Effects of Addition of Fine-grained Zeolite on the Compressibility and Hydraulic Conductivity of Clayey Soil/Calcium-Bentonite Backfills for Vertical Cutoff Walls

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ABSTRACT: Vertical cutoff walls, using backfill consisting of on-site sandy soil and Na-bentonite are widely used as engineering barriers for the purpose of achieving relatively low hydraulic conductivity and high contaminant sorption capacity. At some sites, locally available clayey soil, Ca-bentonite and natural zeolite may be considered as an alternate backfill. However, studies on the compressibility and hydraulic conductivity of zeolite-amended clayey soil/Ca-bentonite backfills for vertical cutoff walls are very limited. A series of one-dimensional consolidation tests is performed to evaluate the compressibility and hydraulic conductivity of fine-grained zeolite-amended clayey soil/Ca-bentonite backfills. Kaolin is used as the control clayey soil, and it is amended with various amounts of Ca-bentonite (5, 10, and 15%) and zeolite (2 - 40%) to prepare zeolite-amended kaolin-bentonite backfills. The results indicate that the addition of fine-grained zeolite has insignificant influence on the compressibility and hydraulic conductivity of clayey soil/Ca-bentonite and sandy soil/Na-bentonite backfills. The hydraulic conductivity of the zeolite-amended clayey soil/Ca-bentonite backfills is generally lower than the typical regulatary limit of 10^{-9} m/s. Two empirical methods, based on the Nagaraj's generalized void ratio (e/e_L) and Sivapullaiah et al.'s method, are assessed to predict the hydraulic conductivity of the backfills. The proposed method based on the Sivapullaiah et al.'s method is shown to estimate the hydraulic conductivity for the fine-grained zeolite-amended clayey soil/Ca-bentonite backfills with reasonable accuracy.

KEYWORDS: Bentonite, Cutoff wall, Hydraulic conductivity, Soil-bentonite backfill, Zeolite.

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 (Sharma and Reddy 2004; Du et al. 2012, 2013, 2014*a*, *b*). Environmental laws and regulations have been promulgated to control the migration and remediation of contaminated groundwater in subsurface (Du et al. 2012, 2013, 2014*a*, *b*; Sharma and Reddy 2004). The soil-bentonite vertical cutoff wall, constructed by the slurry trench excavation method, is widely used as vertical engineered barrier to control the migration of contaminants in groundwater due to its low permeability and cost-effectiveness. The soil-bentonite vertical cutoff wall could also serve as an interim remedial action to reduce immediate risks 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 consist of Na-bentonite and on-site sandy soils to provide low hydraulic conductivity in general (Yeo et al. 2005; Hong et al. 2011; Malusis et al. 2009). The compressibility and hydraulic conductivity of sandy soil-bentonite/Na-bentonite (hereinafter referred to sandy SB) backfills and prediction methods of overburden earth pressure distributed along sandy SB vertical cutoff 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. 2014). Recently, the use of polymerized Na-bentonite is also proposed to improve the chemical compatibility of soil-bentonite backfills (Bohnhoff and Shackelford 2014). It is recognized that the backfills could possess shear strength less 10 kPa due to high water content (Evans and Ryan 2005).

At some sites, especially in developing countries such as China and India, high-quality natural Na-bentonite is scarce; while Ca-bentonite is abundant and can be easily available as alternative to make up soil-bentontie backfills. However, it is suggested that Ca-bentonite has lower sorption capacity of heavy metals, and higher hydraulic conductivity when compared with Na-bentonite (Choi and Oscarson 1996; Kaya and Durukan 2004). Moreover, the on-site predominantly clayey soil may be available instead of sand for preparing backfill at some sites. Under such circumstances, clayey soil mixed with Ca-bentonite can be considered as alternative soil-bentonite backfill materials (Fan et al. 2014).

In order to enhance contaminant containment by enhancing sorption process, amendment of soil-bentonite with zeolite or activated carbon has been proposed (Malusis et al. 2009; Jin et al. 2010; Hong et al. 2011). Natural zeolites are crystalline hydrated aluminosilicate minerals. The open framework, honeycomb structures, and the amorphous 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 bentonite alone can be reversible (Moirou et al. 2001; Hamidpour et al. 2010). In addition, natural zeolites reserves and output are huge in European countries, the US and China, resulting in a lower cost than those of activated carbon and organophilic clay. Thus, it is expected to use zeolite as amendment to enhance the chemical compatibility of compacted soil liners and soil-bentonite vertical cutoff walls (Kayabali 1997; Kaya and Durukan 2004; Jin et al. 2010; Hong et al. 2011; Ören et al. 2011). Some previous studies have shown that a full substitution of zeolite for sand in compacted sand-bentonite liners could result in an increase in hydraulic conductivity by approximately 20 to 30-fold (Ören et al. 2011). However, Hong et al. (2011) indicated that the zeolite type and content had insignificant influence on the compressibility and hydraulic conductivity of sandy SB backfills. Studies to investiagte the effect of zeolite amendment on the compressibility and hydraulic conductivity of clayey soil/Ca-bentonite backfills are non-existent.

The objectives of this study are to: (1) assess the effects of zeolite content and grain-size on the compressibility and hydraulic conductivity of clayey SB backfills; and (2) use two empirical methods for predicting the hydraulic conductivity of zeolite-amended clayey SB backfills based on void ratio (e) and liquid limit (w_L). A comprehensive comparison is made for the results obtained from this study with those reported in previous studies on zeolite-amended conventional sandy soil/Na-bentonite backfills as well as compacted zeolite-bentonite (ZB) liners to understand the impacts of the addition of zeolite on the compressibility and hydraulic conductivity of various engineered barriers. The results obtained from this study are useful to faciliate strageties for the design of zeolite-amended clayey SB backfills for vertical barriers.

2. MATERIALS AND METHODS

2.1 Materials

The zeolite-amended clayey SB backfills are prepared using air-dried kaolin, Ca-bentonite, and natural zeolite (clinoptilolite), which are commercially available 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.

The physical properties of the constituent materials are summarized in Table 1. The liquid limit (w_L) and plastic limit (w_P) are measured as per ASTM D4318 (ASTM 2010*a*). The kaolin is classified as low-plasticity clay (CL), while the bentonite and zeolite are classified as high-plasticity clay (CH) based on ASTM D2487 (ASTM 2011*a*). The specific gravity is measured as per ASTM D854 (ASTM 2010*b*). The grain size distribution of the materials is measured by a Mastersizer 2000. 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 15.48 Å, suggesting that the bentonite used in this study is Ca-bentonite. The pH of the materials is measured as per ASTM D4972 (ASTM 2007). The physical properties of the zeolite, in terms of liquid limit and soil classification, used in this study are quite similar to those reported by Hong et al. (2011).

Table 1 Physical properties of constituent materials used for preparing backfills in this study

Property	Kaolin	Bentonite	Zeolite
Liquid limit	32.3%	331.4%	72.2%
Plastic limit	19.5%	88.2%	23%
Classification	CL	CH	CH
Specific gravity	2.66	2.73	2.33
Clay fraction	25%	33%	20%
Mean grain diameter	0.009 mm	0.007 mm	0.011 mm
Soil pH	8.7	10.0	8.9

2.2 Preparation of backfills

Two types of zeolite-amended clayey SB backfills, denoted as Type 1 and Type 2 backfills, are prepared for oedometer tests. The Type 1 backfills focus on the effects of zeolite on the compressibility and hydraulic conductivity; therefore, the bentonite content is maintained the same. Type 1 backfills are prepared by thoroughly mixing a pre-determined amount of zeolite-kaolin-Ca-bentonite mixture with distilled water for 20 min. The zeolite contents (*ZC*s) are controlled at 0, 2, 4, 6, 8, and 10%, the bentonite content (*BC*) is set at 5%, and the kaolin content is varied from 95 to 85%. All of the constituents are based on the dry weight of the backfills.

For Type 2 backfills, the sample preparation represents the field practice as suggested by Yeo et al. (2005). The backfill is prepared by thoroughly mixing a pre-determined weight of zeolite-kaolin-Ca-bentonite base mixture with bentonite-water slurry for 30 minutes. The zeolite contents of the base mixtures are controlled at 0, 10, 20, and 40%, and the bentonite content is set at 5%. The bentonite-water slurry is prepared by mixing 5% dry bentonite powder with 95% distilled water (weight basis) for 30 minutes and left for hydration for 24 to 48 hours. After hydration, the marsh funnel viscosity, density and pH of the prepared bentonite-water slurry are 38 s, 1.038 g/cm^3 and 10.45, respectively as per API (2009).

All of the mixing processes are carried out with a paddle mixer. The w_L of the Type 2 backfill is determined when water content satisfies a slump of 125 ± 5 mm (w_{BM}). The reason for choosing w_{BM} in determining w_L is because: (1) bentonite content varies with the addition of bentonite-water slurry during the slump tests, which would slightly affect the w_L of the backfill in turn; and (2) $-\Delta H$ = 125 ± 5 mm is often adopted to prepare backfills in previous studies (Malusis et al. 2009; Hong et al. 2011). The bentonite content in the Type 2 backfill is calculated using the following equation:

$$BC = \frac{m_{\text{ben}} + m_{\text{ben,s}}}{m_{\text{total}} + m_{\text{ben,s}}} \tag{1}$$

where m_{ben} is the mass of dry bentonite in base mixture, $m_{\text{ben,s}}$ is the mass of dry bentonite from bentonite-water slurry, and m_{total} is the mass of base mixture. The bentonite contents of the Type 2 backfills with water contents of w_{BM} is calculated as 7.8, 8.0, 8.1, and 8.4% based on Eq. (1), corresponding to zeolite content of 0, 10, 20, and 40%, respectively.

The initial water content of the backfill specimens for oedometer test are adjusted approximately to their corresponding liquid limits using distilled water. A predetermined mass of the backfill is placed in a conventional consolidation ring with 61.8 mm in diameter and 20 mm in height. The entrapped air bubbles are minimized by tapping the ring and backfill at regular time intervals. The backfill specimens are then saturated by immersed in distilled water for 48 h. In addition, an identical backfill specimen for all the specimens is prepared simultaneously and then sacrificed for the measurement of the initial water content immediately after saturation soaking step. The liquid limit and measured initial water content of the prepared backfill specimens for oedometer test are summarized in Table 2. The designation B*i*Z*j* (Backfill ID) is used to denote a backfill specimen with bentonite content of *i*% and zeolite content of *j*%.

Table 2 Bentonite content, liquid limit and initial water content of the prepared specimens for the oedometer test

Backfill ID[1]	Bentonite content	Liquid limit	Initial water content	Backfill type
B5Z0	5%	43.4%	44.0%	Type 1
B5Z2	5%	45.3%	45.9%	Type 1
B5Z4	5%	47.3%	48.3%	Type 1
B5Z6	5%	48.9%	49.7%	Type 1
B5Z8	5%	51.0%	52.1%	Type 1
B5Z10	5%	52.8%	53.4%	Type 1
B7.8Z0	7.8%	55.1%	55.1%	Type 2
B8.0Z10	8%	55.9%	55.0%	Type 2
B8.1Z20	8.1%	57.5%	57.3%	Type 2
B8.4Z40	8.4%	62.9%	63.2%	Type 2

[1]B*i*Z*j* denotes a backfill specimen with bentonite content of *i*% and zeolite content of *j*%.

2.3 Testing methods

The oedometer tests are conducted as per ASTM D2435 (ASTM 2011*b*), except that the initial loading applied on the specimens is 3.125 kPa. This relatively low loading is chosen to avoid squeezing of the soil from the gap that exists between the specimen ring and porous disks (Hong et al. 2010; Fan et al. 2013, 2014). The loading is then doubled for each incremental step until a maximum loading of 1600 kPa is reached. The duration of each loading is 24 hours. At a given average effective vertical compression stress (σ'_{ave}), defined as the mean value of two successive load increments, the hydraulic conductivity for each load increment is evaluated following Terzaghi's one-dimensional consolidation theory, as expressed by:

$$k = c_v m_v \gamma_w \tag{2}$$

where k is the hydraulic conductivity (m/s), c_v is the coefficient of consolidation (m^2/s) determined by using the Taylor (square-root-of-time) method, m_v is the coefficient of volume change (kPa^{-1}), and γ_w

is the unit weight of water (kN/m^3). This method to evaluate k is extensively accepted (Sivapullaiah et al. 2000; Chai et al. 2004; Horpibulsuk et al. 2007; Yong et al. 2009; Mishra et al. 2011; Watabe et al. 2011; Fan et al. 2014). It is likely to underestimate k of clayey soils as reported in the literature (Chapuis 2012), but it is used in this study for relative comparison of hydraulic conductivity of various zeolite-amended clayey SB backfills.

3. RESULTS AND DISCUSSIONS

3.1 Compressibility

Figure 1 shows the compression curves, i.e., void ratio (e) versus vertical compression pressure (σ') on a semi-logarithm scale, for Type 1 and Type 2 backfills. The e-log(σ') compression curves shows an inverse 'S' shape curve when the vertical compression pressure is lower than approximately 25 kPa, which is similar to that of remolded natural clays reported by Hong et al. 2010.

The compression index (C_c) is determined from the linear portion of the e-log (σ') compression curve. The C_c values for Type 1 and Type 2 backfills range from 0.34 to 0.36 and 0.46 to 0.49, respectively. Figures 2(a) and 2(b) present the variation of C_c with zeolite content and bentonite content, respectively. It can be seen from Figure. 2(a) that the addition of fine-grained zeolite marginally affects the C_c values of both the backfills in this study and zeolite-amended sandy SB backfills reported by Hong et al. (2011). In contrast, C_c notably increases with an increase in bentonite content, which suggests that the compressibility of zeolite-amended clayey SB and sandy SB backfills is primarily controlled by the bentonite content. In addition, the C_c values of Type 1 and Type 2 backfills, at a given bentonite content, are higher than those of sandy SB and zeolite-amended sandy SB backfills reported by Yeo et al. (2005), Hong et al. (2011), and Fan et al. (2014), as shown in Figure. 2(b). For instance, C_c of Type 1 backfills, ranging from 0.34 to 0.36, are approximately 1.6 to 1.7 times higher than that of sandy SB backfill (C_c = 0.21) reported by Yeo et al. (2005). This can be attributed to a relatively higher C_c value of clayey soil than that of sand.

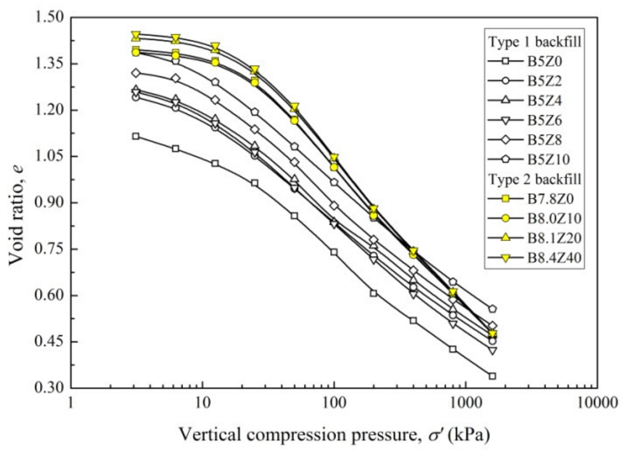

Figure 1 e-log(σ') compression curves of the backfills

3.2 Hydraulic conductivity

Figure 3 presents the relationship between the hydraulic conductivity and void ratio (e) on a semi-logarithmic scale. It is evident that e-log (k) relationship is approximately linear. The hydraulic conductivity of Type 1 and Type 2 backfills is lower than the typical regulatory limit for soil-bentonite vertical cutoff walls (10^{-9} m/s), except for the data obtained from the first two loading increments. For a given void ratio, the hydraulic conductivity of Type 1 backfill is approximately 5 to 10 times higher than that of Type 2 backfill, which is due to a lower bentonite content of Type 1 backfill (BC = 5%) relative to Type 2 backfill (BC = 7.8 – 8.4%). However, the difference in hydraulic conductivity of either Type 1 or Type 2 backfills is insignificantly affected by zeolite content for a given viod ratio. Similar trends are also observed for the zeolite-amended sandy SB backfills and compacted ZB liners in previous studies (Kaya and Durukan 2004; Hong et al. 2011).

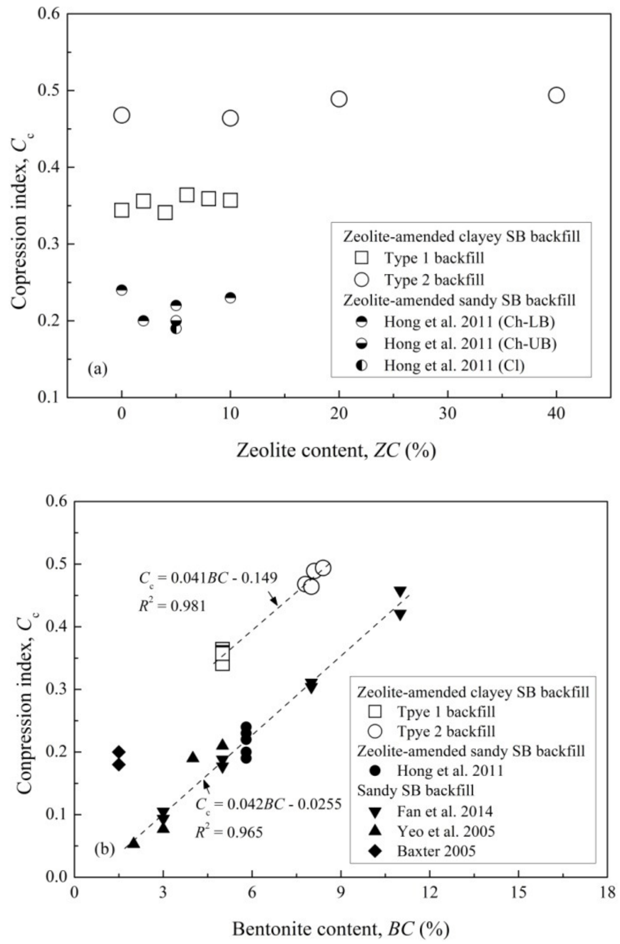

Figure 2 Compression indeies (C_c) for the backfills in this study and from the literature: (a) effect of zeolite content (ZC) and (b) effect of bentonite content (BC).

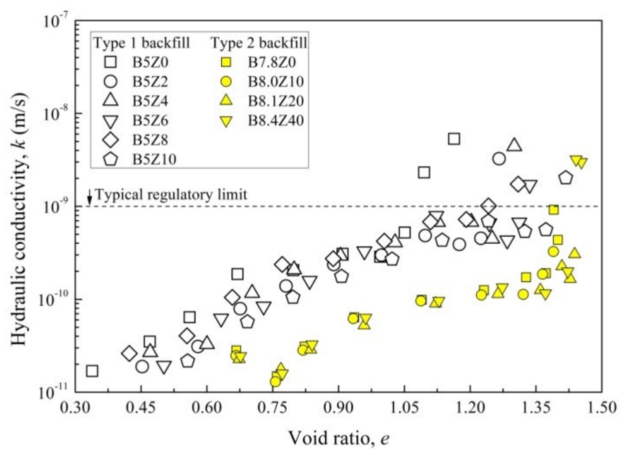

Figure 3 Relationship between hydraulic conductivity (k) and void ratio (e) for the backfills.

To better understand the effects of zeolite content and bentonite content on hydraulic conductivity for various types of soil-bentonite backfills and compacted ZB liners reported in this study and from the literature (Kaya and Durukan 2004; Yeo et al. 2005; Hong et al. 2011; Ören et al. 2011; Fan et al. 2014), k-ZC and k-BC

relationships are presented in Figure 4(a) and 4(b), respectively. In addition, the variation of k with zeolite content and bentonite content corresponding to values of e from 0.95 to 1.0 and from 1.10 to 1.15 are presented in Figures 5(a), 5(b) and 6, respectively. The selected range of e is aimed to cover void ratios reported in the previous studies, and is convenient for comparison of the results obtained from this study with the published studies. It can be seen from Figures. 4(a) and 5 that the hydraulic conductivity for various types of backfills and compacted ZB liners from the literature (Kaya and Durukan 2004; Hong et al. 2011; Ören et al. 2011) as well as this study, is not affected significantly by zeolite content. However, hydraulic conductivity decreases significantly when bentonite content increases from 2 to 6%, and tends to remain constant when $BC > 8\%$, as shown in Figures. 4(b) and 6. Thus, the results indicate that bentonite content is a crucial factor in controlling hydraulic conductivity of both zeolite-amended soil-bentonite backfills and compacted zeolite-bentonite liners.

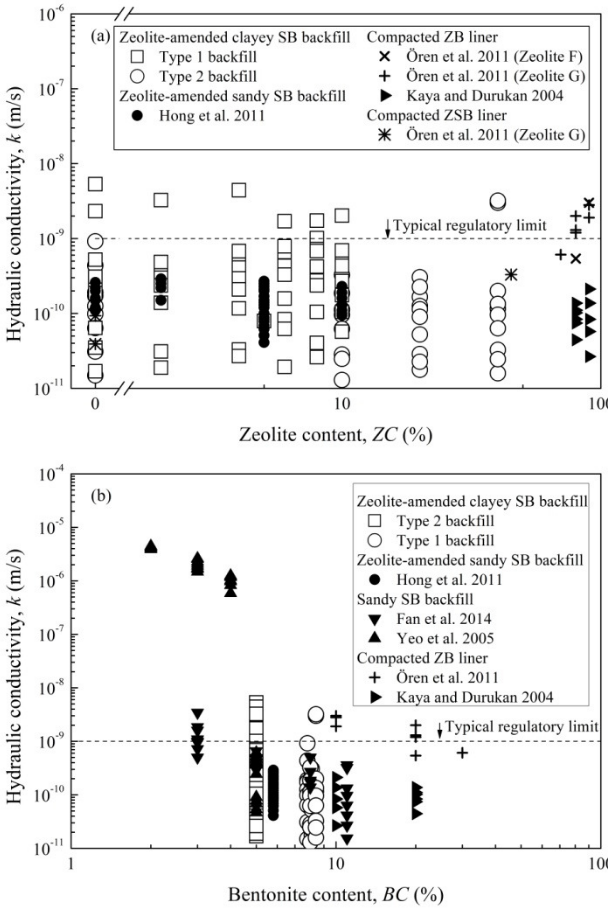

Figure 4 Comparison of the hydraulic conductivity (k) of the backfills in this study and previous studies: (a) effect of zeolite content (ZC) and (b) effect of bentonite content (BC)

It is noteworthy that the grain size of zeolite is likely to noticeably impact the hydraulic conductivity of zeolite-amended soil-bentonite backfills and compacted ZB liners. For instance, Ören et al. (2011) used two types of zeolites (termed as “fine zeolite” and “granular zeolite” by the authors) as alternatives to sand to make up the compacted ZB liners, yet the k values corresponding to e = 1.1 - 1.15 is higher than the typical regulatory limit of 10^{-9} m/s, as shown in Figure 5(b). The classification of these two types of zeolites was not idenfied by Ören et al. (2011) and are, indeed, classified as coarse-grained soils based on the Unified Soil Classification System (ASTM 2011a).

In contrast, the k values of the backfills in this study, the zeolite-amended sandy SB backfills (Hong et al. 2011), and the compacted ZB liners reported by Kaya and Durukan (2004) are lower than the typical regulatory limit of 10^{-9} m/s when e = 1.1 - 1.15. The zeolites used in this study, along with the previous study (Kaya and Durukan 2004; Hong et al. 2011) are all classified as fine-grained soils based on the USCS (ASTM 2011a). In addition, the main grain sizes (D_{50}) of the coarse-grained zeolites used by Ören et al. (2011) are nearly 1 to 2 orders of magnitude greater than those of the fine-grained zeolites used in this study and Hong et al. (2011).

For coarse-grained zeolite-amended soil-bentontie backfills or compacted zeolite-bentonite liners, the zeolite grains, classified as sands in general, may not be fully covered by the hydrated bentonite due to their relatively large grain-size (e.g., more than 50 % retained on No. 200 sieve). In addition, zeolites have a high affinity for water and can attract certain amount of water held in the pores from bentonite during the preparation of soil-bentonite backfills and compacted ZB liners. As a result, the hydration of bentonite will possibly be inhibited to a certain degree, causing an insufficient hydration of bentonite in the backfills or compacted ZB liners, as suggested by Ören et al. (2011). The aforementioned aspects consequently lead to a greater number of seepage channels through inter-granular pores and intra-granular pores induced by the network formed by coarse-grained zeolites in soil-bentonite backfills and compacted ZB liners. As a result, the hydraulic conductivity for coarse-grained zeolite-amended SB backfills and compacted ZB liners is likely to increase noticeably and even exceed the traditional regulatory limit of 10^{-9} m/s, as compared to that of unamended ones.

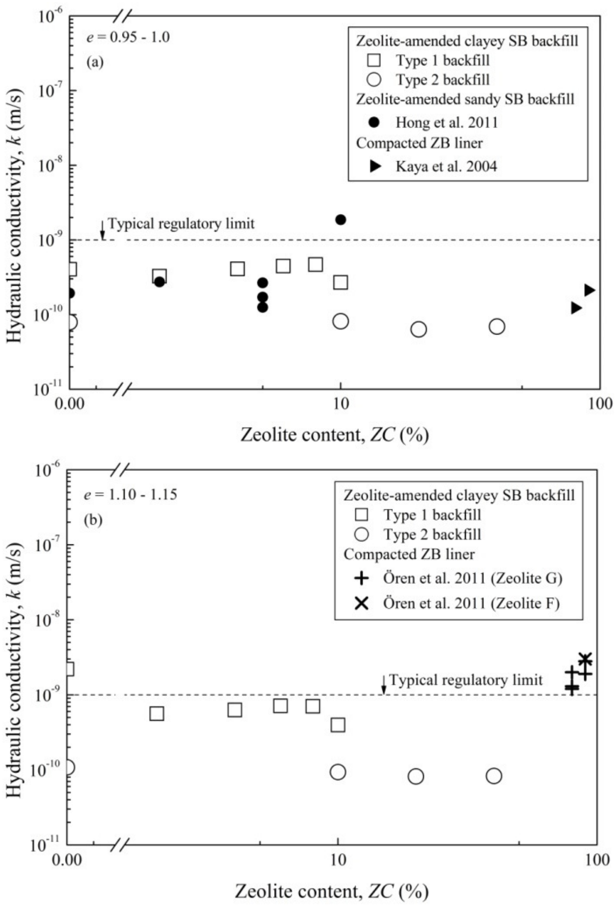

Figure 5 Relationship between zeolite content (ZC) and hydraulic conductivity (k) of the backfills in this study and previous studies: (a) e = 0.95 – 1.10 and (b) e = 1.10 – 1.15

Conversely, zeolite grains in fine-grained zeolite-amended soil-bentonite backfills and compacted ZB liners are likely to be fully covered by the hydrated bentonite due to their small size relative to coarse-grained zeolites. Under such circumstances, the attraction of water from bentonite by zeolites would be suppressed, which leads to a reduced number of seepage channels in soil-bentonite backfills and compacted ZB liners. Thus, the addition of fine-grained zeolite insignificantly affects the hydraulic conductivity for the soil-bentonite backfills and compacted ZB liners; and the hydraulic conductivity meets the typical regulatory limit of 10^{-9} m/s (see Figure 4-5), as indicated in this study and from the literature (Kaya and Durukan 2004; Hong et al. 2011).

In sum, it can be concluded that the addition of fine-grained zeolite will not compromise the integrity of the soil-bentonite vertical cutoff wall in terms of compression index and hydraulic conductivity based on the results obtained in this study and from the literature. Therefore, the fine-grained zeolite will be more favorable as an effective amendment for soil-bentonite backfills; whereas the use of coarse-grained zeolite should be carefully assessed.

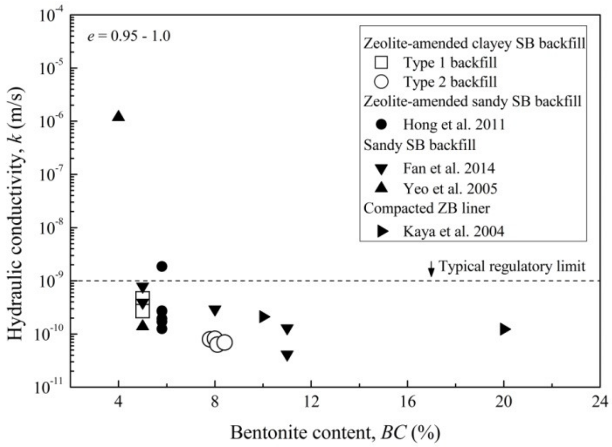

Figure 6 Relationship between bentonite content (BC) and hydraulic conductivity (k) corresponding to e = 0.95 – 1.0 for the backfills in this study and previous studies

3.3 Predictive methods for hydraulic conductivity

There are many types of methods for predicting hydraulic conductivity of clays, and most of them can be expressed as functions of void ratio and liquid limit. In this study, two empirical equations are assessed to predict the hydraulic conductivity of the zeolite-amended clayey SB backfills: (1) Nagaraj's generalized void ratio (e/e_L) method (Nagaraj and Miura 2001) and (2) Sivapullaiah et al.'s (2000) method. Both methods have been used to well predict hydraulic conductivity for bentonite-sand mixtures with bentonite content ranging from 5 to 80% (Pandian et al. 1995; Sivapullaiah et al. 2000).

The Nagaraj's method for predicting hydraulic conductivity value is based on: (1) the result that hydraulic conductivity is likely to be the same order at liquid limit state, where clay microfabric performs identical micropore distribution; and (2) the assumption that two interacting soil particles are parallel plates (i.e., parallel plate model). The hydraulic conductivity values for the sand-bentonite mixtures can be expressed by (Nagaraj and Miura 2001):

$$\log(k) = a\left(\frac{e}{e_L}\right) + b \tag{3}$$

where a and b are dimensionless parameters representing the intercept and slope of the regressed linear e/e_L-log(k) relationship.

Figure 7 presents the relationship between hydraulic conductivity and generalized void ratio in semi-logarithmic scale. A regression analysis using the Least-Square-Root method gives **Eq. (4)** for the zeolite-amended clayey SB backfills tested in this study with a determination coefficient value (R^2) of 0.722, as expressed by:

$$\log(k_p) = 2.56\left(\frac{e}{e_L}\right) - 11.65 \tag{4}$$

where k_p is the predicted hydraulic conductivity in m/s. It can be seen that the hydraulic conductivity values for all zeolite-amended clayey SB backfills is likely to generalized using generalized void ratio, yet the e/e_L-log(k) relationship for the backfill specimens in this study noticeably deviates from the previous studies (Nagaraj et al. 1994; Pandian et al. 1995). One possible reason for such a deviation is the fundamental differences in behavior of the zeolite-amended clayey SB backfills and sand-bentonite mixtures as well as natural clays in the previous studies.

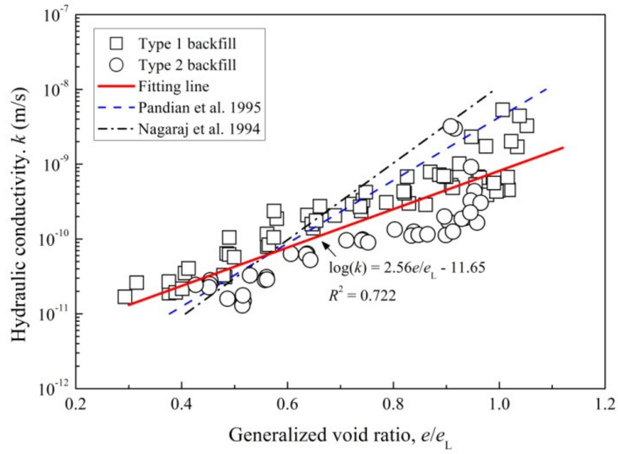

Figure 7 Relationship between generalized void ratio (e/e_L) and hydraulic conductivity (k)

The empirical method suggested by Sivapullaiah et al. (2000) is based on the observation that e-log(k) relationship is represented by a linear function, as expressed by following:

$$e = S_k \log(k) + I_k \tag{5}$$

where the dimensionless parameters S_k and I_k represent the slope and intercept, respectively. Figures 8(a) and 8(b) indicate that both S_k-w_L and I_k-w_L relationships are approximately linear, as expressed by Eqs. (6) and (7). The high R^2 values for Eqs. (6) and (7) are 0.933 and 0.924, respectively. Substituting Eqs. (6) and (7) in Eq. (5) yields Eq. (8) for predicting hydraulic conductivity of the zeolite-amended clayey SB backfill specimens in this study.

$$S_k = 0.0187w_L - 0.396 \tag{6}$$

$$I_k = 0.211w_L - 4.748 \tag{7}$$

$$\log(k_p) = \frac{e - 0.211w_L + 4.748}{0.0187w_L - 0.396} \tag{8}$$

where w_L is in %, kp is the predicted hydraulic conductivity in m/s.

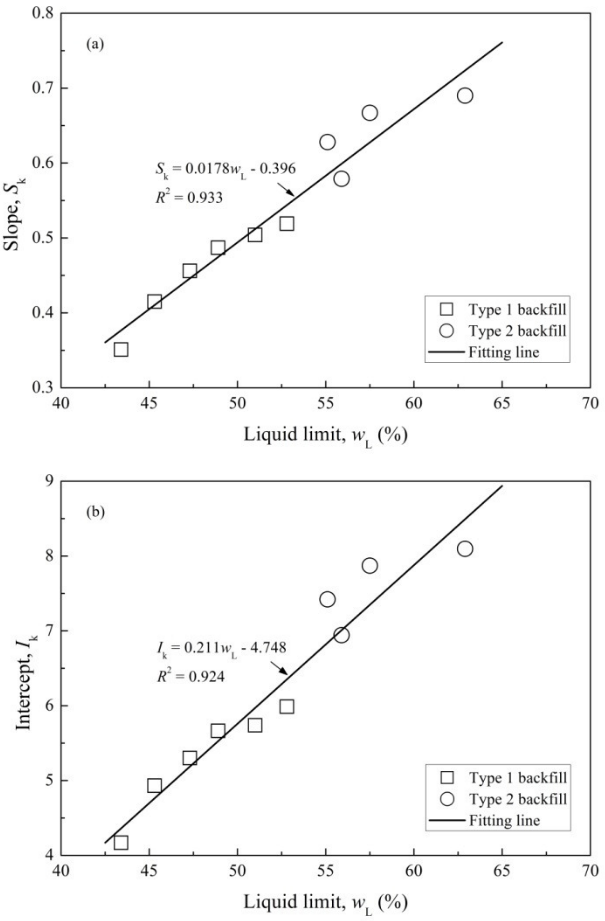

Figure 8 Relationship between liquid limit (w_L) and parameters in the *e*-log(*k*) relationship expressed by Eq. (5) for the backfills: (a) slope (S_k) and (b) intercept (I_k)

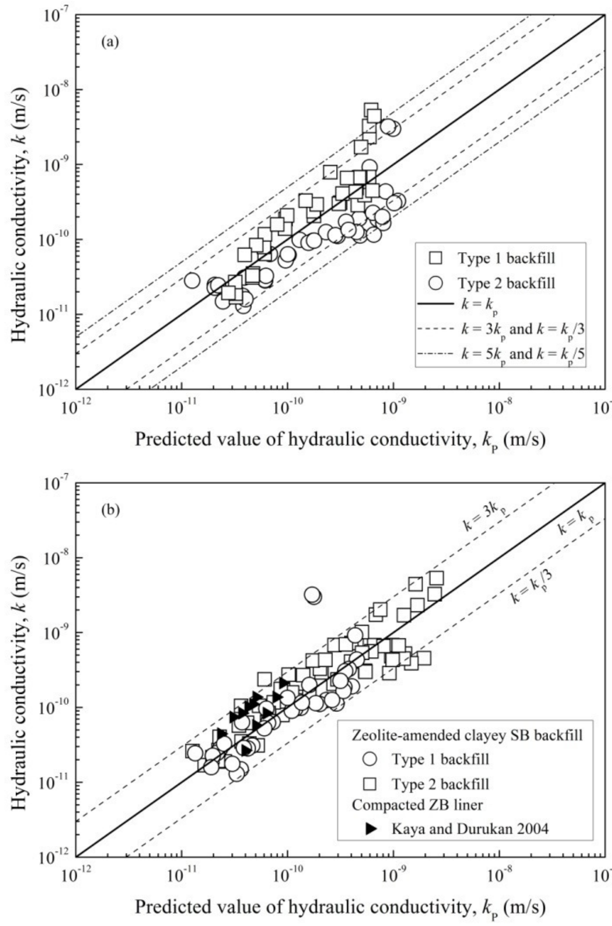

Figure 9 Relationship between the hydraulic conductivity (*k*) evaluated from the oedometer tests and the predicted hydraulic conductivity (k_P): (a) using Eq. 4 and (b) using Eq. 8

The predicted hydraulic conductivity (k_p) values using Eq. (4) and Eq. (8) is compared with those estimated from the oedometer tests, as shown in Figure 9(a) and 9(b), respectively. As shown in Figure 9, 90% of predicted hydraulic conductivity values using Eq. (4) are in the range of 1/3 to 3 times the *k* measured during the oedometer tests; while the remaining 10% of them are approximately in the range of 1/5 to 5 times those obtained from the oedometer tests. The predicted hydraulic conductivity values based on the Sivapullaiah et al.'s method (see Eq. (8)) fall in the range of 1/3 to 3 times those obtained from the oedometer tests.

Thus, it is concluded that the proposed method based on Sivapullaiah et al. (2000) is more reasonably suitable to predict *k* for the zeolite-amended clayey SB backfills with zeolite content that ranges from 2 to 40%. In addition, the proposed method using Eq. (8) can also be used to predict the hydraulic conductivity of the compacted ZB liners reported by Kaya and Durukan (2004), as shown in Figure 9(b).

The hydraulic conductivity in this study are estimated indirectly based on the oedometer test results. Direct measurement of hydraulic conductivity of backfills permeated with tap water and/or calcium chloride ($CaCl_2$) solutions, based on either rigid-wall permeameter or flexible-wall permeameter tests, is recommended in further study.

3. CONCLUSION

A series of oedometer tests are conducted to investigate the effects of fine-grained zeolite amendment on the compressibility and hydraulic conductivity of the clayey soil/Ca-bentonite backfills for soil-bentonite vertical cutoff walls. The results obtained from this study are compared with those for the fine-grained zeolite-amended conventional sandy soil/Na-bentonite backfills and compacted zeolite-bentonite liners from the literature. The following conclusions can be drawn from this study:

(1) The addition of 2 to 40% fine-grained zeolite resulted in insignificant influence on the compressibility and hydraulic conductivity of the clayey soil/Ca-bentonite backfills tested in this study. In contrast, these two engineering properties were critically controlled by the bentonite content. For the backfills with zeolite content of 10%, the compression index increased by 30% and the hydraulic conductivity decreased by a factor of 5 when the bentonite content increased from 5 to 8%.

(2) The hydraulic conductivity values of the clayey soil/Ca-bentonite backfills with zeolite amendement are lower than the typical regulatory limit of 10^{-9} m/s, demonstrating that fine-grained zeolite-amended clayey soil/Ca-bentonite backfills are practical to use for construction of soil-bentonite vertical cutoff walls.

Two empirical methods, based on Nagaraj's generalized void ratio (e/e_L) and Sivapullaiah et al.'s method, The Sivapullaiah et al.'s method (Eq. (8)) is better suited to estimate the hydraulic conductivity values for the zeolite-amended clayey soil/Ca-bentonite backfills in this study.

(3) A comprehensive comparison of the results from present study with those from the literature demonstrates that addition of fine-grained zeolite has negligible effect on hydraulic conductivity of the clayey soil/Ca-bentonite and conventional sandy soil/Na-bentonite backfills as well as compacted bentonite liners. However, potential increase in hydraulic conductivity due to the addition of coarse-grained zeolite requires careful further research.

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