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Research paper

Compressibility and hydraulic conductivity of clayey soil mixed with calcium bentonite for slurry wall backfill: Initial assessment

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ABSTRACT

Soil–bentonite vertical cutoff walls, consisting of a sandy soil mixed with Na-bentonite as backfill, are used extensively as engineered barriers for contaminant containment. However, suitable sandy soil and Na-bentonite may not be available at some sites. Consequently, locally available clayey soil and Ca-bentonite may be considered as an alternative backfill. The use of clayey soil/Ca-bentonite backfill may be advantageous to achieve relatively low hydraulic conductivity, which has equivalent performance as that of conventional sandy soil/Na-bentonite backfills. However, studies on the compressibility and hydraulic conductivity of these clayey soil–bentonite backfills are very limited. This paper presents a comprehensive laboratory investigation on the compressibility and hydraulic conductivity of clayey soil/Ca-bentonite backfill through a series of oedometer tests. Kaolin is used as the control clayey soil and it is amended with different contents of Ca-bentonite, 0 (kaolin alone), 5, 10, and 15% (by dry weight basis), to prepare the clayey soil/Ca-bentonite backfills. The initial water contents for the backfills are selected to be 0.75, 1.0, 1.25, and 1.50 times their corresponding liquid limits. The results reveal that the backfills exhibit a noticeable inverse 'S' shaped e-log(σ') compression curves attributed to the existence of the remolded yield stress (σ'_{yr}). The compressibility, in terms of σ'_{yr} and the compression index (C_c), is significantly affected by the initial water content and bentonite content. The void ratio at an effective vertical compression stress of 1 kPa (denoted as e_1) is a useful characteristic parameter to uniquely correlate with C_c for the clayey soil/Ca-bentonite backfills in this study as well as for sandy soil/Na-bentonite and sandy soil–clay backfills that are reported in previous published studies. Unique relationships are also found between the σ'_{yr}, initial void ratio (e_0), e_1, and the void ratio at liquid limit (e_L). The hydraulic conductivity of the clayey soil/Ca-bentonite backfills is significantly reduced by the bentonite content; generally to less than 10^{-9} m/s. An empirical method based on the framework of Kozeny–Carman equation is proposed to predict the hydraulic conductivity of the clayey soil/Ca-bentonite backfills, and the predicted hydraulic conductivity values using these methods are found to fall in the range of 1/3 to 3 times those obtained from the oedometer tests. The proposed method is shown to estimate the hydraulic conductivity for both the clayey soil/Ca-bentonite backfills in this study and the sandy soil–bentonite backfills from published study with reasonable accuracy. Additional research is warranted to prepare the backfills to simulate typical field practice (e.g., use of tap water) and at workable initial water contents (based on the slump testing).

1. Introduction

Improper past disposal practices and accidental spills at numerous sites worldwide have resulted in the contamination of the subsurface soils and groundwater with high amounts of heavy metals and organic pollutants (Du et al., 2013, 2014a,b; Hu et al., 2010; Xue et al., 2013). Soil–bentonite vertical cutoff walls installed with the slurry trenching technology are widely used as in-situ barriers to control the subsurface migration of contaminated groundwater in the United States, Canada and Japan (Evans et al., 1995; Sharma and Reddy, 2004). In the United States, soil–bentonite vertical cutoff walls are often preferred because they possess relatively low hydraulic conductivity (typically ranges from 10^{-9} to 10^{-11} m/s) and are generally cost-effective (Evans et al., 1995; Sharma and Reddy, 2004).

The effects of the fines content (*FC*), bentonite content (*BC*), gradation of sand, and other amendment content (e.g. zeolite and activated carbon) on the compressibility and hydraulic conductivity (k) of sandy soil/Na-bentonite (hereinafter referred to sandy SB) and/or sand/clay

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(SC) backfills have been extensively investigated in previous studies (Castelbaum and Shackelford, 2009; Fan et al., 2014; Hong et al., 2011; Malusis et al., 2009; Yeo et al., 2005). The chemical compatibility of various types of sandy SB backfills was also evaluated by measuring hydraulic conductivity of the backfills when permeated with salt solutions (Malusis and McKeehan, 2013; Mishra et al., 2009). In addition, the consolidation stresses in the sandy soil/Na-bentonite vertical cutoff walls have been estimated using an arching model (Evans et al., 1995) and a lateral squeezing model (Filz, 1996). The relationship between the compressibility and the lateral deflection of soil–bentonite vertical cutoff wall has been established using a modified lateral squeezing model (Ruffing et al., 2010). It is recognized that the backfill could possess undrained shear strength less than 10 kPa due to its relatively high water content (Evans and Ryan, 2005), and strength is considered as a major design parameter when exposed to external loading (D'Appolonia, 1980). The strength of the backfills depends on their corresponding water contents and liquid limits as suggested in previous studies on reconstituted clays (Shen et al., 2003, 2008). The present is focused on compressibility and hydraulic conductivity of the backfills, and the strength of the backfills be investigated in future studies.

Soil–bentonite backfills generally consist of Na-bentonite, on-site sandy soils, and amendments such as zeolite and activated carbon to provide low hydraulic conductivity and high contaminant sorption capacity (Hong et al., 2011; Malusis et al., 2009; Yeo et al., 2005). However, previous studies have shown that soil–bentonite backfills and Na-bentonite, depending upon the nature and concentration of the contaminants, may undergo a considerable increase in hydraulic conductivity when they are exposed to salts, heavy metals, and organic solutions (Fan et al., 2013; Lo and Yang, 2001; Mishra et al., 2009; Yong et al., 2009). Moreover, at some sites, especially those found in developing countries such as China and India, high-quality natural Na-bentonite is scarce, but Ca-bentonite is abundant as alternative to make up soil–bentonite backfills. Ca-bentonite possesses a lower sorption capacity and higher hydraulic conductivity relative to Na-bentonite; therefore, it is not preferred to be used in soil–bentonite vertical cutoff walls as the sorption capacity and hydraulic conductivity are two important factors that control the performance of soil–bentonite vertical cutoff walls (Du and Hayashi, 2006; Du et al., 2009; Hong et al., 2011; Malusis et al., 2009). Under such circumstances, the use of clayey soil and Ca-bentonite may be an alternative option to prepare clayey soil/Ca-bentonite (hereinafter referred to clayey SB) backfills that could possess low hydraulic conductivity and high contaminant sorption capacity and are comparable to that of conventional sandy soil/Na-bentonite backfills. To date, very few studies have systematically investigated the compressibility and hydraulic conductivity of clayey SB backfills.

Many previous studies often set the initial water content (w_0) for the sandy SB backfills at a constant value approximately corresponding to a target slump ($-\Delta H = 100$ or 125 mm) (Hong et al., 2011; Malusis et al., 2009; Yeo et al., 2005). Very few studies have investigated the effects of different initial water contents on the compressibility of sandy or clayey SB backfills. Assessment of the impact of w_0 on the compressibility of clayey SB backfills is an importance issue as the compression behavior of remolded natural clays is shown to be significantly affected by w_0 (Cerato and Lutenegger, 2004; Hong et al., 2010). The lateral deflection of the soil–bentonite vertical cutoff wall is closely related to the compressibility of soil–bentonite backfill (Ruffing et al., 2010).

In this study, a laboratory investigation is undertaken to: (1) investigate the compressibility and hydraulic conductivity of clayey SB backfills via a series of oedometer tests; (2) evaluate how the initial water content and bentonite content affect the compressibility and hydraulic conductivity of the clayey SB backfills; and, (3) examine empirical relationship to predict hydraulic conductivity value for the clayey SB backfills based on the framework of Kozeny–Carman equation.

2. Materials and methods

2.1. Constituent soils

The clayey SB backfills are comprised of kaolin and Ca-bentonite which are provided by MUFENF mineral processing plant in Zhenjiang City, China. The kaolin is used to simulate 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, and a consistent and uniform mineralogy (Yukselen-Aksoy and Reddy, 2013); and, (3) it has a relatively lower liquid limit and activity, while hydraulic conductivity for kaolin is nearly 10 to 1000 times higher than that for bentonite in general (Mitchell and Soga, 2005). Thus, kaolin is a good control soil for laboratory tests as the base component of the backfills in order to investigate the effect of bentonite content on the compressibility and hydraulic conductivity.

Table 1 shows the physico-chemical properties and mineralogical compositions of the kaolin and bentonite clays used for this study. Based on the Unified Soil Classification System (ASTM, 2011b), the kaolin and bentonite clays are classified as low-plasticity clay (CL) and high-plasticity clay (CH), respectively. The grain size distribution of the soils was measured with a laser particle size analyzer Mastersizer 2000 (Malvern Instruments Ltd., UK). The specific surface area (SSA) was determined by the Ethylene Glycol Monoethyl Ether (EGME) method (Cerato and Luteneggerl, 2002). Based on the X-ray diffraction analysis, the dominant minerals of the kaolin and bentonite clays are found to be kaolinite and montmorillonite, respectively. The basal spacing (001) of the bentonite is identified as 15.48 Å, indicating that the bentonite used in this study is Ca-bentonite, as suggested by Karakaya et al. (2011).

2.2. Preparation of clayey SB backfills

The bentonite content of the clayey SB backfills was selected to be 5, 10 and 15% (dry weight basis). The bentonite content (*BC*) in the clayey SB backfills is calculated using Eq. (1):

$$BC = \frac{m_{\text{ben}}}{m_{\text{kao}} + m_{\text{ben}}} \tag{1}$$

where m_{kao} and m_{ben} are the mass of kaolin and bentonite in the mixture (on dry mass basis), respectively. The range of Ca-bentonite content selected in this study is slightly higher relative to the Na-bentonite (4 to 7%) widely used in practice as suggested by Evans et al. (1995), but may encompass the typical range of Ca-bentonite content for potential use in practice. This study also assessed and compared the compressibility and hydraulic conductivity of the kaolin

Table 1
Properties of constituent soils used in this study.

Property	Testing method	Constituent soil	
		Kaolin	Bentonite
Specific gravity, G_s	ASTM (2010a)	2.66	2.73
Clay fraction, CF (%)	[a]	25%	33%
Liquid limit, w_L (%)	ASTM (2010b)	29.1	331.4
Plastic limit, w_P (%)	ASTM (2010b)	19.5	88.2
Classification	ASTM (2011b)	CL	CH
Specific surface area (m^2/g)	[b]	45.7	378.5
Exchangeable cations (cmol/kg)	ASTM (2010c)		
Ca^{2+}		1.44	22.74
Mg^{2+}		0.08	1.41
Na^{+}		4.75	53.39
K^{+}		0.34	0.53
Sum		6.61	78.07
pH	ASTM (2007)	8.7	10.0

[a] Measured using a laser particle analyzer Mastersizer 2000 (Malvern Instruments Ltd., UK).

[b] Measured using the EGME method according to Cerato and Luteneggerl (2002).