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Workability, compressibility and hydraulic conductivity of zeolite-amended clayey soil/calcium-bentonite backfills for slurry-trench cutoff walls

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ABSTRACT

Soil–bentonite slurry-trench cutoff walls using backfill consisting of on-site sandy soil and Na-bentonite are extensively used as engineering barriers for the purpose of achieving relatively low hydraulic conductivity. The amendments such as zeolite to backfill are considered to improve the contaminant sorptive capacity. At some sites, local clayey soil, Ca-bentonite and natural zeolite may be available for an alternate backfill. However, studies on the workability (in terms of slump), compressibility and hydraulic conductivity of such zeolite-amended clayey soil/Ca-bentonite backfills for the cutoff walls are very limited. This paper presents a comprehensive laboratory investigation on the workability, compressibility, and hydraulic conductivity of fine-grained zeolite-amended clayey soil/Ca-bentonite backfills using several series of slump and oedometer tests. Kaolin is used as the model clayey soil, and it is amended with various amounts of Ca-bentonite (7.8–8.4%) and zeolite (10–40%) to prepare zeolite-amended kaolin–bentonite backfills. The test results are compared with previous studies on zeolite-amended sandy soil/Na-bentonite backfills as well as compacted zeolite–bentonite liners to assess the effects of zeolite content and zeolite grain-size on the compressibility and hydraulic conductivity. The results indicate that the water content required to achieve a target slump (100–150 mm) for the backfills increases with increasing zeolite content. Liquid limit can be a useful index for a preliminary estimation of the water content required to achieve the target slump for the backfills presented in this study and zeolite-amended sandy soil/Na-bentonite backfills reported in previous studies. The results reveal that the hydraulic conductivity of the zeolite-amended clayey soil/Ca-bentonite backfills with void ratio ranging from 0.54 to 1.45 is generally lower than the typical regulatory limit (10^{-9} m/s). The addition of fine-grained zeolite has insignificant influence on the compressibility and hydraulic conductivity of both clayey soil/Ca-bentonite and sandy soil/Na-bentonite backfills. A proposed empirical method based on the framework of Kozeny–Carman equation can predict the hydraulic conductivity of zeolite-amended clayey soil/Ca-bentonite backfills values within the range of 1/3 to 3 times those calculated from the oedometer tests. The proposed method is also shown to estimate the hydraulic conductivity of the compacted zeolite–bentonite liners from previous studies with reasonable accuracy. Additional research is recommended to evaluate the proposed zeolite-amended backfill using tap water and also by direct measurement of hydraulic conductivity using falling-head or constant-head testing method.

1. Introduction

Groundwater contamination due to improper past waste disposal practices, leaking underground storage tanks and accidental spills has been a growing concern on a global scale (Du et al., 2012, 2013, 2014a, 2014b, 2014c, 2014d; Sharma and Reddy, 2004). Environmental laws and regulations have been promulgated to control the migration and remediation of contaminated groundwater in subsurface (Du et al., 2012, 2013, 2014a, 2014b; Sharma and Reddy, 2004). The soil–bentonite slurry-trench cutoff wall, constructed by the slurry trench excavation method, is used extensively as vertical engineered barrier to control the migration of contaminants in groundwater due to its low permeability and cost-effectiveness. The soil–bentonite slurry-trench cutoff wall could also serve as an interim remedial action to reduce the immediate risk to public and the environment, therefore affording to pursue follow-on clean up by long-term in-situ remedial technologies (Sharma and Reddy, 2004).

Soil–bentonite backfills generally consist of Na-bentonite and on-site sandy soils to provide low hydraulic conductivity (Yeo et al., 2005; Malusis et al., 2009; Hong et al., 2011). The compressibility and hydraulic conductivity of sandy soil–bentonite/Na-bentonite (hereinafter referred

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to sandy SB) backfills and prediction methods of overburden earth pressure distributed along sandy SB slurry-trench walls have been extensively investigated (Britton et al., 2004; Evans and Ryan, 2005; Yeo et al., 2005; Malusis et al., 2009; Malusis et al., 2011; Fan et al., 2014a). The investigation of the compressibility of soil–bentonite backfill is necessary since the compressibility significantly affects the deflection of the trench sidewall (Ruffing et al., 2010; Sreedharan and Puvvadi, 2013). The undrained shear strength of the SB backfills is generally less than 10 kPa due to their high water contents (Evans and Ryan, 2005). Previous studies suggest that soil–bentonite mixtures and Na-bentonite, depending on the nature and concentration of the contaminants, may undergo a considerable increase in permeability when they are exposed to salts, heavy metals and organic solutions (Lo and Yang, 2001; Mishra et al., 2009; Yong et al., 2009; Fan et al., 2013; Du et al., 2015). Such a substantial change in hydraulic conductivity is attributed to the squeezing of diffuse double layer of hydrated bentonite (Mishra et al., 2009; Yong et al., 2009; Fan et al., 2013; Du et al., 2015). Recently, the use of polymerized Na-bentonite is also proposed to improve the chemical compatibility of soil–bentonite backfills (Bohnhoff and Shackelford, 2014).

At some sites, especially in developing countries such as China and India, high-quality natural Na-bentonite or polymerized Na-bentonite is scarce, while Ca-bentonite is abundant and may be easily available as alternative to make up soil–bentonite slurry-trench cutoff wall backfills (Murray, 2002; Fan et al., 2014a, 2014b). However, it has been well-known that Ca-bentonite has lower sorption capacity of heavy metals, and relatively higher hydraulic conductivity/effective diffusion coefficient when compared with Na-bentonite (Choi and Oscarson, 1996; Gleason et al., 1997; Kaya and Durukan, 2004). Moreover, at some sites, the on-site predominantly clayey soil may be available instead of a typical sandy soil for preparing backfill. For example, Crawford (2004) presented an investigation on the potential use of local dredged sediment (high plasticity clay) admixed with Na-bentonite as slurry-trench cutoff wall backfill material. Under such circumstances, clayey soil mixed with bentonite may be considered as alternative soil–bentonite backfill material. Recently, Fan et al. (2014b) investigated the compressibility and hydraulic conductivity of such clayey soil/Ca-bentonite backfills for slurry-trench cutoff walls and found them to perform well.

In order to enhance contaminant containment by enhanced sorption process, amendment of soil–bentonite with zeolite or activated carbon has been proposed (Malusis et al., 2009; Hong et al., 2011). It is well understood that zeolite has relatively high adsorption capacity for metals (Turan and Ergun, 2009; Hamidpour et al., 2010; Delkash et al., in press); therefore, zeolites are used extensively as adsorbents for removal of cations (ammonium and heavy metals) in wastewater as well as amendments in compacted soil liners and sandy soil/Na-bentonite slurry-trench cutoff walls for waste containment (Kayabali, 1997; Kaya and Durukan, 2004; Jin et al., 2010; Hong et al., 2011; Ören et al., 2011; Reddy et al., 2014). This beneficial use is due to the fact that the open framework, honeycomb structures, and the isomorphous substitution of Si^{4+} by Al^{3+} enhance the molecular sieve action and catalytic behavior of the natural zeolites (Kayabali, 1997; Ören et al., 2011). When exposed to salt or inorganic acid attack, fixation of heavy metals in zeolite is reported to be stable; whereas the sorption of heavy metals to Na-bentonite alone can be reversible (Moirou et al., 2001). As a result, it is advantageous to use zeolite amendment to enhance the chemical compatibility of the clayey soil/Ca-bentonite backfills. In addition, the natural zeolite reserves and output are high in European countries, the US and China, which results in a lower cost than those of activated carbon or organophilic clay.

However, the addition of amendments should not compromise the integrity of the cutoff wall in terms of traditional design properties, especially the compressibility and hydraulic conductivity of the soil–bentonite backfill. Previous studies have shown that a full substitution of zeolite for sand in compacted sand–bentonite liners could result in an increase in the hydraulic conductivity by approximately 20 to 30-fold (Ören et al., 2011); whereas Hong et al. (2011) indicated that the zeolite type and content had insignificant influence on the compressibility and hydraulic conductivity of sandy SB backfills. Evidently, this contradiction in the existing studies would considerably impede the application of zeolite in soil–bentonite slurry-trench cutoff walls. Nevertheless, studies on the effect of zeolite amendment on the hydraulic conductivity, workability and compressibility of clayey soil/Ca-bentonite backfills are non-existent.

The objectives of this study are to: (1) investigate the workability in terms of determination of water content corresponding to target slump, compressibility and hydraulic conductivity of zeolite-amended clayey soil/Ca-bentonite backfills; (2) assess the effect of zeolite content on the compressibility and hydraulic conductivity of clayey SB backfills; and (3) evaluate the proposed method that is based on the framework of the Kozeny–Carman equation to predict the hydraulic conductivity of zeolite-amended clayey SB backfills. Furthermore, to better understand the impacts of the addition of zeolite on the compressibility and hydraulic conductivity of various engineered barriers for contaminant containment, a comprehensive comparison is made between the results obtained from this study and those reported in previous studies on zeolite-amended conventional sandy soil/Na-bentonite backfills as well as compacted zeolite–bentonite (ZB) liners. The results obtained from this study are useful to facilitate strategies for the design of zeolite-amended clayey soil/Ca-bentonite backfills for vertical cutoff walls.

2. Materials and methods

2.1. Soil, bentonite and zeolite

The zeolite-amended clayey SB backfills are prepared using air-dried kaolin, Ca-bentonite, and natural zeolite (clinoptilolite), which are obtained from commercial sources in Zhenjiang City, China. The kaolin is selected to represent a clayey soil because: (1) it is one of the most common minerals found in natural clays (Grim, 1968); (2) it has a low organic content, consistent and uniform mineralogy (Yukselen-Aksoy and Reddy, 2013); and (3) it has a relatively lower w_L and activity, and its hydraulic conductivity is nearly 10 to 1000 times higher than that for bentonite in general (Mitchell and Soga, 2005). Therefore, kaolin represents an ideal model clayey soil for laboratory tests as the base component of the backfills in order to investigate the effects of bentonite content (*BC*) and zeolite content (*ZC*) on the compressibility and hydraulic conductivity. In addition, it is noted that the hydraulic conductivity of the kaolin tested with water content higher than or equal to the liquid limit fails to meet the typical regulatory limit of 10^{-9} m/s when the effective vertical stress is lower than 100 kPa (Fan et al., 2014b). Ruffing et al. (2011) indicated that the horizontal or vertical effective stress level is typically lower than 100 kPa in the soil–bentonite slurry-trench cutoff walls. Thus, the kaolin tested in this study should be admixed with bentonite to meet the low the hydraulic conductivity requirement to serve as backfill for slurry-trench cutoff wall.

The physico-chemical properties and mineralogical compositions of the selected materials (kaolin, bentonite and zeolite) are summarized in Table 1. The liquid limit (w_L) and plastic limit (w_P) of these materials are measured as per ASTM D4318 (2010a). Based on ASTM D2487 (2011a), the kaolin is classified as low-plasticity clay (CL), while the bentonite and zeolite are classified as high-plasticity clay (CH). The specific gravity is measured as per ASTM D54 (2010b). The grain size distribution of the materials is measured by a Mastersizer 2000. The total surface area is determined by the ethylene glycol monoethyl ether (EGME) method suggested by Cerato and Luteneggerl (2002). The dominant minerals of the kaolin and bentonite are kaolinite and montmorillonite, respectively, based on the X-ray diffraction analysis. In addition, the basal spacing of the montmorillonite is identified as 15.48 Å, which suggests that the bentonite used in this study is Ca-bentonite, as suggested by