite content and biomass accumulation on the expected final hydraulic conductivity of compacted silt–bentonite mixtures. The hydraulic conductivity of the samples decreased as the bentonite content increased. Similar trends were previously reported by others.[40,41] When permeated with DW, the bentonite content is the most significant property controlling the flow rate. Compacted silt–bentonite mixtures required more than 6% bentonite content in order to achieve hydraulic conductivities lower than 1×10^{-9} m/s as required by most of current regulations for landfill liners.[42] The influence of bentonite content was less important in the specimens permeated with the NS given that the flow rate was controlled mainly by biomass accumulation in the soil pores and the consequent reduction in the effective void ratio ($e \downarrow$).

Figure 7 also shows how the hydraulic conductivities of silt–bentonite mixtures permeated with the NS and then injected with antibiotics and antifungals increased significantly. In fact, final hydraulic conductivities of compacted silt–bentonite mixtures permeated with the AAS were higher than that registered when the permeating liquid was DW. The high ionic concentration of NS and AAS can be responsible for this emergent behaviour given the expected reduction of the diffuse double-layer thickness,[43] and explains why this increase appears in barriers with bentonite. There is no evidence of fabric changes due to the microbial growth even that flow path lengths are affected by the biofilms. There is still a need of determining the influence of bacterial growth on fabric changes.

Flow in porous media can be controlled by manipulating biomass growth which also affects mass transport

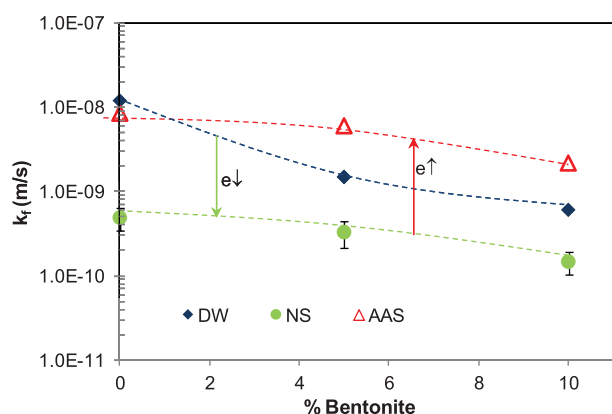


Figure 7. Influence of bentonite content and bacteria growth and decay on the hydraulic conductivity of compacted silt-bentonite mixtures.

Note: DW = distilled water, NS = nutrient solution, AAS = antibiotics and antifungal solution. Error bars represent a 95% confidence interval.

mechanisms.[44] The growth of bacteria requires specific conditions of oxygen and moisture content, temperature, nutrients content, pressure and inhibiting substances; thus, the manipulation of hydraulic conductivity can be performed by controlling these conditions (Figure 7). Low hydraulic conductivity barriers could be obtained by favouring the development of bioclogging mechanisms, and conversely, biomass growth could be diminished if higher flow rate and system performance are needed.

Conclusions

This work analyses the influence of biological activity on the displacement of liquids in porous media. The main conclusions of this work can be summarized as follows:

- The hydraulic conductivity of compacted silt-bentonite mixtures permeated with DW shows negligible changes over time.
- The hydraulic behaviour of compacted soil can be modified by the stimulation of microorganisms in the pores related to the injection of nutrients. The observed decrease in hydraulic conductivity can be mainly related with bioclogging mechanisms.
- The replacement of the NS by an AAS promotes an increase in hydraulic conductivity. The final conductivity of silt-bentonite mixtures is higher when permeated with the AAS in comparison with DW due to the shrinkage of the diffuse double layer around bentonite particles.
- Controlling the hydraulic conductivity of compacted silt-bentonite mixtures shows great potential for the development of effective earthen barriers and the development of new applications for permeable barriers. This effect can be generated by manipulating the growth and decay of microorganisms in soil pores.

- Microorganism growth may contribute to reduce the bentonite content necessary to achieve hydraulic conductivities lower than 10^{-9} m/s. Also, the time required for the percolation of leachate through compacted soil liners increases as a consequence of bio-mediated reactions. However, reduction of hydraulic conductivity cannot be permanent if microorganism development is inhibited.

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