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### Recommended Citation

Hong, Catherine; Shackelford, Charles D.; and Malusis, Michael A.. "Compressibility and Hydraulic Conductivity of Zeolite-Amended Soil-Bentonite Backfills." *Journal of Geotechnical and Geoenvironmental Engineering* (2012) : 15-25.

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# Consolidation and Hydraulic Conductivity of Zeolite-Amended Soil-Bentonite Backfills

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**Abstract:** The effect of zeolite amendment for enhanced sorption capacity on the consolidation behavior and hydraulic conductivity,  $k$ , of a representative soil-bentonite (SB) backfill for vertical cutoff walls was evaluated via laboratory testing. The consolidation behavior and  $k$  of test specimens containing fine sand, 5.8% (dry weight) sodium bentonite, and 0, 2, 5, or 10% (dry weight) of one of three types of zeolite (clinoptilolite, chabazite-lower bed, or chabazite-upper bed) were measured using fixed-ring oedometers, and  $k$  also was measured on separate specimens using a flexible-wall permeameter. The results indicated that addition of a zeolite had little impact on either the consolidation behavior or the  $k$  of the backfill, regardless of the amount or type of zeolite. For example, the compression index,  $C_c$ , for the unamended backfill specimen was 0.24, whereas values of  $C_c$  for the zeolite-amended specimens were in the range  $0.19 \leq C_c \leq 0.23$ . Similarly, the  $k$  for the unamended specimen based on flexible-wall tests was  $2.4 \times 10^{-10}$  m/s, whereas values of  $k$  for zeolite-amended specimens were in the range  $1.2 \times 10^{-10} \leq k \leq 3.9 \times 10^{-10}$  m/s. The results of the study suggest that enhancing the sorption capacity of typical SB backfills via zeolite amendment is not likely to have a significant effect on the consolidation behavior or  $k$  of the backfill, provided that the amount of zeolite added is small ( $\leq 10\%$ ). DOI: 10.1061/(ASCE)GT.1943-5606.0000566. © 2012 American Society of Civil Engineers.

**CE Database subject headings:** Bentonite; Hydraulic conductivity; Backfills; Zeolite.

**Author keywords:** Bentonite; Consolidation; Cutoff wall; Hydraulic conductivity; Soil-bentonite backfill; Zeolite.

## Introduction

Soil-bentonite (SB) vertical cutoff walls historically have been used as in situ barriers for groundwater control during construction (LaGrega et al. 2001). The construction process for SB slurry-trench cutoff walls typically involves excavating a trench into subsurface soils and simultaneously filling the trench with bentonite-water slurry to maintain the stability of the trench before backfilling. Trench spoils or imported materials are mixed with amendments (e.g., dry bentonite) and bentonite-water slurry to create a backfill mixture with appropriate consistency that provides a low hydraulic conductivity,  $k$  (i.e.,  $k \leq 10^{-8}$  m/s), to impede groundwater flow (Xanthakos 1979; D'Appolonia 1980; Spooner et al. 1984; Ryan 1987; Millet et al. 1992; Evans 1994; Rumer and Ryan 1995).

The use of SB cutoff walls in geoenvironmental containment applications to prevent or control subsurface migration of contaminated groundwater also has been prevalent [U.S. Environmental Protection Agency (USEPA) 1984]. The preference for SB cutoff walls for such applications is becoming more common, as these vertical barriers are typically cheaper than treatment systems, cause less

risk of contaminant exposure during construction, and can be used to contain contaminated groundwater until a more efficient and/or more cost-effective treatment technology is developed (Shackelford and Jefferis 2000). For cases in which treatment of subsurface contamination contained with SB cutoff walls is not feasible because of a present lack of cost-effective treatment technologies, the performance period required for cutoff walls to effectively contain the contaminants often is undefined (Inyang and de Brito Galvao 2004). In these cases, a cutoff wall may be expected to perform for a long period (years to decades), such that contaminant diffusion may adversely impact the containment performance of the cutoff wall.

For this reason, increasingly greater consideration is being given to contaminant attenuation (e.g., sorption capacity) as an important mechanism for improving the long-term performance of SB cutoff walls used for geoenvironmental containment (e.g., Shackelford 1999; Daniels et al. 2004; Malusis et al. 2009). Barriers with enhanced sorption capacity can delay solute (contaminant) breakthrough for prolonged periods (e.g., Malusis et al. 2010), and a number of different sorptive amendments have been considered for earthen containment barriers, including zeolites (Evans et al. 1990; Allerton et al. 1996; Evans et al. 1997).

Zeolites are crystalline, microporous aluminosilicates with relatively high cation exchange capacities (CECs), typically on the order of 250 cmol<sub>c</sub>/kg (Dyer 1988; Evans et al. 1990). As a result, zeolites commonly are used commercially as adsorbents for removal of cations from wastewater (Jacobs and Forstner 1999; Yuan et al. 1999; Erdem et al. 2004; Inglezakis 2005). The potential use of zeolite amendments for compacted sand-bentonite mixtures or compacted clay as liners for waste containment applications also has been evaluated in a limited number of studies (Evans et al. 1990; Kayabali 1997; Tuncan et al. 2003; Kaya and Durukan 2004). The results of these studies suggest that amending SB backfill with zeolites also may be useful as a means to enhance the sorption

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Note. This manuscript was submitted on July 2, 2010; approved on May 9, 2011; published online on May 11, 2011. Discussion period open until June 1, 2012; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 138, No. 1, January 1, 2012. ©ASCE, ISSN 1090-0241/2012/1-15-25/\$25.00.

capacity of SB cutoff walls for inorganic contaminants, such as heavy metals (e.g.,  $\text{Cd}^{2+}$ ,  $\text{Zn}^{2+}$ ).

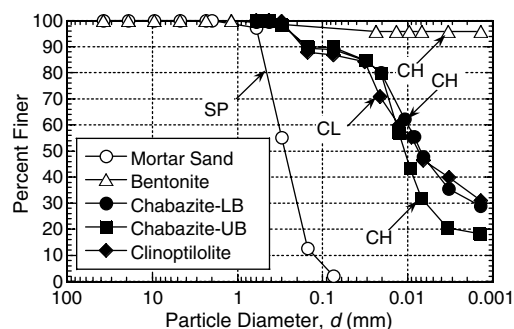
However, adding zeolite to enhance the sorption capacity of an SB cutoff wall should not compromise the integrity of the cutoff wall in terms of traditional design properties, most notably the consolidation behavior and  $k$  of the backfill. For example, the backfill should provide a relatively rigid skeleton with smaller particles filling the voids to minimize settlement, seepage, and piping (D'Appolonia 1980; Ryan 1987; Evans 1994; Evans et al. 1995; Malusis et al. 2009). In addition,  $k \leq 10^{-9}$  m/s typically is specified for vertical barriers used in geoenvironmental containment applications, regardless of any enhanced reactivity exhibited by the barrier material (e.g., LaGrega et al. 2001). On the basis of these considerations, the objective of this study was to evaluate the influence of zeolite amendment on the consolidation behavior and hydraulic conductivity of a representative SB backfill. The evaluation included an assessment of the effects of different amounts of a specific zeolite in the backfill, as well as the effects of the same amount of three different types of zeolite minerals.

## Materials and Methods

### Constituent Materials

The backfills were comprised of clean, fine sand, powdered sodium bentonite and one of three types of zeolite. The sand was the same as that used by Malusis et al. (2009) to represent construction of a slurry-trench cutoff wall through a sandy aquifer. The powdered sodium bentonite is available commercially under the trade name NATURALGEL (Wyo-Ben, Inc., Billings, Montana). NATURALGEL is commonly used in slurry trenching, diaphragm walls, and as a soil-mixture additive and previously has been used as a constituent of model SB backfills (Yeo et al. 2005a, b; Malusis et al. 2009). The three zeolites were obtained from GSA Resources, Inc. (Tucson, AZ) and included two types of product ZS500A chabazite, referred to as chabazite-upper bed (chabazite-UB) and chabazite-lower bed (chabazite-LB), and one type of clinoptilolite (product name ZS403H).

The particle-size distributions of the constituent materials are shown in Fig. 1, and the physical and chemical properties and mineralogical compositions of the constituent materials are summarized in Table 1. In terms of particle-size distributions (Fig. 1), all three zeolites are dominated by silt-sized particles, with distributions ranging between those of the bentonite and the sand. In terms of physical properties (Table 1), the zeolites are characterized by



**Fig. 1.** Measured particle-size distributions (ASTM D422) for constituent materials used in study; letter designations associated with curves represent classifications based on the Unified Soil Classification System (ASTM D2487)

relatively low specific gravities ( $2.35 \leq G_s \leq 2.37$ ) and measurable Atterberg limits, with the two chabazites being classified (ASTM D2487) as high plasticity clays (CH) and the clinoptilolite being classified as a low plasticity clay (CL). In terms of chemical properties (Table 1), the exchangeable and soluble metals of the zeolites and the bentonite are dominated by sodium ( $\text{Na}^+$ ). The pH of the two chabazites and the bentonite are essentially the same (i.e.,  $\text{pH} \sim 8$ ), whereas that of the clinoptilolite is more basic ( $\text{pH} = 9.5$ ). Also, the two chabazites are significantly more electrolytic than the other constituent materials.

As indicated in Table 1, the specific surface areas for the chabazite-LB, chabazite-UB, and clinoptilolite used in this study are 521, 350, and 40  $\text{m}^2/\text{g}$ , respectively. The significantly higher specific surface areas for the two chabazites relative to the clinoptilolite are in contrast to the similar particle-size distributions for all three zeolites (Fig. 1) and are attributed to greater internal specific surface areas for the chabazites relative to that for the clinoptilolite. The higher CECs for the two chabazites relative to the clinoptilolite and the difference in classifications between the two chabazites relative to the clinoptilolite (see Table 1) also can be attributed, in part, to the greater specific surface areas for the two chabazites relative to that for the clinoptilolite.

### Base Mixtures for Backfills

The base mixtures used to prepare the backfills included an unamended soil-bentonite mixture and zeolite-amended soil-bentonite mixtures containing 2, 5, or 10% (dry weight) chabazite-LB, 5% (dry weight) chabazite-UB, and 5% (dry weight) clinoptilolite. The unamended base mixture was comprised of air-dried sand mixed with 4% sodium bentonite (dry weight) and tap water to adjust the gravimetric moisture content to 4.8%. The zeolite-amended base mixtures then were made by mixing the required amount of a given zeolite with the unamended base mixture.

### Bentonite-Water Slurry

Bentonite-water slurry (5% bentonite by weight) was prepared by mixing bentonite and tap water in a blender for 5 min. The measured pH and electrical conductivity, EC, of the tap water at 25°C were 6.6 and 1.35 mS/m, respectively. The slurry was allowed to hydrate for a minimum of 24 h before use. After hydration, the measured density and Marsh funnel viscosity of the slurry were 1.03  $\text{g}/\text{cm}^3$  and 46 s, respectively, and the measured pH and EC of the slurry at 25°C were 8.7 and 114.0 mS/m, respectively.

### Backfill Slump Testing

The bentonite-water slurry was mixed with each of the base mixtures in various proportions using a KitchenAid® six-quart stand mixer to determine the amount of slurry and corresponding water content required to create backfills with a measured slump (ASTM C143) of 125 mm (5 in.), which is within the consistency of 100 to 150 mm (4 to 6 in.) considered as optimum for SB backfills (e.g., Evans 1993). Three slump tests were performed for each backfill at any given water content to evaluate the variability in measured slumps, and the amount of added slurry was varied to provide a range of slump values and a corresponding range in values of the backfill water content,  $w_B$ .

### Backfill Preparation

Bulk volumes of unamended and zeolite-amended backfills used for consolidation and  $k$  testing were prepared separately following the procedures described in Malusis et al. (2009). The backfills were prepared by combining the base mixtures and slurry in the same manner as described above, until a target slump (ASTM C143) of  $125 \pm 12.5$  mm ( $5 \pm 0.5$  in.) was measured in triplicate.

**Table 1.** Physical and Chemical Properties and Mineralogical Compositions of Constituent Materials Used for Backfills

Property	Standard	Constituent material				
		Mortar sand	Bentonite	Zeolite		
				Chabazite-LB	Chabazite-UB	Clinoptilolite
Specific gravity, $G_s$	ASTM D854	2.69	2.67	2.35	2.35	2.37
Liquid limit, LL (%)	ASTM D4318	NA	511	75.2	71.4	48.9
Plastic limit, PL (%)	ASTM D4318	NA	54	29.2	13.1	31.0
Plasticity index, PI (%)	ASTM D4318	NA	457	46.0	58.3	17.9
Classification	ASTM D2487	SP	CH	CH	CH	CL
Specific surface ( $\text{m}^2/\text{g}$ )	<sup>a</sup>	NA	NA	521	350	40
Principal minerals (%):	<sup>b</sup>	NA		NA	NA	NA
Montmorillonite			69			
Cristobalite			14			
Quartz			12			
Plagioclase feldspar			2			
Calcite			3			
Cation exchange capacity, CEC ( $\text{cmol}_c/\text{kg}$ )	<sup>c</sup>	NA	83.4	259	240	182
Exchangeable metals ( $\text{cmol}_c/\text{kg}$ ):	<sup>c</sup>	NA				
Ca <sup>2+</sup>			4.9	30.9	19.9	20.6
Mg <sup>2+</sup>			8.8	14.5	21.6	0.3
Na <sup>+</sup>			73.4	194	188	114
K <sup>+</sup>			1.1	7.1	6.8	37.6
Sum			88.2	246.5	236.3	172.5
Soluble metals ( $\text{mg}/\text{kg}$ ):	<sup>c</sup>	NA				
Ca <sup>2+</sup>			46.1	231	175	33.2
Mg <sup>2+</sup>			15.3	199	144	530
Na <sup>+</sup>			2,042	3,797	3,707	1,506
K <sup>+</sup>			58.4	71.8	76.6	143
Soil pH	ASTM D4972	6.8	8.1	8.0	8.2	9.5
Electrical conductivity, EC ( $\text{mS}/\text{m}$ ) @ 25°C	<sup>c</sup>	6.5	200	1450	1570	150

<sup>a</sup>From GSA Resources, Inc., Tucson, AZ.<sup>b</sup>Based on X-ray diffraction analysis performed by Mineralogy Inc., Tulsa, OK.<sup>c</sup>Procedures described in Shackelford and Redmond (1995).

The masses of sand, dry bentonite, zeolite, and slurry were adjusted to maintain the zeolite content (i.e., 0, 2, 5, or 10% by dry weight) and total bentonite content (5.8% by dry weight) of each backfill, while obtaining the slump within the target range of  $125 \pm 12.5$  mm ( $5 \pm 0.5$  in.). This method was chosen to eliminate bentonite content as a variable in the testing program. Further details of the procedure for preparing the backfills are provided in Malusis et al. (2009).

### Consolidation Testing

Each backfill was subjected to one-dimensional consolidation (i.e., confined compression) using a fixed-ring oedometer cell and incremental loading following the procedures described by Yeo et al. (2005a) and Malusis et al. (2009). The tests were conducted in accordance with ASTM D2435, except that the hydraulic conductivity,  $k$ , was measured at the end of each loading increment, before placement of the subsequent load (e.g., Yeo et al. 2005a).

Each specimen of prepared backfill was placed in a fixed-ring oedometer, rodded to eliminate large voids, and subjected to a small seating load for a minimum of 24 h before initiating an incremental loading sequence. The loading began at 24 kPa (3.5 psi or 0.25 tsf) and was subsequently doubled after each loading stage, up to a maximum vertical effective stress of 1,532 kPa (222 psi or 16 tsf). The specimens then were unloaded by reducing the loading

by a factor of four for each stage (Yeo et al. 2005a; Malusis et al. 2009).

After deformation was complete for each stage of the loading sequence (i.e., a minimum of 24 h after the loading), the specimens were permeated with tap water using the falling-head procedure until the termination criteria described in ASTM D5084-03 for flexible-wall hydraulic conductivity testing were achieved, i.e., (1) the results of three  $k$  values were within 25% of the mean, (2) the ratio of the inflow rate to the outflow rate was between 0.75 and 1.25, and (3) no distinct upward or downward trend in  $k$  was observed. The maximum hydraulic gradients ranged between 30 and 50 for all specimens, and  $k$  was calculated using the final (postdeformation) thickness of the specimens after each loading increment, i.e., the thickness of the specimens before permeation (Yeo et al. 2005a; Malusis et al. 2009).

### Flexible-Wall Hydraulic Conductivity Testing

Flexible-wall hydraulic conductivity tests using tap water as the permeant liquid also were conducted on duplicate specimens of each backfill, in accordance with the falling headwater-rising tailwater method (Method C) described in ASTM D5084-03. The experimental procedures and testing apparatus were the same as those described by Malusis et al. (2009) and involved the use of a custom-fabricated, rigid acrylic cylinder placed around the flexible membrane to provide lateral support for the soft backfill before



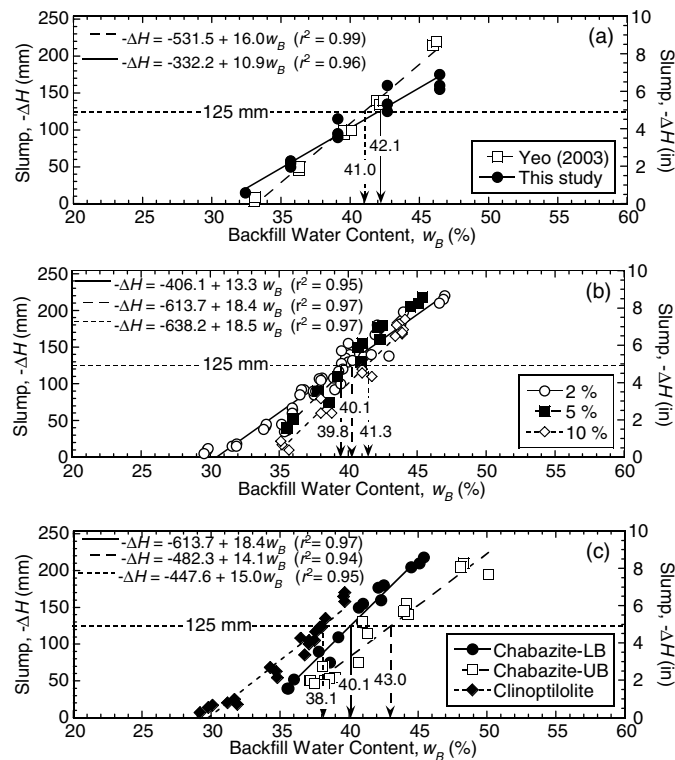
consolidation. Briefly, test specimens were prepared by depositing the backfill within the stretched membrane in three lifts, with each lift being rodded several times to eliminate large voids before the top filter paper, porous stone, and end cap were set in place. The cell was assembled and filled, and a cell pressure of 34.5 kPa (5.0 psi) was applied for a minimum of 24 h.

Before permeation, each specimen was back-pressured under a constant effective confining stress,  $\sigma'$ , of 34.5 kPa (5.0 psi) by increasing the cell pressure and pore-water (back) pressure in equal increments over several hours until a  $B$  value of  $\geq 0.95$  was achieved in accordance with ASTM D5084-03. To ensure that an average effective stress of 34.5 kPa (5.0 psi) and a hydraulic gradient less than 30 were maintained during permeation (as required by ASTM D5084-03 for  $k < 10^{-9}$  m/s), the hydraulic gradient was applied by setting the cell pressure at 345 kPa (50.0 psi) and the headwater (bottom) pressure at 321 kPa (46.5 psi) and leaving the tailwater (top) pressure at 300 kPa (43.5 psi). Each specimen was permeated until the aforementioned termination criteria described in ASTM D5084-03 were achieved. Further details on the procedures for performing the flexible-wall hydraulic conductivity tests can be found in Malusis et al. (2009).

## Results

### Slump

The measured values of the slump,  $-\Delta H (= H_o - H_f)$ , in which  $H_o$  and  $H_f$  = initial and final heights, respectively, of the specimen in the slump cone), are plotted versus  $w_B$  for all of the backfills in Fig. 2. As indicated in Fig. 2, an increase in  $w_B$  results in an increase in  $-\Delta H$  for a given backfill composition.



**Fig. 2.** Backfill slump versus backfill gravimetric water content: (a) unamended backfill compared with the results of Yeo (2003); (b) backfills amended with different percentages of the same zeolites (chabazite-LB); (c) backfills amended with same amount (5%) of different types of zeolites

As shown in Fig. 2(a), the value of  $w_B$  corresponding to  $-\Delta H = 125$  mm (5 in.) for the unamended sand-bentonite backfill tested in this study was 42.1%, which is close to the value for  $w_B$  of 43.2% at  $-\Delta H = 125$  mm (5 in.) for the same unamended sand-bentonite backfill reported by Malusis et al. (2009). The results in Fig. 2(a) for the unamended sand-bentonite backfill used in this study also are shown to be similar to those reported by Yeo (2003) for a backfill consisting of the same bentonite and slurry but a different sand.

As shown in Fig. 2(b), the values of  $w_B$  at  $-\Delta H = 125$  mm (5 in.) for the sand-bentonite backfills amended with 2, 5, and 10% chabazite-LB were 39.8, 40.1, and 41.3%, respectively, whereas those for the sand-bentonite backfills amended with either 5% clinoptilolite or 5% chabazite-UB shown in Fig. 2(c) were 38.1 or 43.0%, respectively. Thus, the value of  $w_B$  required to achieve a slump of 125 mm (5 in.) for the unamended sand-bentonite backfill was affected only slightly by the addition of 2 to 10% zeolite.

Finally, the  $w_B$  value at  $-\Delta H = 125$  mm (5 in.) for each of the backfills was greater than the measured liquid limit, LL, for the same respective backfill composition (see Table 2). This relative difference is expected on the basis of the liquid consistency required of backfills to properly displace the bentonite slurry within the excavated trench during backfilling (USEPA 1984).

### Stress-Strain Behavior

The stress-strain curves resulting from the consolidation tests are plotted in the form of void ratio,  $e$ , versus logarithm of the consolidation effective stress,  $\sigma'$ , or  $e - \log \sigma'$  curves, in Fig. 3. As expected with remolded soils, no stress history (i.e., preconsolidation stress) is apparent in the results. The compression and swell indices ( $C_c$  and  $C_s$ , respectively) listed in Fig. 3 represent the slopes of the loading and unloading portions of the  $e - \log \sigma'$  curves, respectively, for each backfill.

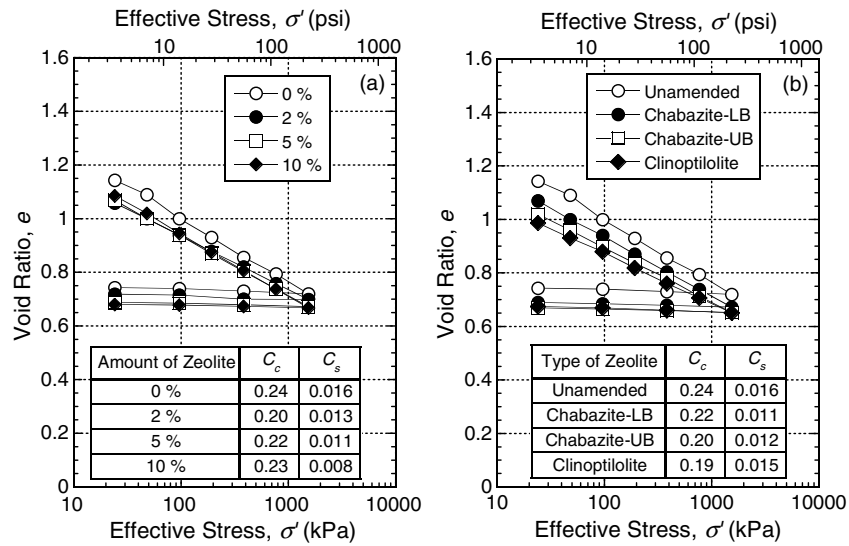
### Hydraulic Conductivity

The  $k$  values measured in the fixed-ring oedometer cells at the end of each loading stage of the consolidation tests are summarized in Table 3 and plotted as a function of  $\sigma'$  in Fig. 4. As illustrated in Fig. 4, the measured  $k$  of a given backfill decreased with increasing  $\sigma'$ , as expected on the basis of the inverse relationship between  $\sigma'$  and  $e$  (Fig. 3). The bentonite distribution within the pore space between the larger sand particles is a critical factor affecting the  $k$  of sand-bentonite mixtures (Kenney et al. 1992), and inadequate bentonite is a primary reason for high  $k$  values and lack of correlation between  $k$  and  $\sigma'$  in sandy SB backfills (Yeo et al. 2005a). Thus, the low measured  $k$  values and the trend of decreasing  $k$  with increasing  $\sigma'$  suggest that the bentonite distribution was sufficiently uniform for each backfill.

The results of the flexible-wall hydraulic conductivity tests for all of the backfills are summarized in Table 4. The duplicate

**Table 2.** Atterberg Limits (ASTM D4318) of Backfills with Compositions Corresponding to Those for a 125-mm (5-in.) Slump

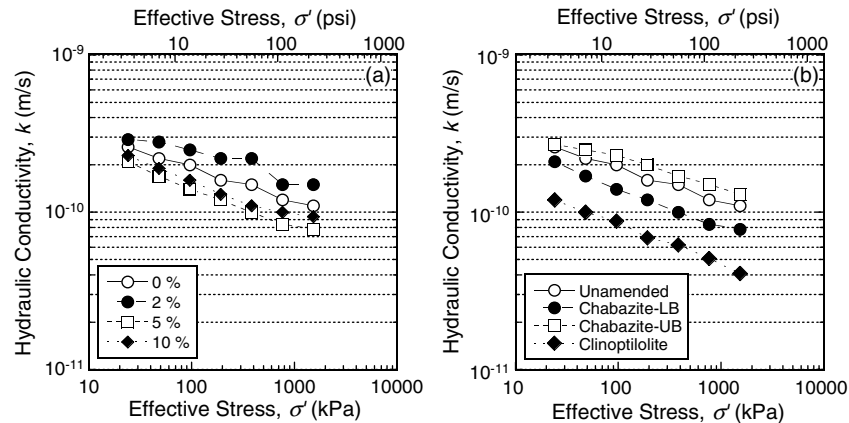
Amount and type of zeolite amendment	Atterberg limits		
	Liquid limit, LL (%)	Plastic limit, PL (%)	Plasticity index, PI (%)
0% (unamended)	31.2	10.5	20.7
2% Chabazite-LB	31.3	7.3	24.0
5% Chabazite-LB	30.0	6.7	23.3
10% Chabazite-LB	34.1	19.0	15.1
5% Chabazite-UB	32.1	20.1	12.0
5% Clinoptilolite	30.7	4.8	25.9



**Fig. 3.** Stress-strain curves for confined compression of unamended and zeolite-amended sand-bentonite backfills: (a) effect of different amounts of the same zeolite (chabazite-LB); (b) effect of same amount (5%) of different types of zeolite.  $C_c$  = compression index;  $C_s$  = swell index

**Table 3.** Hydraulic Conductivity ( $k$ ) and Porosity ( $n$ ) of Zeolite-Amended Sand-Bentonite Backfills with a Total Bentonite Content of 5.8% (Dry Weight) Measured in Fixed-Ring Oedometer Cell as a Function of Consolidation Effective Stress

Effective stress, $\sigma'$ [kPa (psi)]	Amount and type of zeolite amendment											
	0% (unamended)		2% Chabazite-LB		5% Chabazite-LB		10% Chabazite-LB		5% Chabazite-UB		5% Clinoptilolite	
	$k$ (m/s)	$n$	$k$ (m/s)	$n$	$k$ (m/s)	$n$	$k$ (m/s)	$n$	$k$ (m/s)	$n$	$k$ (m/s)	$n$
24 (3.5)	$2.6 \times 10^{-10}$	0.532	$2.9 \times 10^{-10}$	0.513	$2.1 \times 10^{-10}$	0.516	$2.3 \times 10^{-10}$	0.519	$2.7 \times 10^{-10}$	0.503	$1.2 \times 10^{-10}$	0.496
48 (7.0)	$2.2 \times 10^{-10}$	0.520	$2.8 \times 10^{-10}$	0.499	$1.7 \times 10^{-10}$	0.499	$1.9 \times 10^{-10}$	0.503	$2.5 \times 10^{-10}$	0.488	$1.0 \times 10^{-10}$	0.481
96 (14)	$2.0 \times 10^{-10}$	0.498	$2.5 \times 10^{-10}$	0.483	$1.4 \times 10^{-10}$	0.483	$1.6 \times 10^{-10}$	0.484	$2.3 \times 10^{-10}$	0.471	$8.8 \times 10^{-11}$	0.467
192 (28)	$1.6 \times 10^{-10}$	0.480	$2.2 \times 10^{-10}$	0.466	$1.2 \times 10^{-10}$	0.463	$1.3 \times 10^{-10}$	0.465	$2.0 \times 10^{-10}$	0.453	$6.9 \times 10^{-11}$	0.449
383 (56)	$1.5 \times 10^{-10}$	0.459	$2.2 \times 10^{-10}$	0.448	$1.0 \times 10^{-10}$	0.443	$1.1 \times 10^{-10}$	0.445	$1.7 \times 10^{-10}$	0.436	$6.2 \times 10^{-11}$	0.430
766 (111)	$1.2 \times 10^{-10}$	0.440	$1.5 \times 10^{-10}$	0.428	$8.4 \times 10^{-11}$	0.421	$1.0 \times 10^{-10}$	0.422	$1.5 \times 10^{-10}$	0.413	$5.1 \times 10^{-11}$	0.412
1,532 (222)	$1.1 \times 10^{-10}$	0.415	$1.5 \times 10^{-10}$	0.408	$7.8 \times 10^{-11}$	0.397	$9.4 \times 10^{-11}$	0.398	$1.3 \times 10^{-10}$	0.392	$4.1 \times 10^{-11}$	0.392



**Fig. 4.** Hydraulic conductivity measured in fixed-ring oedometer cells as a function of consolidation effective stress for unamended and zeolite-amended sand-bentonite backfills: (a) effect of different amounts of the same zeolite (chabazite-LB); (b) effect of same amount (5%) of different types of zeolite

specimens prepared from a given backfill exhibited similar values of porosity, dry unit weight, and  $k$ . Also, as shown in Fig. 5, the values of  $k$  measured using the flexible-wall cells (Table 4) at an average  $\sigma'$  of 34.5 kPa (5.0 psi) generally were similar to those

measured using the fixed-ring oedometer cells (Table 3) at similar values of  $\sigma'$  [i.e., 24 kPa (3.5 psi) and 48 kPa (7.0 psi)]. The notable exception in Fig. 5 pertains to the backfill containing 2% chabazite-LB, where the  $k$  values measured using the fixed-ring oedometer

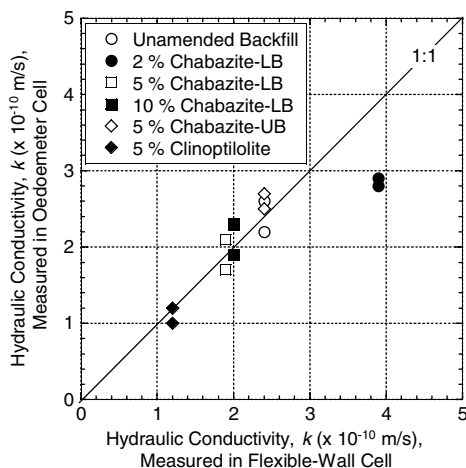
**Table 4.** Flexible-Wall Hydraulic Conductivity Test Results for Replicated Specimens of Zeolite-Amended Sand-Bentonite Backfills with a Total Bentonite Content of 5.8% by Dry Weight

Amount and type of zeolite amendment	Porosity, $n$	Dry unit weight, $\gamma_d$ [kN/m <sup>3</sup> (lb/ft <sup>3</sup> )]	Hydraulic conductivity, $k$ (m/s)		
			Measured value	Arithmetic mean	Geometric mean
0% (unamended)	0.469	13.8 (87.6)	$4.3 \times 10^{-10}$	$2.8 \times 10^{-10}$	$2.4 \times 10^{-10}$
	0.482	14.0 (89.3)	$1.3 \times 10^{-10}$		
2% Chabazite-LB	0.403	13.7 (86.9)	$4.3 \times 10^{-10}$	$3.9 \times 10^{-10}$	$3.9 \times 10^{-10}$
	0.462	14.0 (89.0)	$3.5 \times 10^{-10}$		
5% Chabazite-LB	0.467	13.7 (87.2)	$2.7 \times 10^{-10}$	$2.0 \times 10^{-10}$	$1.9 \times 10^{-10}$
	0.477	14.3 (90.8)	$1.4 \times 10^{-10}$		
10% Chabazite-LB	0.455	13.9 (88.7)	$1.9 \times 10^{-10}$	$2.0 \times 10^{-10}$	$2.0 \times 10^{-10}$
	0.441	14.4 (91.9)	$2.2 \times 10^{-10}$		
5% Chabazite-UB	0.362	14.6 (92.7)	$2.1 \times 10^{-10}$	$2.5 \times 10^{-10}$	$2.4 \times 10^{-10}$
	0.533	13.1 (83.6)	$2.8 \times 10^{-10}$		
5% Clinoptilolite	0.443	14.0 (89.2)	$1.4 \times 10^{-10}$	$1.2 \times 10^{-10}$	$1.2 \times 10^{-10}$
	0.442	15.2 (96.8)	$9.5 \times 10^{-11}$		

cells ranged from 38 to 74% of the geometric mean of the duplicate  $k$  values measured using the flexible-wall cells. However, these differences in measured  $k$  are not significant.

### Coefficients of Consolidation

Coefficients of consolidation,  $c_v$ , computed by both the Casagrande (logarithm-of-time) and Taylor (square-root-of-time) methods are displayed graphically in Fig. 6. Both the Casagrande and Taylor methods yielded  $c_v$  values that are similar in range (i.e., between  $10^{-5}$  and  $10^{-7}$  m<sup>2</sup>/s) and increase with increasing  $\sigma'$ . These results and trends are consistent with those reported by Yeo et al. (2005a) for a sandy SB backfill, as well as those reported by Malusis et al. (2009) for the same unamended, base backfill as evaluated in this study and the base backfill amended with from 2 to 10% activated carbon. The increasing trend in  $c_v$  with increasing  $\sigma'$  is attributed to a greater decrease in the coefficient of volume compressibility,  $m_v$ , with increasing  $\sigma'$  relative to the decrease in  $k$  with increasing  $\sigma'$  (Yeo et al. 2005a; Malusis et al. 2009).



**Fig. 5.** Correlation between geometric mean of hydraulic conductivity,  $k$ , measured in flexible-wall cell at an average effective stress,  $\sigma'$ , of 34.5 kPa (5.0 psi) versus  $k$  measured in fixed-ring oedometer cell at  $\sigma'$  of 24 kPa (3.5 psi) and 48 kPa (7.0 psi)

## Discussion

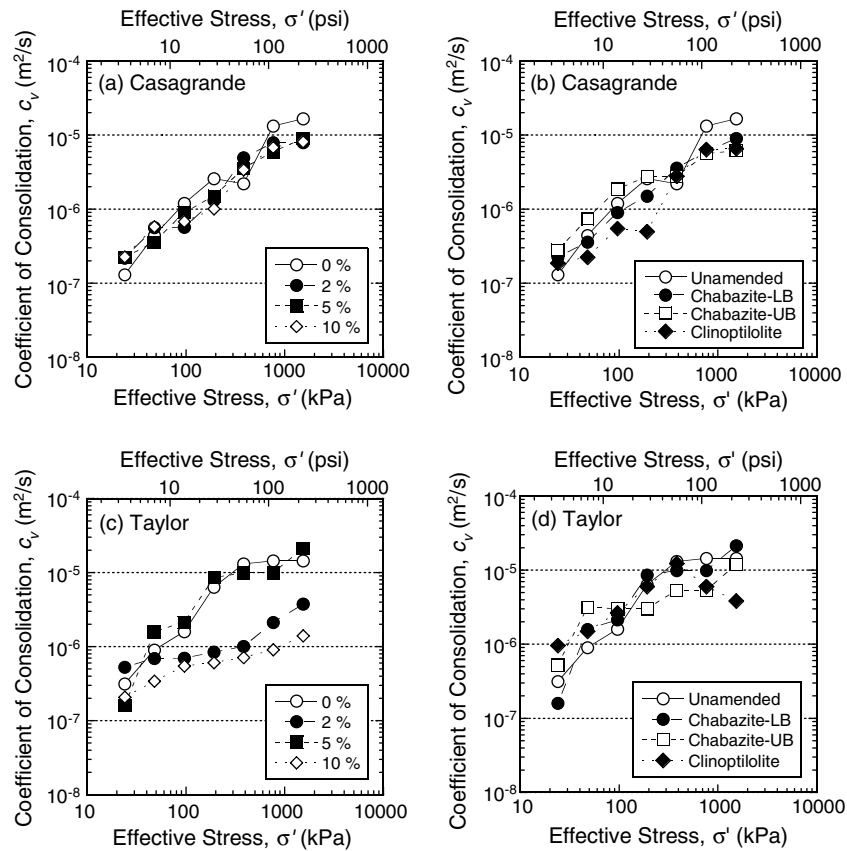
### Effect of Zeolite on Slump

The effects of the zeolite content,  $X_Z$ , and type of zeolite on the backfill water content,  $w_B$ , required to achieve a slump,  $-\Delta H$ , of 125 mm (5 in.) based on the results of the slump tests (Fig. 2) are shown in Fig. 7. For a given amount and/or type of zeolite, the possible range in  $w_B$  values based on the variability in the measured data indicated in Fig. 7 was determined by assuming lines with the same slopes as the best-fit linear regressions shown in Fig. 2 through each data point and determining the resulting minimum and maximum values of  $w_B$  corresponding to  $-\Delta H = 125$  mm (5 in.).

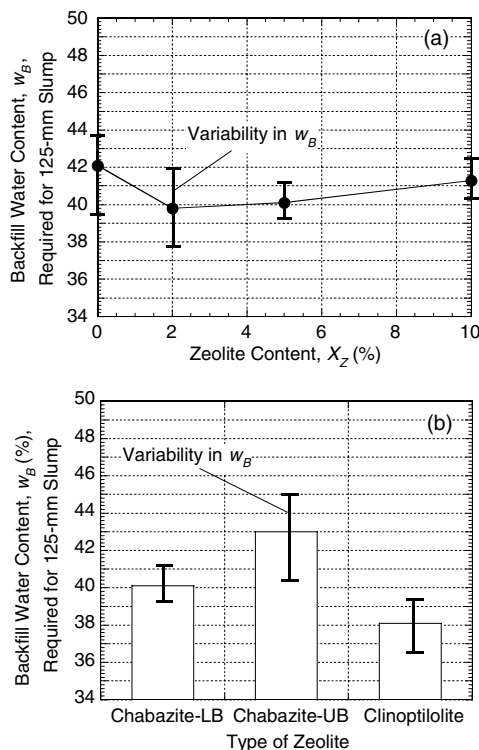
As indicated in Fig. 7(a), the values of  $w_B$  corresponding to  $-\Delta H = 125$  mm (5 in.) based on the linear regressions to the slump testing results for the chabazite-LB-amended backfills [Fig. 2(b)] increased slightly from 39.8 to 41.3% as  $X_Z$  increased from 2 to 10%, respectively. However, this range in values of  $w_B$  corresponding to  $-\Delta H = 125$  mm (5 in.) is within the range of variability associated with the unamended backfill (i.e.,  $39.5\% \leq w_B \leq 43.7\%$ ). Thus, amending the sand-bentonite backfill with chabazite-LB had little effect on the resulting  $w_B$  corresponding to a  $-\Delta H$  of 125 mm (5 in.).

As shown in Fig. 7(b), for the backfills amended with the same amount (5%) of different types of zeolites, the values of  $w_B$  corresponding to a  $-\Delta H$  of 125 mm (5 in.) fell in the order: clinoptilolite ( $w_B = 38.1\%$ ) < chabazite-LB ( $w_B = 40.1\%$ ) < chabazite-UB ( $w_B = 43.0\%$ ). Both of these values of  $w_B$  for the two backfills containing 5% chabazite are within the range of variability of  $w_B$  associated with the unamended backfill (i.e.,  $39.5\% \leq w_B \leq 43.7\%$ ), whereas the value of  $w_B$  for the 5% clinoptilolite was slightly lower than this range. Therefore, amending the sand-bentonite backfill with 5% of either chabazite also had little effect on the resulting  $w_B$  corresponding to a  $-\Delta H$  of 125 mm (5 in.). These results are in contrast to those reported by Malusis et al. (2009) for the same base sand and bentonite but a different amendment, i.e., activated carbon (AC) instead of zeolite, in that the  $w_B$  required to achieve a slump of 125 mm (5 in.) increased significantly with an increase in the amount of AC. The differences in the results are undoubtedly related to the differences between the characteristics of the two different amendment materials.

For example, the AC used by Malusis et al. (2009) is inherently hydrophobic, whereas the zeolites used in this study are inherently



**Fig. 6.** Coefficients of consolidation based on Casagrande and Taylor methods for unamended and zeolite-amended sand-bentonite backfills as a function of consolidation effective stress: (a), (c) effect of different amounts of the same zeolite (chabazite-LB); (b), (d) effect of same amount (5%) of different types of zeolite



**Fig. 7.** Backfill water content required to achieve a 125-mm (5-in.) slump: (a) effect of different amounts of the same zeolite (chabazite-LB); (b) effect of the same amount (5%) of different types of zeolite

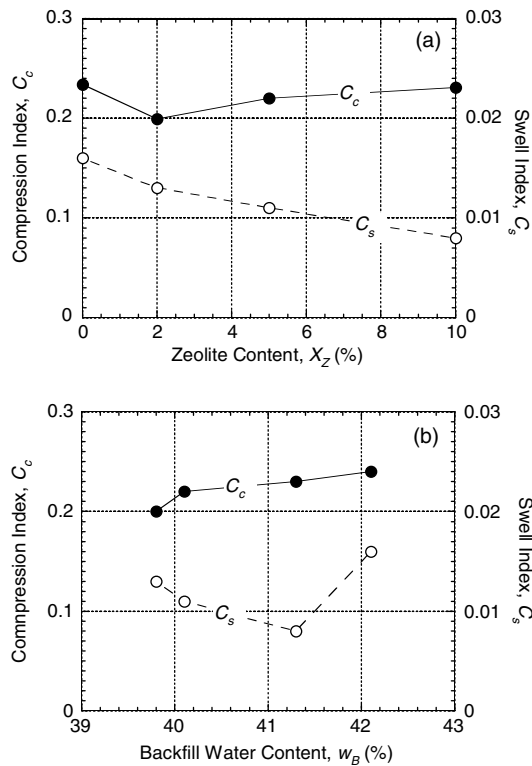
hydrophilic. Thus, similar to bentonites, the zeolites would tend to attract water, whereas the AC would tend to repel water. Also, although the particle sizes of the AC used by Malusis et al. (2009) were coarser than those of the zeolites used in this study, the specific surface areas of the granular AC ( $1,166 \text{ m}^2/\text{g}$ ) and the powdered AC ( $1,140 \text{ m}^2/\text{g}$ ) as reported by Malusis et al. (2010) were significantly greater than those of the zeolites used in this study (see Table 1) attributable to the dominance ( $\geq 80\%$ ) of an internal (intra-particle) surface area associated with the two ACs (Malusis et al. 2010). This difference in surface area suggests that the AC, despite being hydrophobic, would have more intra-particle capacity available for storing water. Regardless of the actual mechanisms causing the different results, the primary conclusion is that different amendments to an otherwise identical backfill can result in significantly different behaviors.

### Effect of Zeolite on Compression and Swell

Values of the compression index,  $C_c$ , and the swell index,  $C_s$ , for the backfills amended with different amounts of chabazite-LB are plotted in Fig. 8(a) as a function of  $X_Z$ . The values of  $C_c$  for the zeolite-amended backfills increased slightly from 0.20 to 0.23 as  $X_Z$  increased from 2 to 10%, respectively, although all of these values of  $C_c$  were slightly lower than the value of  $C_c$  ( $= 0.24$ ) for the unamended backfill (i.e.,  $X_Z = 0$ ). In contrast, the values of  $C_s$  steadily decreased from 0.016 to 0.008 as  $X_Z$  increased from 0 to 10%, respectively.

As indicated in Fig. 8(b), the trend in  $C_c$  is consistent with the water content of the backfill,  $w_B$ ; i.e., the compressibility of the mixture tended to increase with increase in  $w_B$ . In contrast, the swelling behavior of the chabazite-LB amended backfills tended to





**Fig. 8.** Compression and swell indices for unamended sand-bentonite backfill and sand-bentonite backfills amended with the same zeolite (chabazite-LB): (a) effect of amount of zeolite; (b) effect of backfill water content

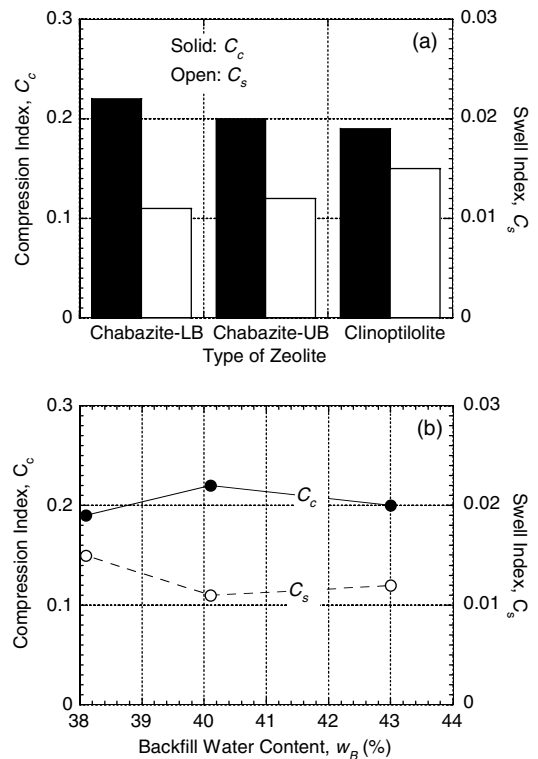
decrease with increasing  $w_B$ , except for the unamended backfill at the highest value for  $w_B$  of 42.1%, which correlated with the overall highest value for  $C_s$  of 0.016. The correlation between  $C_c$  and  $w_B$  is consistent with a weakening of the backfill with increasing  $w_B$ , whereas the reason for the lack of correlation between  $C_s$  and  $w_B$  is not entirely clear, especially since all backfills contained the same amount (i.e., 5.8%) of high-swelling bentonite. Nonetheless, the results indicate that  $C_c$  correlated better with  $w_B$  than  $X_Z$ , whereas  $C_s$  correlated better with  $X_Z$  than  $w_B$ .

The effect of amending the backfill with the same amount (5%) of the three different types of zeolite is illustrated Fig. 9(a). The differences in the values of  $C_c$  and  $C_s$  are relatively minor, with the only apparent trends being that  $C_c$  decreased in the order chabazite-LB > chabazite-UB > clinoptilolite, whereas  $C_s$  increased in the order chabazite-LB < chabazite-UB < clinoptilolite. As indicated in Fig. 9(b), no apparent trend existed between  $C_c$  or  $C_s$  and  $w_B$  based on type of zeolites, likely because of the relative similarity among the values for  $C_c$  and  $C_s$ .

Overall, the value of  $C_c$  tends to increase with increasing initial void ratio,  $e_o$ , independent of the amount or type of zeolite amendment, as shown in Fig. 10. This relationship between  $C_c$  and  $e_o$  is common for natural soils (e.g., see Rendon-Herrero 1980) and illustrates further that the compression behavior of the backfills was affected more by the initial void ratio than by the amount or type of zeolite in the amended backfill.

### Effect of Zeolite on Hydraulic Conductivity

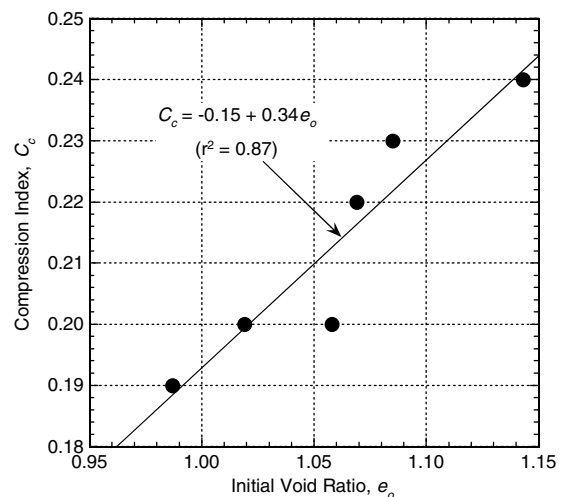
The measured values of hydraulic conductivity,  $k$ , for the backfills amended with different amounts of chabazite-LB are plotted in Fig. 11 as a function of  $X_Z$  with the results based on the flexible-wall tests shown in Fig. 11(a) and the results based on



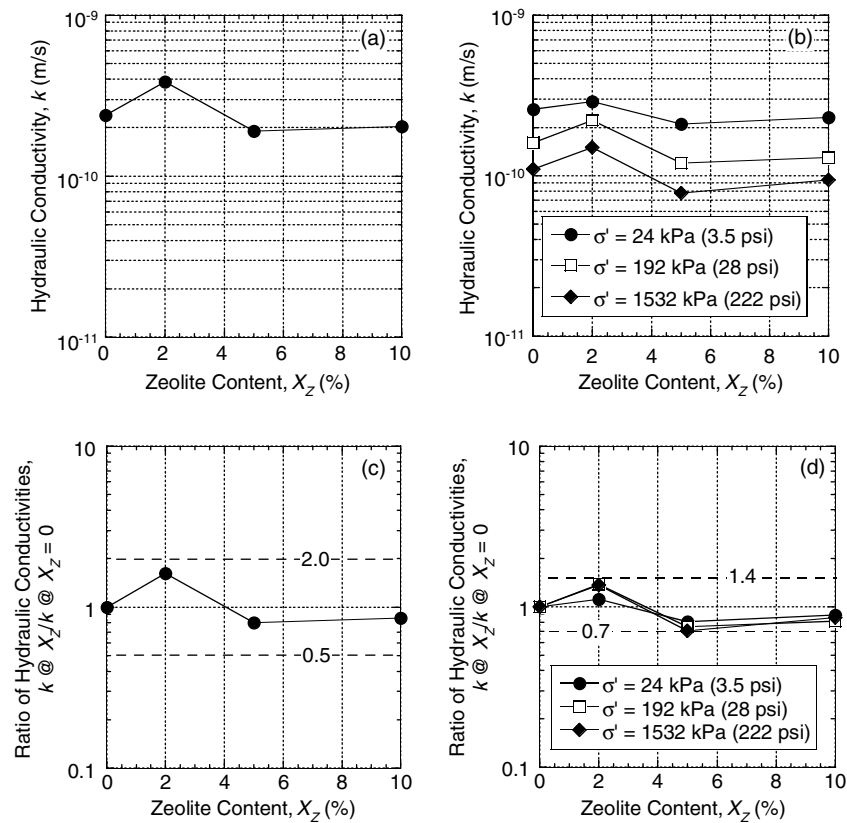
**Fig. 9.** Compression and swell indices for sand-bentonite backfills amended with the same amount (5%) of different types of zeolites: (a) effect of type of zeolite; (b) effect of backfill water content

the fixed-ring oedometer tests at three values of the consolidation effective stress,  $\sigma'$ , shown in Fig. 11(b). The values of  $\sigma'$  for which  $k$  values are reported in Fig. 11(b) represent the minimum, maximum, and geometric mean of the range of  $\sigma'$  applied in the consolidation tests.

Regardless of method of measurement or value of  $\sigma'$ , the trends in the measured  $k$  values in terms of  $X_Z$  are identical, i.e., the value of  $k$  decreases in the order:  $k$  at  $X_Z = 2\% > k$  at  $X_Z = 0\% > k$  at  $X_Z = 10\% > k$  at  $X_Z = 5\%$ . However, as shown in Fig. 11(c), the geometric means of the  $k$  values measured using flexible-wall cells



**Fig. 10.** Correlation between initial void ratio and compression index of sand-bentonite backfills amended with different amounts and/or types of zeolites

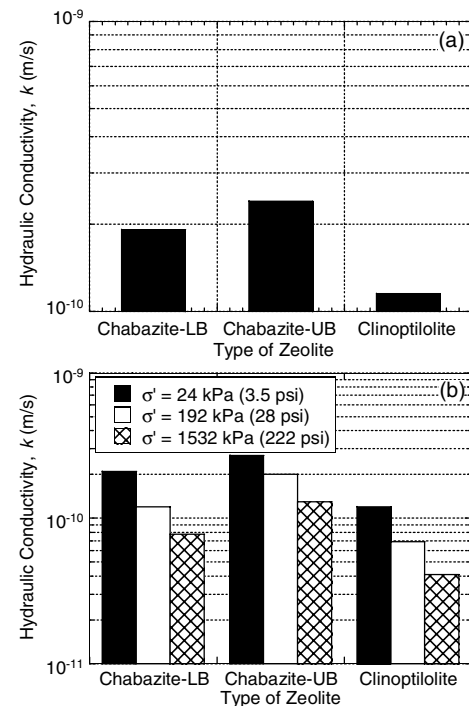


**Fig. 11.** Effect of the amount of the same zeolite (chabazite-LB) on the hydraulic conductivity,  $k$ , of zeolite-amended sand-bentonite backfills: (a) geometric mean of  $k$  values measured using flexible-wall cells; (b)  $k$  values measured in fixed-ring oedometer cells as a function of consolidation effective stress,  $\sigma'$ ; (c) ratio of geometric mean  $k$  values measured using flexible-wall cells; (d) ratio of  $k$  values measured in fixed-ring oedometer cells as a function of  $\sigma'$

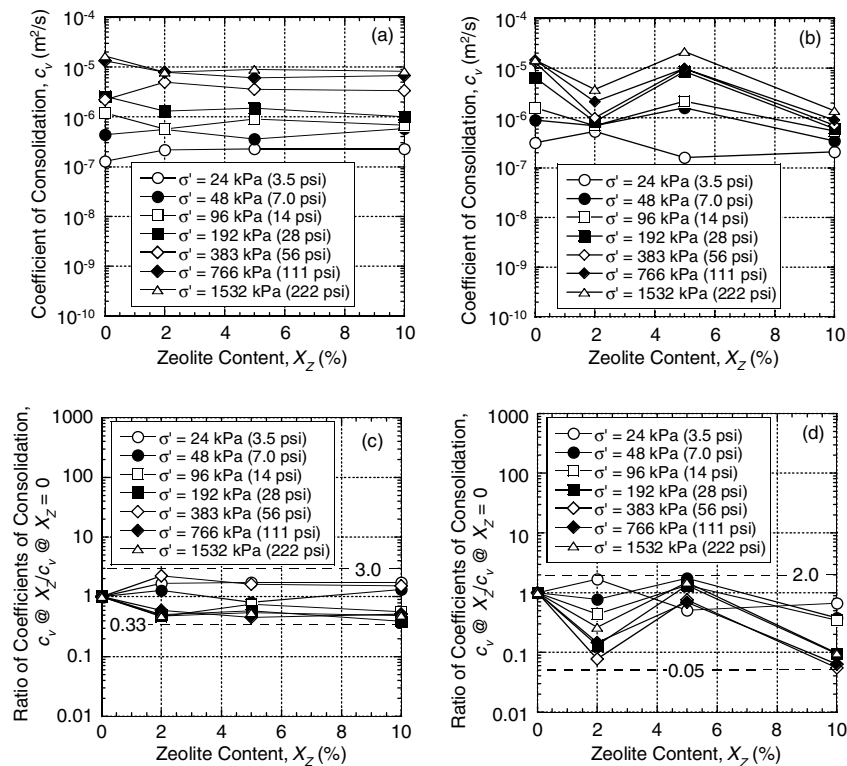
varied only by a factor of approximately 2 over the entire range in  $X_z$  evaluated in the study, whereas the  $k$  values measured using the fixed-ring oedometer cells varied only by a factor of approximately 1.4 over the same range in  $X_z$ , as shown in Fig. 11(d). Thus, amending the backfill with 2 to 10% of chabazite-LB had little effect on  $k$ , regardless of method of measurement or magnitude of effective stress.

The effect of amending the backfill with the same amount (5%) of the three different types of zeolite on the measured  $k$  values is illustrated Fig. 12, with the results based on the flexible-wall tests shown in Fig. 12(a) and the results based on the fixed-ring oedometer tests shown in Fig. 12(b). Regardless of the method of measurement or the value of  $\sigma'$ , the values of  $k$  always were in the order:  $k$  for chabazite-UB >  $k$  for chabazite-LB >  $k$  for clinoptilolite. However, regardless of method of measurement or magnitude of effective stress,  $k$  varied by a factor of  $\leq 3.2$  in all cases, indicating that amending the backfill with the same amount of the three different types of zeolite had little effect on  $k$ .

The relative insensitivity in  $k$  to amount or type of zeolite in the backfills can be attributed to the dominance of the bentonite component of the backfills in governing the hydraulic behavior of the backfills. Although the zeolites used in this study were predominately silt-sized particles (Fig. 1), the zeolites do not exhibit the same swelling behavior as the bentonite and, therefore, do not contribute to reducing the  $k$  based on swelling in the same manner as the bentonite component. Thus, because the bentonite content in all of the backfills was held constant at 5.8%, the  $k$  of the backfills also was relatively constant (i.e., all other factors being the same).



**Fig. 12.** Effect of the same amount (5%) of different zeolites on the hydraulic conductivity,  $k$ , of zeolite-amended sand-bentonite backfills: (a) geometric mean of  $k$  values measured using flexible-wall cells at an average consolidation effective stress,  $\sigma'$ , of 34.5 kPa (5.0 psi); (b)  $k$  values measured in fixed-ring oedometer cells at different values of  $\sigma'$



**Fig. 13.** Effect of the amount of the same zeolite (chabazite-LB) on the coefficient of consolidation,  $c_v$ , of zeolite-amended sand-bentonite backfills as a function of consolidation effective stress,  $\sigma'$ : (a)  $c_v$  based on Casagrande method; (b)  $c_v$  based on Taylor method; (c) ratio of  $c_v$  based on Casagrande method; (d) ratio of  $c_v$  based on Taylor method

### Effect of Zeolite on Coefficient of Consolidation

The values of the coefficient of consolidation,  $c_v$ , based on Casagrande and Taylor methods for the backfills amended with different amounts of chabazite-LB are plotted as a function of  $X_z$  in Figs. 13(a) and 13(b), respectively. The variability in the  $c_v$  values as a function of  $X_z$  obtained by the Taylor method is noticeably greater than that obtained by the Casagrande method. However, as shown in Fig. 13(c), the  $c_v$  values for the zeolite-amended backfills based on the Casagrande method vary at most by a factor of 3 relative to that for the unamended backfill. In terms of the Taylor method of analysis, the upper limit in the range of the  $c_v$  values for the zeolite-amended backfills relative to that for the unamended backfill is only approximately a factor of 2 [Fig. 13(d)], whereas the lower limit in the range of the  $c_v$  values for the zeolite-amended backfills relative to that for the unamended backfill is significantly greater by a factor of approximately 20. Nonetheless, amending the sand-bentonite backfill with 2 to 10% of chabazite-LB had little effect on the resulting values of  $c_v$  regardless of the magnitude of effective stress, especially when considering the  $c_v$  values based on the Casagrande method of analysis. Again, this relative insensitivity in  $c_v$  to the amount or type of zeolite in the backfill implies that the  $c_v$  value is dominated by the hydraulic conductivity of the backfill, which, as previously noted, is also relatively insensitive to the amount or type of zeolite in the backfill, i.e., attributable to the constant content of bentonite in the backfills.

### Summary and Conclusions

The objective of this study was to evaluate, via laboratory testing, the effects of three types of zeolites, viz, chabazite-LB, chabazite-UB, and clinoptilolite, as amendments to a typical sand-bentonite backfill on the consolidation behavior and hydraulic conductivity,

$k$ , of the backfill. The purpose of the zeolite amendment is to enhance the sorption capacity of the backfill for inorganic contaminants (e.g.,  $\text{Cd}^{2+}$ ,  $\text{Zn}^{2+}$ ) and, thereby, improve the long-term sustainability in the containment function of the backfill used in a vertical cutoff wall. The backfills consisted of clean sand mixed with dry bentonite, zeolite (0–10% by dry weight), and bentonite-water slurry to achieve a slump of  $125 \pm 12.5$  mm ( $5 \pm 0.5$  in.) with a total bentonite content of 5.8% (by dry weight). The zeolite-amended backfills were amended with chabazite-LB (2, 5, and 10%), chabazite-UB (5%), or clinoptilolite (5%).

The results of the testing indicated that addition of a zeolite had little impact on either the consolidation behavior or the  $k$  of the backfill, regardless of the amount or type of zeolite. For example, the compression index,  $C_c$ , for the unamended backfill specimen (i.e., 0% zeolite) was 0.24, whereas values of  $C_c$  for the zeolite-amended specimens were in the range  $0.19 \leq C_c \leq 0.23$ . Similarly, the  $k$  for the unamended specimen based on flexible-wall tests was  $2.4 \times 10^{-10}$  m/s, whereas values of  $k$  for zeolite-amended specimens were in the range  $1.2 \times 10^{-10} \leq k \leq 3.9 \times 10^{-10}$  m/s. Finally, values of the coefficient of consolidation,  $c_v$ , for the chabazite-LB-amended backfills based on the Casagrande method of analysis varied at most by a factor of 3 relative to that for the unamended backfill. Variability in  $c_v$  based on the Taylor method of analysis was somewhat greater. Similarly, the same amount (5%) of the three different zeolites had little or marginal impact of the values of  $C_c$ ,  $k$ , and  $c_v$  relative to those for the unamended backfill. Overall, the results of the study suggest that enhancing the sorption capacity of typical SB backfills via zeolite amendment is not likely to have a significant effect on the consolidation behavior or  $k$  of the backfill, provided that the amount of zeolite added is small ( $\leq 10\%$ ).

## Acknowledgments

Financial support for this work was provided by the National Science Foundation (NSF) through Grant No. 0624104. The opinions and recommendations provided in this paper are solely those of the authors and are not necessarily consistent with the policies of NSF. The authors thank Central Builders Supply (Lewisburg, PA), GSA Resources (Tucson, AZ), and Wyo-Ben (Billings, MT) for donating materials used in this study.

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