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Hydraulic properties of dune sand–bentonite mixtures of insulation barriers for hazardous waste facilities

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ABSTRACT

This paper presents a study on the valorization of local materials such as desert dune sand obtained from Laghouat region in the South Algeria and mine bentonite intended for the realization of liner base layers in the conception of insulation barriers for hazardous waste facilities. In practice, an economical mixture satisfying the hydraulic requirements is generally concerned. First, in order to get an adequate dune sand–bentonite mixture compacted to the optimum Proctor condition, an investigation on saturated hydraulic behavior is carried out in this study for different mixtures. Using oedometer test (indirect measurement), the adequate mixture of 85% dune sand and 15% bentonite satisfies the conditions of saturated hydraulic conductivity ($k < 10^{-9}$ m/s). This result of the adequate mixture is also confirmed by direct measurement of saturated hydraulic conductivity using triaxial cell. Second, the unsaturated hydraulic conductivity of the adequate mixture is measured with an original vapor equilibrium technique (VET) used for $S_r < 30\%$ (very high suction $s > 3$ MPa). This technique is conducted based on the exploitation of the water retention curve in order to establish the relationships between hydraulic conductivity, degree of saturation, and suction. It shows that the hydraulic conductivity increases with the degree of saturation and decreases with the suction. However, the hydraulic conductivity has a constant value for suctions larger than 20 MPa. The selected dune sand–bentonite mixture satisfies the regulation requirements and hence constitutes a good local and economical material for the conception of barrier base liners.

1. Introduction

Rapid technological advances and population needs lead to the generation of increasing quantities of hazardous wastes, for which two fundamental issues will be encountered, e.g., waste management and pollution risk control. One of the solutions for handling these contamination problems is enclosing the wastes in a specific location using insulation barriers. Many different barrier materials exist, for example, plastic membranes, sand–bentonite compacted layers, cement stabilized soils (Santucci de Magistris et al., 1998). The permeability of insulation barriers has been studied by many authors for different types of soils, compacted clays, silty soils, clay and sand–bentonite mixtures (Daniel, 1984; Holtz, 1985; Chapuis, 1990; Blatz et al., 2002; Montañez, 2002; Watabe et al., 2003; Chalermyanont and Arrykul, 2005; Cui et al., 2008). The efficiency of these insulated barriers depends largely on their hydraulic behaviors along with their abilities of contaminant retention (Booker et al., 2004; Sangam and Rowe, 2005; McWatters and Rowe, 2010; Scalia et al., 2013).

Compacted sandy soil with small additions of bentonite (bentonite–sand mixture) has been proposed and used as an adequate material for these insulation layers. In order to be efficient for insulation, the insulation barriers should fulfill some specifications:

(1) Permeability at saturated state ranges between 10^{-8} m/s and 10^{-10} m/s (Chapuis, 1990; Parker et al., 1993; Marcoen et al., 2001; Pierson et al., 2004; Souli et al., 2008).
(2) Physical stability of the material in contact with water (Thériault, 2000).

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(3) A swelling potential that ensures good contact with the host rock and permits the replenishment of existing cracks or that will develop in the future (Yilmaz and Marschalko, 2014).
(4) The sand should possess some characteristics of grain size distribution (GSD), in order to prevent bentonite leaching from the skeleton, hence ensuring the hydraulic stability of the mixture (Malusis and Di Emidio, 2014).

In current engineering applications, soil–bentonite mixtures are mainly used to build impervious cores of earth dams and contain groundwater pollution. Many authors reported different percentages of bentonite additions, and they have found the percentages of 5–8% for sodium bentonite and 9–15% for calcium bentonite (Chapuis, 1990; Egloffstein, 2001; Graham et al., 2001; Montañez, 2002).

Algeria generates (12–14) $\times$ 10^6 tons of household wastes each year, where 3000 illegal dumping sites are observed. These landfills occupy a total area of about 150,000 ha (MPET, 2013). In the South Algeria, the rapid development of urban areas and the growth of oil industry begin to generate enormous quantities of hazardous wastes. In order to avoid groundwater pollution and environment degradation, an insulation barrier using dune sand is proposed for construction of waste disposal sites. Dune sand is an available and economical local material, which can be enhanced by a small addition of bentonite. Generally, the free swelling ratio between sodium bentonite and calcium bentonite is about 3, and hence results in a low hydraulic conductivity of the mixtures (Ait Saadi, 2003). The ratio of hydraulic conductivity between sodium bentonite and calcium bentonite is about 10^{-2} (Pierson et al., 2004; Rowe et al., 2012; Du et al., 2015). However, the sodium bentonite is less available through the world; instead, the calcium bentonite is used in the study, which is brought from Maghnia region in the west of Algeria. The study presented herein describes laboratory-testing techniques and analyzes the experimental results of dune sand-bentonite mixtures, suggesting an adequate combination in order to satisfy the regulation criteria.

An investigation study is carried out on several mixtures with different percentages of bentonite additions, which vary from 3% to 15%, for an adequate mixture purpose. The adequate amount of bentonite addition, which satisfies the required conditions on the saturated hydraulic conductivity, is obtained using oedometer test. After then, the saturated hydraulic conductivity under different confining stresses is investigated with direct methods using triaxial cell. The measurement of unsaturated hydraulic conductivity is conducted using vapor equilibrium technique (VET). The VET couples the total soil suction control in desiccators with saturated salt solutions, and water mass is measured from a digital balance laboratory (Fredlund and Rahardjo, 1993; Taibi et al., 2009). This paper presents an investigation in order to valorize local materials based on desert dune sand and bentonite for the design of insulation barriers intended to the realization of the hazardous waste facilities.

2. Materials and methods

2.1. Materials

The bentonite used in this study is extracted from Maghnia mine (Hammam Boughrara, 600 km west of the capital Algiers). The GSD curve of the bentonite is shown in Fig. 1. It is very fine clay; more than 60% of particles have a diameter less than 2 μm. Liquid limit (w_L) and plasticity index (PI) of the bentonite are 141% and 93%, respectively. The PI of bentonite indicates that the bentonite is a very highly plastic material and has high swelling potential, which is characterized by a large specific surface area (S_s = 462 m^2/g).

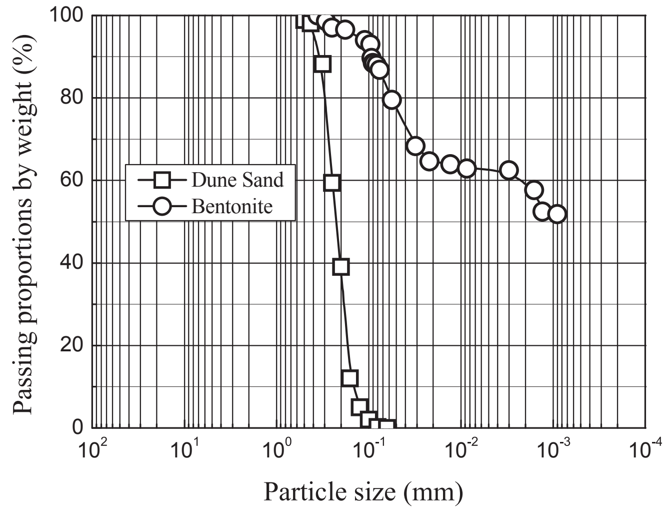

Fig. 1. Grain size distribution of bentonite and dune sand.

According to the Skempton classification based on the activity (Skempton, 1953), the bentonite from Maghnia presents a high percentage of calcite montmorillonite (Ca^{2+}). X-ray diffraction is one of the widely used methods for identification of clay minerals and studying their crystal structure within the soils. Diffraction test with X-ray diffraction method carried out on bentonite shows that the predominant clay mineral is the montmorillonite group. In addition, quartz, calcite, and traces of kaolinite and illite are observed. Results of chemical analysis show that Maghnia bentonite is composed mostly of silicate, with 17% aluminates (Table 1). The ratio of SiO_2 to Al_2O_3 is around 3.77, which is in agreement with the reported values of 2–5.5 (Pierson et al., 2004).

Dune sand known as desert sand is a material largely available in the South Algeria. The GSD curve of the dune sand is shown in Fig. 1. The corresponding coefficient of uniformity (C_u) and coefficient of curvature (C_c) are 1.7 and 1.1, respectively. According to the unified soil classification system (USCS), the dune sand is classified as poorly graded fine sand. The chemical analysis (Table 1) shows that the major component of dune sand is the silicate groups SiO_2 (about 95%).

2.2. Test methods

In order to get the required soil combination, several dune sand–bentonite mixtures have been considered in this study: 3% B + 97% S, 5% B + 95% S, 10% B + 90% S, 12% B + 88% S, 15% B + 85% S (B: bentonite, S: dune sand). Determination of the minimum proportion of bentonite to sand (B/S, %) should yield a suitable hydraulic conductivity (i.e. 10^{-8} – 10^{-10} m/s) or smaller (Chapuis, 1990; Parker et al., 1993), thus both the consolidation and compaction tests were used.

2.2.1. Compaction test

Compaction tests were carried out to assess the optimum water contents and the maximum dry unit weights of sand–bentonite mixtures. Sand–bentonite mixtures were prepared by mixing 3 kg of oven-dried dune sand with air-dried bentonite. The bentonite contents used were 0%, 3%, 5%, 10%, 12% and 15% by weight. For each sand–bentonite mixture, the optimum water content and the maximum dry unit weight were determined using standard Proctor compaction method (ASTM D698-91, 1991). The maximum dry unit