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# Hydraulic conductivity study of compacted clay soils used as landfill liners for an acidic waste

Noureddine Hamdi *, Ezzeddine Srasra

*Centre National des Recherches en Science des Matériaux, Borj Cedria Techno-Park, B.P. 95-2050, Hammam Lif, Tunis, Tunisia*

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ABSTRACT

Three natural clayey soils from Tunisia were studied to assess their suitability for use as a liner for an acid waste disposal site. An investigation of the effect of the mineral composition and mechanical compaction on the hydraulic conductivity and fluoride and phosphate removal of three different soils is presented. The hydraulic conductivity of these three natural soils are $8.5 \times 10^{-10}$, $2.08 \times 10^{-9}$ and $6.8 \times 10^{-10}$ m/s for soil-1, soil-2 and soil-3, respectively. Soil specimens were compacted under various compaction strains in order to obtain three wet densities (1850, 1950 and 2050 kg/m$^3$). In this condition, the hydraulic conductivity ($k$) was reduced with increasing density of sample for all soils. The test results of hydraulic conductivity at long-term (>200 days) using acidic waste solution (pH = 2.7, charged with fluoride and phosphate ions) shows a decrease in $k$ with time only for natural soil-1 and soil-2. However, the specimens of soil-2 compressed to the two highest densities (1950 and 2050 kg/m$^3$) are cracked after 60 and 20 days, respectively, of hydraulic conductivity testing. This damage is the result of a continued increase in the internal stress due to the swelling and to the effect of aggressive wastewater. The analysis of anions shows that the retention of fluoride is higher compared to phosphate and soil-1 has the highest sorption capacity.

## 1. Introduction

Clays are essential materials to reduce the hydraulic conductivity of natural soil liners in landfill sites. Naturally abundant clay soils and re-compacted clay liners can represent a key component of landfills. It is known that clays with high plasticity absorb several times as much water as their weights. The clay soil liners subjected to water pressure in landfills can generate an increase of hydraulic conductivity in time and instability problems due to the expansive capacity of the clay. In general, this water pressure can be measured using the triaxial cells and this pressure generates an increase of the charge on the specimen, hence an increase of the hydraulic conductivity. According to some authors (Brandl, 1992; Kayabaly, 1997; Cazaux and Didier, 2000), the main requirements of liners are to ensure the minimization of pollutant migration over the long-term, low swelling and shrinkage, and resistance to shearing. These measures generally involve the applications of low permeable clay soils at the natural state or at different compaction degrees (Van Ree et al., 1992). Compacted clay soils are widely used in solid waste landfills due to their cost effectiveness and large capacity of attenuation (Yahia et al., 2005). Though the compacted clay soils possess many advantages such as low hydraulic conductivity (<$10^{-9}$ m/s), they have high shrinkage and high expansive potential causing instability problems (Mitchell, 1993; Di Maio et al., 2004). For this reason, the choice of an adequate clay soil is needed for construction of a landfill. Clay minerals such as kaolinite and illite may ensure reliable performance of clayey liners. In practice, however, natural clay soils found in the vicinity of the dumping sites are often used. Quite infrequently, highly swelling clays (e.g., smectites) are utilized. The hydraulic performance of the natural clay, however, might be more problematic than that of kaolinite and/or illite (Rowe et al., 1997). Therefore, it is important to correlate the hydraulic conductivity with natural clay properties. In addition, leachate flow in compacted soil is controlled by the size, shape, and connectivity of microscale pores. According to several authors the migration of contaminants in a waste disposal site usually involves one or more of the following processes: advection, diffusion and interactions between the waste solution and the soil solids, such as adsorption, ion exchange, and precipitation (Rajasekaran et al., 2005; Li and Li, 2001; Tamotsu et al., 1999; Berry and Bond, 1992). These are complex processes, and depending on the pH of the medium, the mineralogy and the density of materials, they can be of varying degrees of significance (if the contaminant has an acidic property, this can degrade the clay liner and increase the hydraulic conductivity). In general, the reaction of a clay liner to a specific contaminant depends on two factors: the ability of the clay in the liner to resist increases in

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* Corresponding author.
*E-mail address:* nouryhamdi@gmail.com (N. Hamdi).

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hydraulic conductivity caused by the contaminant and the capacity of the liner to retard the migration of contaminants through sorption (Li and Li, 2001). On the other hand, among these contaminants the phosphate and fluoride are usually considered as the main ions causing environmental deterioration of ground water (Edzwald et al., 1976; Brett et al., 2005; Reardon and Wang, 2000). However, phosphate and fluoride anions removal from wastewater by soils and there influences on hydraulic conductivity were widely studied by some authors (Kau et al., 1997a, 1998; Peterson and Gee, 1985; Robert, 1993). The ability to predict leaching rates of both anions through soils to ground and surface water is therefore essential for the long-term management of a site for disposal of waste.

In the present study, the protection of groundwater from fluoride and phosphate contamination for human consumption is of primary importance in terms of the storage of highly acidic waste charged with $F^-$ and $PO_4^{3-}$ anions. The aim here is to examine the effects of mineral composition and mechanical compaction on hydraulic conductivity and fluoride and phosphate infiltration rate for three Tunisian clay soils suitable to be used as an engineered barrier. This is of special importance since there is no information available, at present, on the fluoride and phosphate retention and the long-term hydraulic conductivity of Tunisian clay soils.

## 2. Materials

### 2.1. Physicochemical characterization of soils

Three Tunisian soils were used to determine the relationship between the hydraulic conductivity, compression state and mineralogical properties: a palygorskitic soil (soil-1), a smectitic soil (soil-2) and a illito-kaolinitic soil (soil-3). The investigated clay soils originate from three regions of Gabes, southeast Tunisia, that have been designated as possible sites for acidic waste storage. The samples (cores) were taken from depths of 17.4, 8.9 and 12.7 m for soils 1, 2 and 3, respectively. Cores and specimens were packed in PVC tube closed on both sides. They were placed in a humidity moderate chamber temperature below 20 °C approximately.

The quantitative mineralogical analysis was extracted from the powder XRD data using an internal standard for each mineral (Jozja, 2003; Cody and Thompson, 1976). The clay fraction was quantified, after purification, using the same method as above, and based on a pure, standard clay mineral (Hamdi and Srasra, 2008). The mineralogical composition of these samples, the cation exchange capacities (CECs) (Bergaya and Vayer, 1997), the total surface ($S_T$) (Eltantawy and Arnold, 1974) and the specific surface areas ($S_{BET}$) are summarized in Table 1. These results show that the CEC of the soil-2 is higher comparing to soil-1 and soil-3. This is due to the smectite fraction, which is confirmed by the higher total surface areas.

**Table 2**
Geotechnical properties of three soils.

| | Soil-1 | Soil-2 | Soil-3 |
|---|---|---|---|
| *Atterberg limits* | | | |
| Liquid limit (%) | 50.9 | 81.4 | 49.3 |
| Plastic limit (%) | 25.2 | 50 | 25.4 |
| Plasticity index (%) | 25.7 | 31.4 | 23.9 |
| Initial moisture content, $W_0$ (%) | 24.9 | 32.3 | 22.7 |
| Initial wet density (kg/m$^3$) | 1720 | 1670 | 1780 |
| Compression index $C_c$ | 0.08 | 0.22 | 0.05 |
| Swelling index $C_s$ | 0.023 | 0.066 | 0.026 |
| pH in distilled water | 8.3 | 7.8 | 7.4 |

### 2.2. Waste solution

The industrial waste to be disposed of consists of significant amounts of solid (phosphogypsum) combined with a liquid solution of pH 2.7; the waste contains large amounts of harmful material, including fluoride and phosphate with the concentration of 2360 mg/L and 1500 mg/L respectively, chloride is also present, but at lesser concentrations. This real waste solution was used in the hydraulic conductivity tests.

### 2.3. Geotechnical characterization of clay soils

The physical properties of natural clay soils used in the tests such as Atterberg limits and consolidation were determined in accordance with D 4318 and D 2435, respectively. The properties of untreated soils are given in Table 2. The Atterberg limits and clay content are also given in Table 2, which shows that soil-2 has significantly higher liquid and plastic limits. Fig. 1 shows the grain size distribution for all soils. It can be seen that in the coarser fraction (>0.1 mm) the three soils are very similar. Finer than 0.01 mm, soil 2 has a higher proportion of silty material although at the silt/clay boundary (0.002 mm) all three soils have between 30% and 40% clay. In addition, Fig. 2 shows that the three soils have different consolidation properties with the initial void ratio ($e_0$) ranging between 0.4 and 0.9. Soil-2 has a higher compressibility and swelling index than the other two samples (Table 2), which is due to the smectite clay fraction.

## 3. Methods

### 3.1. Uniaxial compaction

Three test specimens of each soil were mechanically compressed by a uniaxial system (Fig. 3) at different pressures in order to obtain three wet densities (1850, 1950 and 2050 kg/m$^3$). These densities are chooses after a preliminary study of compaction of each sample when we can conclude that the density between

**Table 1**
Mineralogical composition, specific surface areas and cationic exchange capacities of samples.

| Sample | Mineralogical composition of clay samples (%) | | | | | | | $S_{BET}$ (m$^2$/g) | $S_T$ (m$^2$/g) | CEC (meq/100 g) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Paly | Smec | Kao | Il | Q | Ca | Do | | | |
| Soil-1 | 35.5 | 2 | 15 | – | 28.5 | 19 | – | 35.4 | 55.7 | 16.5 |
| Soil-2 | – | 56 | 6 | – | 12 | 26 | – | 57.1 | 209.8 | 49.8 |
| Soil-3 | – | – | 23 | 63 | 9 | – | 5 | 91.5 | 133.4 | 24.6 |

Paly: Palygorskite, Smec: Smectite, Kao: Kaolinite, Il: Illite, Q: Quartz, Ca: Calcite, Do: Dolomite.
$S_{BET}$: Specific surface areas by application of the Brunauer–Emmett–Teller (BET) method.
$S_T$: Total specific surface areas.
CEC: Cationic exchange capacities.