Field Permeability Tests Using Organic Liquids in Compacted Brazilian Soils

S.L. Machado, Z.S. Carvalho, M.F. Carvalho, D.F. Mariz

Abstract: This paper presents results of field and laboratory permeability tests aimed at evaluating the performance of mineral barriers for the containment of organic liquids (Non Aqueous Phase Liquids, NAPL). Experimental landfills were constructed following optimal ranges of variation of soil index properties proposed previously and the performance of the landfills was evaluated under two distinct weather conditions (rainy and dry periods). A primary test campaign was performed during the rainy period (March to August). Then a second testing campaign was performed from November 2013 to January 2014 (months of low rainfall). The obtained results corroborate several results published in the technical literature: fluids with a low dielectric constant (non polar) tend to present higher intrinsic permeability ($K_\text{intrinsic}$) than polar fluids and the presence of water, the most wettable fluid, reduces the NAPL permeability. Soils with a higher plasticity index, $I_p$, presented higher $K_\text{w}/K_\text{NAPL}$, (ratio water/NAPL intrinsic permeability) showing that the values of $K$ are dependent on the interactions between solid particles and interstitial fluid. Based on laboratory and field results, optimal ranges of variation of soil index properties are proposed for the construction of mineral barriers for organic liquid containment.

Keywords: intrinsic permeability, hydrocarbons, compacted soil barriers, NAPL.

1. Introduction

Leakage of organic fluids such as aromatic solvents, liquid fuels and polycyclic aromatic hydrocarbons (PAHs) from storage tanks and distribution/transport structures has been identified as one of the most important sources of contamination of soils and water (CETESB, 2013). As well as this, petroleum derivates are most frequently Light Non Aqueous Phase Liquids (LNAPL) whose characteristics such as density, surface tension, viscosity and polarity (or dielectric constant) differ substantially from water. If these substances are released into the environment a NAPL plume will migrate downward in the subsoil, eventually reaching the capillary fringe and the ground water table. Once in contact with the groundwater, LNAPL will form a volume of free phase that can depress the water table and move laterally in the direction of the groundwater flow. In addition, the soluble constituents of LNAPL can dissolve in the water and migrate under advection, dispersion and retention phenomena.

It is also worth noting that Brazilian gasoline normally contains 24% anhydrous alcohol. When in contact with soil interstitial water and mainly when the contamination plume reaches the ground water table, the alcohol is stripped to water bringing together many gasoline compounds such as BTEX (Benzene, Toluene, Ethyl-benzene and Xylene) which are recognized as carcinogenic. This phenomenon is normally referred to as co-solvency. Fate and transport of petroleum derivates have been studied in Brazil by several authors such as Corseuil & Marins (1997), Kaipper (2003), Silveira (2004), Schneider (2005) and Amorim Jr. (2007), N. Filho et al. (2013), among others.

Mineral liners are the most commonly used containment structures for storage terminals of oil derivates and they are perhaps the most evident example of soil structures where soil permeability is of paramount importance. To protect the environment from possible contamination by pollutants, oil storage areas must be lined. Mineral layers of compacted soil with or without additives are often used because of their relatively low cost, accessibility, durability, high resistance to heat and other factors (Wang & Huang, 1984). However, parameters such as shear strength, shrinkage susceptibility and the compatibility between the contained species and the barrier materials should be addressed in the design of soil liners (Daniel & Benson, 1990, Daniel & Wu, 1993, Shackelford, 2014). Based on Brazilian standards for sanitary landfill construction, compacted soil liners must present water coefficients of permeability values, $k_w < 1 \times 10^{-9} \text{ m/s}$ (NBR 13896, 1997), while in the case of emergency levees for petroleum derive storage areas the NBR 17505-1 (2006) recommends $k_w < 1 \times 10^{-7} \text{ m/s}$.

The use of water as a reference fluid for such structures mostly induces the use of clayey soils. On the other hand, the coefficient of permeability of clayey soils is affected by factors such as specific surface, particle arrangements, degree of saturation, porosity, chemistry and concentration of electrolytes, clay electro-chemical properties and external pressure (Mitchell, 1976). In the case of NAPL flow, the relationship between permeability and the...
physical and chemical properties of the fluid is even more complex, mainly because the dielectric nature of these fluids is very often quite different from water. Petroleum derivatives usually have non-polar compounds which have low relative dielectric constants, \( \varepsilon_r \) (\( \varepsilon_r \) represents the ratio between the dielectric constant of the medium and the dielectric constant of the vacuum). Water, a high polarity fluid, presents values of \( \varepsilon_r = 80 \) whereas most organic fluids present smaller \( \varepsilon_r \) values. In clayey soils, the electrical phenomena that take place around the clay particles make the properties of the fluids present in the pores an important factor in its permeability (Budhu et al., 1991; Goodarzi et al., 2016). Table 1 summarizes the properties of some common liquids which are stored in petroleum industrial areas.

The most widely accepted conceptual model to represent the interactions between the fluid and the clay surface is the diffuse double layer system. This model was developed from the theory proposed by Helmholtz-Smoluchowski and was improved by Gouy-Chapman and Quincke. The diffuse double layer system consists of clay particles, adsorbed cations and water molecules in one layer, while the other is a diffuse layer with the presence of counterions. Although this model ignores the effect of the potential energy in the oriented molecules of water that surround the clay particles, it is useful to explain some basic phenomena in a clay-water-electrolyte system (Fang, 1997). Eq. 1 can be used to predict the double layer thickness, \( t \), based on the Gouy-Chapman theory,

\[
t = \frac{\varepsilon_r \cdot K_b \cdot T}{8 \pi n_e \cdot e^2 \cdot v^2}
\]

where \( K_b \) is the Boltzmann constant, \( T \) is the temperature, \( n_e \) is the electrolyte concentration, \( e \) is the elementary charge and \( v \) is the ionic valence.

As can be seen from Eq. 1, a decrease in the fluid dielectric constant reduces the double layer thickness. As part of the double layer thickness is fixed, reducing its thickness will provide more space in the voids of the soil for fluid flow, increasing the soil permeability. Although this is a very simplistic approach, it is completely corroborated by profuse experimental evidence. Fig. 1 illustrates the effect of the fluid dielectric constant on the soil permeability. According to Anandarajah (2003) among others, the shrinkage of clusters resulting in localized cracks in the soil can also explain part of the wide variations in the measured coefficient of permeability.

The concept of intrinsic permeability, \( K \) [L²], Eq. 2, was proposed by Nutting (1934) and assumes that it depends solely on the soil properties. It is normally used to convert water permeability values in the expected value of permeability for another fluid in the same soil. Eq. 1 normally provides good results in the case of coarse soils, without the presence of considerable amounts of clay. As the clay content of the soil increases, however, the intensity of the solid surface/fluid interactions also increases and begins to play an important role in the values of \( K \) (Brown & Anderson, 1983; Brown & Thomas, 1984; Fernandez & Quigley, 1985; Schramm et al., 1986; Budhu et al., 1991; Amarasinghe et al., 2012; Parker et al., 1986 and Oliveira, 2001).

\[
k = \frac{K \cdot \rho \cdot g}{\mu}
\]

where \( g \) [LT⁻²] is gravity acceleration, \( \rho \) [ML⁻¹] is the fluid density and \( \mu \) is fluid dynamic viscosity [ML⁻¹T⁻¹].

The influence of the liquid polarity (or \( \varepsilon_r \)) on the \( K \) value has been recognized by many authors (Mesri & Ol-

Table 1 - Liquid properties at 20 °C (Carvalho, 2015).

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Density ( \rho ) [gcm⁻³]</th>
<th>Dynamic viscosity ( \mu ) [gcm`s⁻¹]</th>
<th>Mobility (( \rho/\mu )) [scm⁻²]</th>
<th>Relative dielectric constant - ( \varepsilon_r ) (-)</th>
<th>Surface tension [mN.m⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.998</td>
<td>0.0107</td>
<td>93.03</td>
<td>80.08</td>
<td>72.00</td>
</tr>
<tr>
<td>Bio-diesel</td>
<td>0.883</td>
<td>0.0630</td>
<td>14.02</td>
<td>4.5</td>
<td>23.85</td>
</tr>
<tr>
<td>Commercial diesel</td>
<td>0.829</td>
<td>0.0351</td>
<td>23.62</td>
<td>2.13</td>
<td>27.30</td>
</tr>
<tr>
<td>Brazilian commercial gasoline</td>
<td>0.767</td>
<td>0.0123</td>
<td>62.36</td>
<td>9.06</td>
<td>22.23</td>
</tr>
</tbody>
</table>
son, 1971; Fernandez & Quigley, 1985; Schramm et al., 1986; Fernandez & Quigley, 1988; Graber & Mingelgrin, 1994; Kaya & Fang, 2000; Oliveira, 2001; Anandarajah, 2003; Kaya & Fang, 2005; Amorim Jr., 2007; and Cardoso, 2011; Akinwumi et al. 2014). As a general rule, the higher the fluid \( \varepsilon_f \), the lower the soil \( K \). Eq. 3 was proposed by Budhu et al. (1991) in order to take into account the influence of the fluid dielectric constant \( \varepsilon_f \) in the soil intrinsic permeability. \( \varepsilon_r \) is the water relative dielectric constant.

According to Budhu et al. (1991), \( \lambda \), the parameter that reflects this influence varies with soil type, although there is no indication as to which soil properties affect the value of \( \lambda \).

\[
K_f = \frac{K_w}{\lambda^{\left(1 - \frac{\varepsilon_f}{\varepsilon_r}\right)}} \tag{3}
\]

where \( K_f \) [L\(^2\)] is the soil intrinsic permeability concerning the fluid used and \( K_w [L\(^2\)] \) is the soil intrinsic permeability for water.

\[
k_f = \frac{\rho_f \mu_w}{\mu_f} \cdot k_w \cdot 10^{a \left(\frac{\varepsilon_f}{\varepsilon_r} - 1\right) + b \left(1 - \exp\left(-\frac{\varepsilon_f}{\varepsilon_r} \cdot \frac{\mu_f}{\mu_w}\right)\right) + c + d \cdot \log\left(\frac{\varepsilon_f}{\varepsilon_r}\right) - e\left(\frac{\varepsilon_f}{\varepsilon_r}\right)} \tag{5}
\]

where \( I_r [-] \) is the soil plasticity index, \( k_w [LT^{-1}] \) is a reference permeability, \( k_r [LT^{-1}] \) is the water soil permeability, \( S_r [-] \) is the soil water saturation, \( \varepsilon_r [-] \) is the water relative dielectric constant, \( \varepsilon_f [-] \) is the NAPL fluid dielectric constant. \( a, b, c, d, e [-] \) and \( k_w [LT^{-1}] \) are model fitting constants. Water and fluid density and viscosity are also required.

In the model, \( I_r \) and \( \log(k_w) \) were used to represent the ability of the soil to interact with fluids and the variable \( \left(e_f/e_r - 1\right) \) was used to represent the ability of the fluid to interact with soil particles. The fourth variable used in the model was \( 1 - S_r \). It reflects the influence of the soil water content on the soil NAPL permeability. As water is normally the most wettable fluid, an increase in \( S_r \) will reduce the void space for NAPL to flow. In other words, this variable takes into account the fact that in most of the tests performed to evaluate NAPL permeability there is a considerable amount of water in the soil (as in the case of compacted soils, optimum moisture content). Therefore, the measurement being made is the soil effective permeability (multiphase flow) rather than soil permeability.

In the case of miscible fluids, such as ethanol, \( S_r \) must be set to zero. On the other hand, the mixture of fluids inside the pore spaces will change the \( \varepsilon_r \) value, which should be calculated using Eq. 6.

\[
\varepsilon_{rf} = \varepsilon_{ro} \cdot S_r + (1 - S_r) \cdot \varepsilon_{rf} \tag{6}
\]

The following values were used for fitting parameters by Machado et al. (2016): \( a = 0.263, b = 0.20, c = 5.00, \) \( d = 1.19, e = -0.259 \) and \( k_w = 1.34 \times 10^{-4} m/s (I_r \) values in %). A value of \( R^2 = 0.915 \) was obtained considering a data set of 541 tests (133 average values) embracing soils of very different textures. Considering a confidence interval of 90% the error obtained was around 6.4. For the sake of comparison, errors higher than 100,000 were obtained when directly using the Nutting equation on the data set.

From our earlier discussion it can be concluded that using \( k_e \) as the base permeability for performance evaluation of mineral barriers for containment of petroleum derivatives (ABNT NBR 17505-1, 2006) is not reliable. \( k_{soil} \) experimental values might surpass in several magnitude orders the values estimated using \( k_e \) and the Nutting equation.

Another noteworthy aspect is that mineral barriers designed to contain organic fluids must be specified differently from those for water. Clayey soils are not effective in the containment of organic fluids because of the less effective particle/liquid interactions. In this case, the clay fraction must act as filler, complementing the grain size curve of the soil.

In this paper some soil specifications based on laboratory tests results are compared with the field performance of mineral barriers in water and organic fluids containment. Experimental landfills were constructed and field and laboratory tests were performed in order to evaluate the behavior of the barriers over a period of about one year. Field values were used to test the validity of Eq. 5 and to improve the proposed ranges of soil properties for mineral barrier construction focusing on NAPL containment.
2. Previous Studies: Laboratory Tests

Previous to the field tests, a laboratory research program was performed sponsored by Brazilian Petroleum Company, PETROBRAS. Two typical soils of the Metropolitan Region of Salvador were used: the residual soil from Granulite/Gneiss and the sand clayey sedimentary soil from tertiary formation denominated Barreiras. These soils were used alone (first laboratory phase) and as part of mixtures in varying proportions (second laboratory phase). The first set of permeability tests was performed using the normal and modified Proctor energies, varying soil moisture and water, diesel and alcohol as permeating fluids. 47 permeability tests were performed using Barreiras soil (BS) and 50 tests for residual soil from Granulite/Gneiss (RSG). The main purpose of these tests was to evaluate the effect of the soil structure and moisture content on NAPL soil permeability. Eight mixtures were prepared using different proportions of BS and RSG, resulting in 144 permeability tests (second laboratory phase). Table 2 provides a summary of the soil-mixture characteristics and the average permeability values obtained for different fluids. Fig. 2 shows the variation in the soil permeability in such tests with some soil index parameters. For all the test results in Fig. 2 the modified Proctor energy was used because no sample compacted with normal energy reached the target permeability value of $k_{\text{NAPL}} < 1 \times 10^{-8}$ m/s, as required by the Brazilian Standard ABNT NBR 17505-1 (2006).

For the same mixture, the use of modified Proctor energy and the resulting increase in the dry density ($\rho_d$) of the soil compared to normal Proctor energy, reduced the $k_{\text{NAPL}}$ by around two orders of magnitude. Considering the results presented in Table 2 and Fig. 2, both the $k_{\text{NAPL}}$ and $k_w$ decreased as the $\rho_d$ increases. This can be explained by the decrease in the mixture clay content, as well known from principles of soil mechanics. However, the effect of the $\rho_d$ or clay content in the $k_{\text{NAPL}}$ is less evident.

As expected, diesel (non polar fluid, $\epsilon_r = 2.13$) leads to critical results (larger permeability values) in most cases thus requiring the construction of mineral barriers for organic fluid containment. Alcohol presented an intermediate behavior. It can be observed in Fig. 2 that values of $k < 1 \times 10^{-8}$ m/s are obtained for clay contents higher than 26%. However, from this point on, the effect of the clay content on the soil diesel permeability is much less pronounced. Considering that high plasticity soils present high volume variations and have associated shrinkage cracks due to wetting/drying cycles, it is prudent to adopt an upper limit for the clay content of the soil.

A similar behavior can be observed considering the soil optimal moisture content, $w_{\text{opt}}$, and the plasticity index,

![Figure 2 - Coefficient of permeability ($k$) as a function of some index properties - Laboratory tests.](image-url)
Considering the dry density ($\rho_d$) values reached in the compaction curves, admissible $k_{nAPL}$ values are obtained for values of $\rho_d < 1.9$ g/cm$^3$. Based on these results, the specifications presented in Table 3 were proposed for the construction of mineral barriers for the containment of organic fluids. These ranges of variations were the basis on which the construction of the experimental landfills experiment were made.

### 3. Materials and Methods

In order to check the validity of the ranges proposed in Table 3, field landfills were constructed using mixtures of RSG/BS soils. Six landfills were constructed using different proportions of RSG and BS and a seventh landfill was constructed using soil borrowed from a sedimentary *Barreiras* layer which had a relatively high clay content. The activities performed in field are discussed below.

#### 3.1. Field location and weather characteristics

The experimental area is located about 21 km from Salvador, Bahia (12°50'50.4" S 38°22'42.4" W), Brazil. The rainfall was about 2,100 mm per year in the period from 1998 to 2014 (measurements from a weather station close to the area). Rainfall is seasonal, usually from April to July. The average temperature is 25.2 degrees Celsius, with little variation throughout the year.

#### 3.2. Materials and compaction process

Table 4 summarizes the properties of the soil-mixtures used to construct the landfills. The following ABNT standards were used in the tests: NBR 6457 (1986); NBR 6508 (1984); NBR 7181 (1984); NBR 6459 (1984); NBR 7180 (1984) and NBR 7182 (1986). The RSG/BS proportions were chosen in such a way that mixtures 1 to 4 fit the $F_c$ criterion presented in Table 3. Mixtures 5 to 7 were made with coarse soils. The idea was to study not only the soil hydraulic behavior just after compaction, but also the long term behavior of the landfills. Fine grained mixtures tend to have a better short term behavior (before first drying cycle), however, since coarse soils are less sensitive to changes in environmental conditions, the long term performance tends to be more effective for coarse soils.

### Table 3 - Optimal ranges of index properties for the construction of mineral barriers for organic fluid containment.

<table>
<thead>
<tr>
<th>Index property</th>
<th>Proposed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasticity Index ($I_p$)</td>
<td>28%-42%</td>
</tr>
<tr>
<td>Fine (clay + silt) content ($F_c$)</td>
<td>33%-60%</td>
</tr>
<tr>
<td>Clay content ($C_c$)</td>
<td>27%-45%</td>
</tr>
<tr>
<td>Sand content ($S_c$)</td>
<td>34%-57%</td>
</tr>
<tr>
<td>Optimal moisture content ($w_{o,p}$)</td>
<td>14%-20%</td>
</tr>
<tr>
<td>Maximum dry density ($\rho_{max}$)</td>
<td>1.65-1.83 (g/cm$^3$)</td>
</tr>
</tbody>
</table>
All the RSG and BS soils used in the experiments were homogenized prior to mixing using a backhoe and the total amount of soil used in each landfill was calculated based on the landfills geometry and physical indices of the compacted mixture. The landfills were compacted in four layers with a final total height of 0.6 m (4 layers of 0.15 m). The nominal dimensions of the landfills were 2.2 x 5.0 m, except for mixture 6 which had nominal dimensions of 2.2 x 10 m. Fig. 3 provides a sketch of the experimental landfills. The filled gray area represents the area used for the field tests and undisturbed blocks sampling. RSG/BS proportions were used to calculate the amount of dry mass of each soil to be used in the compaction process.

Using the field moisture content, the mass of compacted soil used in layers was calculated. This mass was converted into an equivalent number of backhoe shells. In order to do this, the mass of the empty backhoe along with the mass of the backhoe filled with each soil was determined using the field balance of 20 Mg. The necessary amount of soil for each layer was then mixed and water was added to reach the desired water content. After the mixing and wetting procedures, the soil layers were allowed to settle for 24 h so that the moisture would become uniform.

The soil layers were then compacted using a 24 Mg sheepsfoot roller going over it 9 to 10 times. Compaction control was made based on moisture content ($w_{\text{opt}} - 1\% < w < w_{\text{opt}} + 3\%$) and compaction efficiency, $CE = \frac{\rho_{\text{final}}}{\rho_{\text{max}}} > 0.95$. The water content was determined in the field using speedy test and infrared balances and in the laboratory (24 h later) using standard procedures. Density was determined using the reservoir tubes. The inner tube is used for low permeability soils. The shape factor, $\alpha$, can be obtained using Fig. 6. Unfortunately, the use of the rigorous method (use of two $H$ values) sometimes leads to unrealistic (negative) values of $k_{\psi}$. This occurs normally when the assumptions adopted for solving Eq. 7 (homogeneous porous material and matric potential in the unsaturated flow zone) are not present in the field. In order to overcome this, Elrick et al. (1989) suggest the use of the $k_{\psi}$ parameter in order to estimate $k_{\psi}$ using a single head and field test days are represented by a vertical line. As can be observed, during most of the first campaign there were rainy days. As the soil was close to 100% saturation just after compaction, the rain in this period reduced the occurrence of shrinkage and cracks. In the case of the second campaign, the opposite weathering conditions could be observed. Water, diesel, biodiesel and commercial gasoline were the percolation fluids. Two tests were performed for each fluid making up eight tests for each landfill, 56 tests in each campaign and 112 tests in total.

Field permeability tests were performed using Guelph permeameter which meets the requirement of ASTM D5126/D5126M-90 (2010)e1. The Guelph permeability problem of flow was solved by Reynolds & Elrick (1985), using Richards’ equation and the assumption of steady state flow in a cylindrical cavity, taking into account the soil matric suction:

$$Q = \left( \frac{2\pi \cdot H^2}{C} + \pi \cdot a^2 \right) \cdot k_{fs} + \left( \frac{2\pi \cdot H}{C} + \pi \cdot a^2 \right) \cdot \varphi_{m} \quad (7)$$

where $Q$ [LT$^{-1}$] is the flow rate entry into the soil; $H$ [L] is the hydraulic head inside the cavity; $C$ is a shape factor; $a$ [L] is the cavity radius; $k_{fs}$ [LT$^{-1}$] is the soil permeability and $\varphi_{m}$ [L$^2$T$^{-1}$] corresponds to the water flow due to soil matric potential (see Eq. 8).

$$\varphi_{m} = \int k(\psi) \cdot d\psi \quad (8)$$

where $k(\psi)$ [LT$^{-1}$] is the hydraulic conductivity function and $\psi$ [L] is the matric potential.

The Guelph permeameter was developed by Reynolds et al. (1983) to carry out field permeability tests in steady state conditions. A Mariotte tube is used to assure a constant hydraulic head ($H$) inside the bore hole and the flow rate, $Q$, is measured using the reservoir tubes. The inner tube is used for low permeability soils. The shape factor, $C$, can be obtained using Fig. 6. Unfortunately, the use of the rigorous method (use of two $H$ values) sometimes leads to unrealistic (negative) values of $k_{\psi}$. This occurs normally when the assumptions adopted for solving Eq. 7 (homogeneous porous material and matric potential in the unsaturated flow zone) are not present in the field. In order to overcome this, Elrick et al. (1989) suggest the use of the $\alpha$ [L$^{-1}$] parameter in order to estimate $k_{\psi}$ using a single head

![Figure 3 - Sketch of the field experimental landfills.](image)
Table 5 - \(\alpha\) values suggested by the authors for different types of soils.

\[
\alpha = \frac{k_{f_s}}{\varphi_m} \quad (9)
\]

\[
k_{f_s} = \frac{CQ}{2\pi H^2 + \pi a^2 \cdot C + 2\pi H/\alpha} \quad (10)
\]

A standard permeameter was used for water whereas a modified permeameter, developed in the UFBA Geo-environmental Laboratory (GEOAMB), was used for commercial gasoline, diesel and biodiesel. The modified permeameter was developed for testing organic and/or aggressive fluids and is made of mostly steel and glass. Its design prevents direct contact with fluid (the permeameter is filled from bottom to top using a vacuum pump) and the measurements can be taken visually from the glass tubes or be seen on a LCD panel of a pressure transducer (measures are stored in a datalogger). This is particularly useful in the case of opaque fluids. The internal tube of the permeameter has a smaller inner diameter compared to standard models which makes it more appropriate for low permeability soil testing. Both permeameters were checked exhaustively against leaks before tests. During the tests, the annular gap between the permeameter rod and the wall of the boreholes was covered by a cardboard sheet to prevent evaporation (Fig. 7a). Furthermore, tests were performed to estimate the evaporation rate and correct field reading. All the tests were performed at a depth of 20 cm and used two hydraulic heads. More details can be found in Carvalho (2015).

Field permeability was calculated according to Eq. 10 and the adopted \(k\) was the average value for the two heads used. Laboratory permeability tests were also performed using undisturbed blocks (0.3 x 0.3 x 0.3 m). Blocks were extracted from landfills at a depth of 0.1 m. The extraction of the blocks occurred in the period from January 24th to March 12th, 2014, just after the second field campaign (see Fig. 5). The landfill borders were avoided for the extraction of undisturbed blocks because of the bad compaction conditions. Flexible permeameters (triaxial chambers) were used and the falling head procedure was adopted (NBR 14545, 2000). Samples had nominal dimensions of 0.05 x 0.05 x 0.05 cm.

Table 5 - \(\alpha\) values proposed by Elrick et al. (1989) for different soil types

<table>
<thead>
<tr>
<th>(\alpha) (cm(^{-1}))</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>Compacted clays</td>
</tr>
<tr>
<td>0.04</td>
<td>Unstructured clays</td>
</tr>
<tr>
<td>0.12</td>
<td>Clay to fine sand (or structured soils)</td>
</tr>
<tr>
<td>0.36</td>
<td>Coarse sand. structured soils with cracks and macro pores</td>
</tr>
</tbody>
</table>
0.10 m. Fig. 8 illustrates undisturbed block extraction, sample trimming and one of the flexible wall permeameters used.

4. Results and Analysis

Fig. 9 compares the field results for water and diesel (all the mixtures considered) with the results presented in Fig. 2. As can be observed, both the field and laboratory results are consistent. The field results plotted in Fig. 9 correspond to the first campaign as the laboratory tests were performed using $w_o$ and $p_{\text{max}}$ conditions. Considering the obtained results, the landfills were able to achieve good results even for relatively lower $I_p$ and $w_o$ values. These results make possible the refinement of the previously pro-

Figure 4 - (a) weighing the backhoe filled with soil; (b) layer being released and allowed to settle for 24 h for moisture equalization (c) compaction process and (d) compaction control.

Figure 5 - Daily rainfall during the field tests.
posed ranges. Tables 6 to 8 present the coefficient of the permeability results obtained in field. Values of $k \leq 1 \times 10^{-8}$ m/s are highlighted. Some observations can be made concerning the results presented in Tables 6 to 8:

a) Mixtures 1 to 5 and 7 showed good performance in the first field campaign. Only for Brazilian gasoline $k > 1 \times 10^{-8}$ m/s, which is probably due to its higher mobility (see Table 1). Besides this, commercial gasoline contains about 24% ethanol which will be stripped to the pore water during flow (Corseuil & Marins, 1997; Kaipper, 2003). However, even in this case, mixtures present $k$ around $1 \times 10^{-8}$ m/s. Mixture 2 presents $k \leq 1 \times 10^{-8}$ m/s for all the tested fluids. The obtained results are consistent with the previous phase of study because mixtures 1 to 5 meet the fine content criteria (see

![Figure 6](image-url) **Figure 6** - Shape factor, $C$, as a function of the ratio $H/a$. Reynolds *et al.* (1983).

![Figure 7](image-url) **Figure 7** - a) Permeability tests using water and diesel and b) details of the cover adopted to reduce evaporation.

![Figure 8](image-url) **Figure 8** - a) Undisturbed blocks extraction; b) samples trimming and c) flexible wall permeameter.
Table 6 - Field permeameter results. First field campaign.

<table>
<thead>
<tr>
<th>Fine content (Fc)/mixture</th>
<th>45%</th>
<th>40%</th>
<th>37%</th>
<th>35%</th>
<th>33%</th>
<th>18%</th>
<th>27%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>5E-07</td>
<td>7E-07</td>
<td>6E-07</td>
<td>2E-07</td>
<td>1E-07</td>
<td>5E-06</td>
<td>1E-05</td>
</tr>
<tr>
<td>Commercial diesel</td>
<td>4E-07</td>
<td>3E-07</td>
<td>5E-07</td>
<td>4E-07</td>
<td>1E-06</td>
<td>7E-06</td>
<td>1E-06</td>
</tr>
<tr>
<td>Brazilian gasoline</td>
<td>3E-06</td>
<td>1E-06</td>
<td>2E-06</td>
<td>2E-06</td>
<td>2E-06</td>
<td>5E-06</td>
<td>7E-07</td>
</tr>
<tr>
<td>Bio-diesel</td>
<td>3E-07</td>
<td>3E-07</td>
<td>1E-07</td>
<td>9E-07</td>
<td>1E-07</td>
<td>4E-06</td>
<td>1E-06</td>
</tr>
</tbody>
</table>

Table 7 - Field permeameter results. Second field campaign.

<table>
<thead>
<tr>
<th>Fine content (Fc)/mixture</th>
<th>45%</th>
<th>40%</th>
<th>37%</th>
<th>35%</th>
<th>33%</th>
<th>18%</th>
<th>27%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>5E-06</td>
<td>1E-06</td>
<td>7E-07</td>
<td>1E-05</td>
<td>1E-06</td>
<td>2E-05</td>
<td>1E-06</td>
</tr>
<tr>
<td>Commercial diesel</td>
<td>2E-06</td>
<td>8E-07</td>
<td>3E-06</td>
<td>6E-06</td>
<td>2E-06</td>
<td>2E-05</td>
<td>8E-07</td>
</tr>
<tr>
<td>Brazilian gasoline</td>
<td>4E-06</td>
<td>1E-05</td>
<td>6E-07</td>
<td>7E-05</td>
<td>5E-06</td>
<td>4E-05</td>
<td>4E-06</td>
</tr>
<tr>
<td>Bio-diesel</td>
<td>4E-06</td>
<td>2E-06</td>
<td>1E-06</td>
<td>2E-06</td>
<td>4E-06</td>
<td>7E-06</td>
<td>1E-05</td>
</tr>
</tbody>
</table>

Figure 9 - Comparison between field (first campaign) and laboratory (previous research phase) results.
Tables 3 and 4) and mixture 7 has a fine content of 27% which is close to the minimum fine content of the proposed range (33%).

b) The second campaign, performed during the dry period, presented higher $k$ values compared to the first one. The only exceptions were the results for mixture 7, water and diesel fluids. As expected, because of their higher fine content, mixtures 1 and 2 presented higher permeability ratios between the second and the first campaigns ($k_2/k_1$). The presence of shrinkage cracks was more evident in these soils. Mixture 4 behaved unexpectedly with the highest permeability ratios between the first and second campaigns. It is worth pointing out, however, that this landfill was constructed away from the other landfills, resulting in a larger exposed area for evaporation and shrinkage (a larger number of shrinkage cracks could be observed in field). Despite the increase in the permeability values over time, the authors consider the obtained $k_2/k_1$ ratios to be quite acceptable, since there are many variables that could affect the obtained results in field. 29% of the $k_2/k_1$ ratios values presented in Table 8 are higher than 10.

Fig. 10 shows how the intrinsic permeability, $K$, varies as a function of the fluid and the water content of the soil. In this graph, $K_w$ refers to the average soil intrinsic permeability calculated using water as the base fluid whereas $K_{NAPL}$ refers to the average value calculated using diesel, biodiesel and gasoline. As expected, because NAPL has a lower dielectric constant relative to water, $K_{NAPL}$ values are higher than $K_w$, for the same water content. On the other hand, because water has a higher wettability than NAPL (water is the most wettable fluid), lower moisture contents will increase available spaces for NAPL flow, increasing the $K_{NAPL}$ value. The subscripts 1 and 2 refer to the first and second field campaign, respectively. These results emphasize the need for barrier specifications not to be based on water permeability but rather on results obtained from testing the same fluids as those to be stored in the field.

Table 9 and Fig. 11 compare the laboratory and field results (second campaign). Note that the undisturbed blocks were collected in the same period as the second field campaign. Besides the coefficient of permeability, this ta-

**Table 8 - Values of $k_2/k_1$.**

<table>
<thead>
<tr>
<th>Fine content ($Fc$)</th>
<th>Mixture 1</th>
<th>Mixture 2</th>
<th>Mixture 3</th>
<th>Mixture 4</th>
<th>Mixture 5</th>
<th>Mixture 6</th>
<th>Mixture 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>45%</td>
<td>11.03</td>
<td>2.11</td>
<td>1.19</td>
<td>57.55</td>
<td>9.17</td>
<td>3.34</td>
<td>0.11</td>
</tr>
<tr>
<td>40%</td>
<td>5.23</td>
<td>2.56</td>
<td>5.39</td>
<td>14.33</td>
<td>2.22</td>
<td>3.33</td>
<td>0.52</td>
</tr>
<tr>
<td>37%</td>
<td>1.59</td>
<td>11.81</td>
<td>0.30</td>
<td>32.70</td>
<td>2.54</td>
<td>8.82</td>
<td>6.62</td>
</tr>
<tr>
<td>35%</td>
<td>13.24</td>
<td>5.67</td>
<td>14.98</td>
<td>2.59</td>
<td>35.52</td>
<td>1.69</td>
<td>8.75</td>
</tr>
<tr>
<td>33%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 10 - Intrinsic permeability values calculated based on water, $K_w$ and NAPL (gasoline, diesel and bio-diesel), $K_{NAPL}$ and their variation with soil water content.**

**Table 9 - Laboratory x field coefficient of permeability.**

<table>
<thead>
<tr>
<th>Mix.</th>
<th>$k_{s,lab}$</th>
<th>$k_{s,orig}$</th>
<th>$w$ (m/s)</th>
<th>$\alpha_{s,lab}$</th>
<th>$\alpha_{s,orig}$</th>
<th>$k_{s,lab}$</th>
<th>$k_{s,orig}$</th>
<th>$\alpha_{s,lab}$</th>
<th>$\alpha_{s,orig}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix. 1</td>
<td>2E-08</td>
<td>5E-08</td>
<td>13.37</td>
<td>0.010</td>
<td>6E-08</td>
<td>1E-07</td>
<td>0.033</td>
<td>3E-09</td>
<td>1E-09</td>
</tr>
<tr>
<td>Mix. 2</td>
<td>8E-09</td>
<td>1E-08</td>
<td>9.68</td>
<td>0.010</td>
<td>3E-08</td>
<td>5E-08</td>
<td>0.045</td>
<td>1E-07</td>
<td>9.77</td>
</tr>
<tr>
<td>Mix. 3</td>
<td>3E-08</td>
<td>7E-09</td>
<td>9.58</td>
<td>0.010</td>
<td>1E-07</td>
<td>4E-08</td>
<td>0.077</td>
<td>2E-08</td>
<td>9.39</td>
</tr>
<tr>
<td>Mix. 4</td>
<td>6E-08</td>
<td>1E-07</td>
<td>7.51</td>
<td>0.010</td>
<td>5E-07</td>
<td>8E-07</td>
<td>0.211</td>
<td>1E-07</td>
<td>8.75</td>
</tr>
<tr>
<td>Mix. 5</td>
<td>2E-08</td>
<td>1E-08</td>
<td>7.93</td>
<td>0.010</td>
<td>4E-08</td>
<td>2E-08</td>
<td>0.020</td>
<td>1E-07</td>
<td>7.80</td>
</tr>
<tr>
<td>Mix. 6</td>
<td>2E-07</td>
<td>2E-07</td>
<td>7.00</td>
<td>0.010</td>
<td>1E-06</td>
<td>6E-07</td>
<td>0.054</td>
<td>1E-06</td>
<td>6.80</td>
</tr>
<tr>
<td>Mix. 7</td>
<td>8E-09</td>
<td>1E-08</td>
<td>7.00</td>
<td>0.010</td>
<td>6E-08</td>
<td>7E-08</td>
<td>0.144</td>
<td>1E-08</td>
<td>7.40</td>
</tr>
</tbody>
</table>
Table 10 - Optimal ranges of index properties for the construction of mineral barriers for containment of organic fluids.

<table>
<thead>
<tr>
<th>Index property</th>
<th>Proposed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasticity Index ($I_p$)</td>
<td>12%-25%</td>
</tr>
<tr>
<td>Fine (clay + silt) content ($F_{c}$)</td>
<td>25%-45%</td>
</tr>
<tr>
<td>Clay content ($C_c$)</td>
<td>20%-35%</td>
</tr>
<tr>
<td>Sand content ($S_{c}$)</td>
<td>45%-70%</td>
</tr>
<tr>
<td>Optimal water content ($w_{ot}$)</td>
<td>10%-17%</td>
</tr>
<tr>
<td>Maximum dry density ($\rho_{max}$)</td>
<td>1.65-2.0 (g/cm$^3$)</td>
</tr>
</tbody>
</table>

Figure 11 shows the initial moisture content of the soil and the $\alpha$ value adopted when computing field permeability. In this table $\alpha_{avg}$ means the adoption of the $\alpha$ values suggested in Table 5 ($\alpha = 0.01$) and $\alpha_m$ means the average $\alpha$ value obtained considering the valid field permeability results for each landfill. The subscript 2 refers to the second field campaign. As can be seen, the laboratory and field samples had similar moisture contents before the tests. Laboratory and field permeability values showed fair agreement. Discarding the three most discrepant results, the maximum difference between the values is around 10.

As discussed earlier, second field campaign was performed during the dry season when the soil had a lower moisture content and after the soil had undergone the first wetting/drying cycle. This resulted in higher $k$ values compared to the first campaign. On the other hand, the laboratory results tended to be lower than the field results of the second campaign. This is probably due to the hydraulic anisotropy of the compact soil, which presents higher $k$ values in the horizontal direction compared to the vertical. Laboratory tests measured the vertical coefficient of permeability whereas Guelph permeameter measured flow rate in both directions.

Table 10 shows the proposed refinement for the ranges of index properties presented earlier in Table 3. As can be observed, all the indexes were changed toward the use of coarser soils. These changes reflect the good response of the landfills constructed using mixtures with fine contents close to the minimum value of the original range (33%) or even lower than stipulated, as in the case of mixture 7, in which a fine content of 27% was used. The new range is based on the expected long-term performance of the barriers, since clayey soils tend to increase $k$ over time in a more pronounced way than coarse soils.

Changes in the weather, which causes the appearance of shrinkage cracks.

Fig. 12 compares the field and laboratory results predicted by Eq. 5 and obtained experimentally. In Fig. 12(a) the field results were calculated assuming $\alpha = 0.01$ whereas Fig. 12(b) presents the field results calculated using the values of $\alpha_m$ shown in Table 9. As can be observed, the use of the $\alpha_m$ values improved the performance of the model compared to the adoption of a single value for all the landfills ($\alpha = 0.01$). However, the number of experimental points located outside the confidence interval is larger than 10%. A higher scattering in the field results had been expected because field tests are less controlled than those in a laboratory environment and the landfills undergo the influence of changes in the weather, which causes the appearance of shrinkage cracks.

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5. Conclusions

This paper presents the results of field permeability tests that were carried out in landfills constructed using optimal ranges of soil index properties for mineral barriers for the containment of organic fluids. The obtained results corroborate several results published in the technical literature (Fernandez & Quigley, 1985; Budhu et al., 1991; Oliveira, 2001; Amarasinghe et al., 2012 and Cardoso, 2011): fluids with low dielectric constants (non-polar) tend to present higher intrinsic permeabilities than polar fluids because they reduce the double layer thickness, providing more space in the voids of the soil for NAPL flow. On the other hand, the presence of water, the most wettable fluid, reduces the permeability of NAPL as interstitial water reduces the available pore spaces for NAPL (Machado et al., 2016 and Cardoso, 2011).

Clayey soils tend to have a lower long term performance due to field wetting/drying cycles and the consequent appearance of cracks and fissures. Despite the increase in the permeability values over time, however, the authors consider the obtained increase in the permeability values over time, however, the frequent appearance of cracks and fissures. Despite the performance due to field wetting/drying cycles and the consequent ranges of index properties. However, considering the studies performed in the laboratory in order to establish optimal ranges of index properties. These indexes were changed towards the use of soil permeability is perhaps the most sensitive soil parameter and there are many variables that could affect the obtained results in the field. Only 29% of the values presented in Table 8 are higher than 10.

The obtained field results are coherent with previous studies performed in the laboratory in order to establish optimal ranges of index properties. However, considering the obtained results as a function $w_{opt}$ and $I_p$, the landfills showed good results even for relatively low $I_p$ and $w_{opt}$ values.

Although there was good agreement between the fine content range proposed previously and the obtained results in the field, some changes were required to improve the soil index ranges. These indexes were changed towards the use of coarser soils relative to the original specifications obtained in laboratory and were proposed based on the expected long-term performance of the barriers, since clayey soils tend to increase k over time in a more pronounced way than coarse soils.

The results presented in this paper emphasize the need for the design and construction of barriers not to be based on water permeability but rather on results obtained from testing the specific fluid that they will be required to contain in the field. As low polarity fluids tend to present higher permeabilities than water in clayey soils, the use of water as a base fluid for calculation may lead to the poor performance of the mineral barriers in the field.

References


