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Natural smectitic soils for protective liners in arid climate[☆]

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ABSTRACT

Compacted clay liners (CCL) can be used to isolate hazardous wastes like the soil and military scrap contaminated with depleted uranium that emanated from the Iraqi wars in 1991 and 2003. Near-surface repositories for such dangerous waste can preferably be located in the Iraqi deserts, which make up 60% of the territory of Iraq. CCLs are usually constructed using a mixture of clayey soil and coarse material compacted in air-dry form or suitably wetted. In the present study, two smectitic soils from Iraq, termed green and red clays, were investigated for potential use in CCLs. The shear strength, swelling pressure, hydraulic conductivity and creep properties were determined and used for preliminary design of top and bottom-liners. The engineering properties were determined for various dry densities and water contents ranging from air-dry to fully saturated conditions. The results showed that mixtures of sand and 30%–50% green clay and mixtures of sand and 40%–60% red clay are suitable for constructing top-liners with a hydraulic conductivity between 1×10^{-10} and 1×10^{-9} m/s. For bottom-liners, mixtures of sand and 70% green clay and mixtures of sand and 80% red clay can be considered. They were found to have a hydraulic conductivity of 1×10^{-11} m/s for a density at saturation of 2.1 g/cm^3 (dry density, 1.7 g/cm^3). As to the slope stability of top-liners, the shear strength for different clay percentages was found to guarantee slope stability for 18° inclination under both air-dry and water saturated conditions.

1. Introduction

Compacted clay liners (CCL) are used for constructing hydraulic/gas barriers in landfills and near surface repositories (NSR), with wastes ranging from municipal to hazardous ones (Koch, 2002; Chien et al., 2006), Fig. 1. In Iraq, this option, which represents cost-effective and sufficiently safe disposal of dangerous waste, can also be adopted for disposing DU-contaminated soil and military scrap emanating from the 1991 and 2003 wars (Bertell, 2006; IAEA, 2010). These structures can preferably be located in Iraqi deserts, which make up 60% of the country and are ideal for hosting NSRs of radioactive waste (Al-Taie et al., 2012; Al-Taie et al., 2013). The design principle in Fig. 1 can be used also for low- and intermediate-level short-lived radioactive waste in containers placed in concrete vaults as proposed for Spain and Lithuania. The encircled parts of the top-liner require particular care in design and construction with respect to 1) percolation of rain, 2) slope stability, and 3) discharge of surface water.

CCLs are commonly composed of clay–rich soil mixed with coarser material ("ballast[1]") layerwise placed and compacted (0.25–0.50 m thick). Since there are presently no national regulations respecting location and design we have followed, in principle, the United States Environmental Protection Agency's (USEPA) rules and the German Geotechnical Society (DGGT) regulations (USEPA, 1990; DGGT, 1993). In this study, we considered arid areas and recognized that compaction of wetted clay liner material can cause difficulties, like liquefaction and inhomogeneity of clayey soils (Benson and Daniel, 1990; Koerner and Daniel, 1997; Pusch and Yong, 2006). The placement and compaction of air-dry materials was in focus, which can also be more effective and cheaper. This option minimizes many technical problems regarding, e.g., the availability of suitable water for the mixing process, the generation of desiccation cracks and the difficulties in meeting quality measures concerning mixture homogeneity (Daniel and Wu, 1993; Camp et al., 2010).

Many issues have to be considered by geotechnical engineers in the design of CCLs for making them perform acceptably over the years. The required operational time of an NSR hosting low- and intermediate (short-lived) radioactive waste has been specified by various regulatory

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[1] Ballast: any soil material other than expanding clay minerals.

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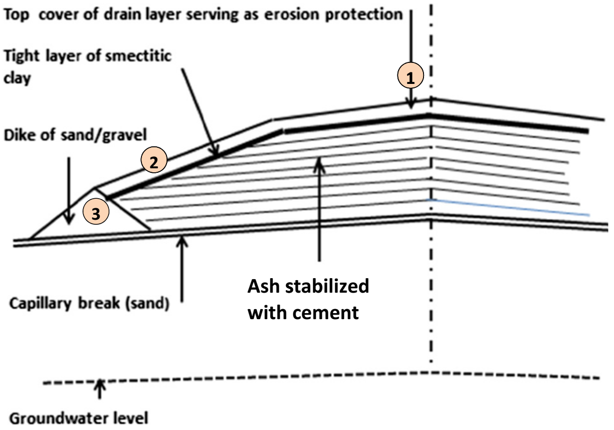

Fig. 1. Principle of designing a landfill of hazardous waste like contaminated soil or incinerated organic waste. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

authorities to be 300 years (Chien et al., 2006), which is the time considered in the present study. We are primarily concerned with design of the liners, which requires that candidate clay materials must be characterized with respect to their basic physical properties: hydraulic/gas[2] conductivity, swelling pressure and shear strength (Fig. 2). To this comes the criterion that the long-term chemical stability must be ensured keeping in mind that chemical impact on the minerals also controls the physical performance. Thus, liners placed below the waste —"bottom-liners"—can be percolated by solutions that have passed through wastes and become very acid or basic, leading to rapid dissolution of the smectite components and to significant changes in mechanical strength and permeability by ion exchange processes and dissolution (Mohamed and Antia, 1998; Pusch and Yong, 2006). The risk of failure of bottom-liners depends on how effectively the top-liners can hinder precipitated water from reaching and percolating the waste mass, and the aim is naturally to select water-tight ("geological") top-liners although bottom-liners may have to be installed for fulfilling the requirements set by authorities. The top-liners will control water penetration to the waste body and eventually to the bottom-liner and they should ideally have a high content of expandable clay (Pusch and Khil, 2004). The density should be high for providing best possible tightness, but the high swelling pressure that goes with it can displace and degrade the overburden that is required for erosion protection. Both the content of expandable minerals (commonly montmorillonite) and the density must therefore be balanced to give optimum performance (Stewart et al., 2003). The water uptake of initially air-dry CCL can take place as finger-like flow paths (loose structure) or by diffusive migration (dense structure). The wetting front advance (WFA) is a function of dry density and clay percentage as well as of the initial water content (El Shafei, 1988). At sufficiently high dry density, high clay percentage and low initial water content, the WFA will be slow leading to enhanced performance of waste isolation.

The aim of this paper is to describe a study of two smectitic soils from Iraq for potential use as CCL. An attempt is made to select suitable clay-sand mixture compacted at low water contents for simulating common field conditions in deserts. The hydraulic conductivity, swelling pressure, shear strength and creep behaviour were studied for the selection of suitable mixtures for top and bottom-liners.

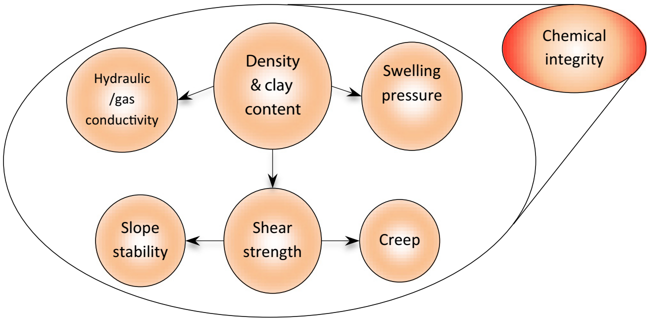

Fig. 2. Factors affecting the design of CCL and their performance. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Identification and Index properties

Two smectitic clays, termed green and red clays, were investigated. They belong to the Fatha formation, Iraq, which is of Lower Miocene Age. Both clays are found within the Al-Jazira and Western Deserts and appeared as hard greenish and reddish rocks (Jassim and Goff, 2006; Al-Bassam, 2007). They are also present in the Al-Qadiya district in Mosul city. The samples were taken from about 2 m thick layers exposed at the ground surface. They were disintegrated by use of a jaw crusher and passed through 1 mm sieve for laboratory testing. Grain size analyses were determined following two sieving procedures, dry and wet sieving. The gradation of the dry material was determined following ASTM D 6913. The wet sieving was conducted on dispersed samples following the ASTM D 1140. Further, Material finer than 0.063 mm was analysed separately using the pipette method (BS 1377, 1975).

The clay samples were disintegrated by ultrasonic treatment before conducting Atterburg limits (ASTM D 4318) and specific gravity (ASTM D 854) tests (Müller Vonmoos et al., 1990). The green and red clays are concluded to be weakly cemented by precipitated calcite compounds in virgin form.

2.2. Mineralogy

The clay and non-clay minerals were identified by X-ray diffraction of randomly oriented powder. The Empyrean-PANalytical diffractometer at the division of Sustainable Process Engineering, Luleå University of Technology, was utilized for identification of major clay minerals and for semi-quantitative analyses. The back-loading technique was adopted in the preparation of air-dry powder mounts. Another set was prepared for ethylene glycol solvation for better detection of expanding clay minerals like montmorillonite (Mt). The powder mounts were left inside a desiccator containing about 200 ml of ethylene glycol. The desiccator was kept at 60 °C oven for 24 h for enhancing exposure to ethylene glycol vapour (Moore and Reynolds, 1997). The diffraction patterns for the air-dry and glycolated samples were determined using CuKα radiation with Ni-filter at 40 mA and 45 kV. The divergence slit was kept in automatic mode (sample length 10 mm, radiation length 10 mm), the diffraction angle (2θ) ranged between 5° and 90° running at a speed of 0.026°/s.

2.3. Compaction of mixtures

The Harvard miniature compaction tool (Head, 2006) was utilized to determine the maximum dry density and optimum moisture content according to the modified Proctor compaction method. Clay–sand mixtures were prepared by hand mixing of the dry components. Each sample contained 400 g of dry soil material. Distilled water was added to the mixture using hand sprayer. The wet mixture was stored in tight plastic

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[2] Permeability is the ability of fluids (water or gas) to pass through a porous medium like soil or rock. Hydraulic conductivity and permeability are related by Darcy law. In principle, clay liners should be identified with respect to water percolation (hydraulic conductivity) and gas leakage (gas conductivity) depending on the type of waste.