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# Chemical Compatibility of Model Soil-Bentonite Backfill Containing Multiswellable Bentonite

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# Chemical Compatibility of Model Soil-Bentonite Backfill Containing Multiswellable Bentonite

Michael A. Malusis, Ph.D., P.E., A.M.ASCE[1]; and Matthew D. McKeehan[2]

**Abstract:** The objective of this study was to evaluate the chemical compatibility of model soil-bentonite backfills containing multiswellable bentonite (MSB) relative to that of similar backfills containing untreated sodium (Na) bentonite or a commercially available, contaminant-resistant bentonite (SW101). Flexible-wall tests were conducted on consolidated backfill specimens (effective stress = 34.5 kPa) containing clean sand and 4.5–5.7% bentonite (by dry weight) using tap water and calcium chloride ($CaCl_2$) solutions (10–1,000 mM) as the permeant liquids. Final values of hydraulic conductivity ($k$) and intrinsic permeability ($K$) to the $CaCl_2$ solutions were determined after achieving both short-term termination criteria as defined by ASTM D5084 and long-term termination criteria for chemical equilibrium between the influent and effluent. Specimens containing MSB exhibited the smallest increases in $k$ and $K$ upon permeation with a given $CaCl_2$ solution relative to specimens containing untreated Na bentonite or SW101. However, none of the specimens exhibited more than a fivefold increase in $k$ or $K$, regardless of $CaCl_2$ concentration or bentonite type. Final $k$ values for specimens permeated with a given $CaCl_2$ solution after permeation with tap water were similar to those for specimens of the same backfill permeated with only the $CaCl_2$ solution, indicating that the order of permeation had no significant effect on $k$. Also, final $k$ values for all specimens were within a factor of two of the $k$ measured after achieving the ASTM D5084 termination criteria. Thus, use of only the ASTM D5084 criteria would have been sufficient to obtain reasonable estimates of long-term hydraulic conductivity for the specimens in this study. **DOI: 10.1061/(ASCE)GT.1943-5606.0000729.** *© 2013 American Society of Civil Engineers.*

**CE Database subject headings:** Backfills; Bentonite; Chemicals; Cutoffs; Hydraulic conductivity; Barriers.

**Author keywords:** Backfill; Bentonite; Chemical Compatibility; Cutoff wall; Hydraulic Conductivity; Vertical barrier.

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## Introduction

Soil-bentonite (SB) slurry trench cutoff walls containing sodium (Na) bentonite are commonly employed in the United States as in-situ vertical barriers to contain subsurface pollutants at contaminated sites. The typical construction approach is to excavate a trench while simultaneously filling the trench with bentonite-water slurry (typically 4–6% bentonite by weight) to maintain trench stability. The excavated soil is combined with necessary amendments (e.g., dry Na bentonite) and mixed with slurry to create a homogeneous SB backfill with appropriate consistency (slump). The backfill then is placed into the trench, resulting in a barrier with low hydraulic conductivity, $k$ (typically $k \leq 10^{-9}$ m/s). The bentonite content required for a backfill to exhibit the desired $k$ can range from ~1% (the contribution of bentonite from the slurry) for backfill containing appreciable native fines to 6% or more for backfill containing minimal native fines (D'Appolonia 1980; McKnight and Owaidat 2001; Ryan and Day 2003).

The potential for incompatibility between the backfill and the site groundwater is an important consideration for SB cutoff walls in geoenvironmental applications (D'Appolonia 1982; Evans 1993). For example, increases in $k$ of SB backfill may occur over time due to interactions between the backfill and inorganic cations in groundwater, as suggested by the results of numerous studies on bentonite filter cakes, geosynthetic clay liners (GCLs), and compacted sand-bentonite mixtures permeated with electrolyte solutions (Alther et al. 1985; Shackelford 1994; Stern and Shackelford 1998; Jo et al. 2005; Lee and Shackelford 2005a,b, Katsumi et al. 2008; Shackelford et al. 2010). Such increases in $k$ may be particularly significant for solutions containing multivalent cations [e.g., calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$)], which inhibit bentonite swelling to a greater extent than monovalent cations (e.g., $Na^{+}$) (Amorim et al. 2007).

The current body of literature pertaining to chemical compatibility of SB backfills indicates that the native soil composition and bentonite content are important factors affecting the resistance of backfills to chemical attack. In particular, backfills prepared from well-graded base soils with appreciable native fines require less bentonite and are generally less susceptible to increases in $k$ relative to backfills with low native fines contents (D'Appolonia 1982; Evans 1993; Evans et al. 1995). For example, D'Appolonia (1982) reported that a low to moderate increase in $k$ (i.e., 1–5×) may be expected for backfills containing 30–40% native fines and 1% bentonite and permeated with solutions containing 1,000–10,000 mg/L $Ca^{2+}$ or $Mg^{2+}$. In contrast, Evans et al. (1995) reported a 10-fold increase in $k$ of a sand-bentonite backfill specimen (<5% native fines) permeated with a 4-mg/L chromium ($Cr^{3+}$) solution. This latter study indicated that backfills most vulnerable to chemical attack are those in which $k$ is controlled by the bentonite fraction.

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Approaches that have been investigated for improving the chemical compatibility of bentonite-rich barriers include replacement of the Na bentonite with more inert clay minerals, such as attapulgite (palygorskite), or use of bentonite that has been modified (treated) for enhanced resistance against chemical attack (Alther et al. 1985; Ryan 1987; Day 1994; Kajita 1997; Stern and Shackelford 1998; Cheeseman et al. 1999; Ashmawy et al. 2002; Patton et al. 2007; Katsumi et al. 2008; Shackelford et al. 2010). Regarding the latter approach, a modified bentonite known as multiswellable bentonite (MSB) has attracted recent interest due to the ability of MSB to exhibit osmotic swelling, or interlayer expansion yielding a basal spacing greater than ~40 Å [see Meleshyn and Bunnenberg (2005)], in both fresh water and electrolyte solutions (Shackelford et al. 2000; Mazzieri et al. 2005; Katsumi et al. 2008). As described by Onikata et al. (1996), MSB is created by compounding Na bentonite with propylene carbonate (PC), which activates osmotic swelling by developing hydrogen bonds with the hydration shells of the interlayer cations. The enlarged hydration shells created by the PC result in greater expansion of the interlayer spaces between silica sheets, such that osmotic swelling is possible even in the presence of high electrolyte concentrations (Onikata et al. 1999; Katsumi et al. 2008).

Recently, MSB has been shown to exhibit greater swelling relative to Na bentonite in a wide variety of electrolyte solutions, including solutions with $Ca^{2+}$ concentrations as high as 1.0 M (Shackelford et al. 2000; Katsumi et al. 2008). Also, Katsumi et al. (2008) reported $4.4 \times 10^{-11} \leq k \leq 6.5 \times 10^{-11}$ m/s for granular MSB permeated with solutions containing 100–500 mM $CaCl_2$, whereas Jo et al. (2005) reported $1.1 \times 10^{-9} \leq k \leq 1.7 \times 10^{-9}$ m/s for granular Na bentonite permeated with 100–500 mM $CaCl_2$ under similar stress conditions. Thus, MSB offers the potential for better resistance to degradation of $k$ in solutions containing multivalent cations. Moreover, although use of MSB in SB cutoff walls has been given little consideration to date, Malusis et al. (2010) showed that conventional design requirements for bentonite-water slurry (i.e., viscosity, density, filtrate loss, and pH) and SB backfill (i.e., slump and $k$ to water) can be readily achieved using MSB in lieu of Na bentonite. Based on these considerations, the objective of this study is to evaluate the influence of multivalent electrolyte (i.e., $CaCl_2$) solutions on $k$ of SB backfills containing MSB. The results of flexible-wall $k$ tests performed on model soil-MSB backfills, using both tap water and $CaCl_2$ solutions, are presented and compared against the results of similar tests performed on model backfills containing Na bentonite or a commercially-available, contaminant-resistant bentonite (SW101).

## Materials and Methods

### Solid Materials

The model SB backfills tested in this study were composed of locally supplied mortar sand (Central Builders Supply, Lewisburg, PA) and one of three different powdered bentonite clays, viz, (1) NaturalGel (NG; Wyo-Ben, Inc., Billings, MT), a natural (unmodified) Na bentonite commonly used in SB cutoff walls, (2) SW101 (Wyo-Ben, Inc., Billings, MT), a modified, contaminant-resistant bentonite developed for use in drilling and cutoff wall applications where exposure to seawater is expected, and (3) MSB (MultiGel S-225, Hojun Corp., Japan) containing 25% PC by mass. The mortar sand is poorly graded, predominantly fine sand (Malusis et al. 2009) that was chosen to simulate SB cutoff wall installation in a clean sand aquifer. The measured $k$ (ASTM D2434 [ASTM 2006a]) for the sand compacted at a void ratio ($e$) of 0.92 was $1.4 \times 10^{-4}$ m/s. NaturalGel was chosen as a control for comparison with the two modified bentonites, whereas SW101 was chosen based on recent testing of SW101 for an SB cutoff wall at the Rocky Mountain Arsenal remediation site in Colorado (Patton et al. 2007). The treatment used to create SW101 is unknown (proprietary).

The physical and chemical properties of the three bentonites are summarized in Table 1. The distilled water (DW) swell indexes in Table 1 were measured in accordance with ASTM D5890 (ASTM 2006b), where 2 g of air-dried bentonite is added to 100 mL of DW in a graduated cylinder, and the swell volume is recorded after 24 h. Although all three bentonites contained reasonably comparable percentages of montmorillonite, MSB exhibited a ~40% lower cation exchange capacity (CEC) relative to NG and SW101. The lower CEC for MSB is due, in large part, to a dilution effect created by compounding the bentonite with PC (i.e., the PC comprises 25% of the mass of the MSB but does not contribute to the CEC). The MSB also exhibited the lowest liquid limit (LL), plasticity index (PI), and DW swell index of the three clays. These results are consistent with the lower CEC and the lesser fraction of exchangeable Na (and the greater fractions of exchangeable Ca and Mg) for MSB relative to NG and SW101.

### Permeant Liquids

The permeant liquids included tap water [pH = 6.6, electrical conductivity (EC) = 22.2 mS/m, $Ca^{2+}$ concentration = 0.5 mM) and

**Table 1.** Properties and Mineralogy of Bentonites Tested in Study

| Property | Standard | Value | | |
|---|---|---|---|---|
| | | MSB | NG | SW101 |
| Soil classification | ASTM D2487 | CH | CH | CH |
| Liquid limit (%)[a] | ASTM D4318 | 547 | 583 | 1007 |
| Plasticity index (%)[a] | ASTM D4318 | 502 | 530 | 965 |
| Swell index (mL/2 g)[b] | ASTM D5890 | 28.5 | 35.0 | 43.0 |
| Principal minerals (%)[c] | | | | |
| Montmorillonite | | 74 | 69 | 86 |
| Cristobalite | | 10 | 14 | 6 |
| Quartz | | 2 | 12 | 3 |
| Plagioclase feldspar | | 4 | 2 | 2 |
| Other | | 10 | 3 | 3 |
| Cation exchange capacity ($cmol_c$/kg)[d,e] | | 49.8 | 83.4 | 85.7 |
| Exchangeable metals ($cmol_c$/kg)[d,e] | | | | |
| Ca | | 7.7 | 4.9 | 6.1 |
| Mg | | 6.1 | 8.8 | 10.2 |
| Na | | 33.3 | 73.4 | 64.1 |
| K | | 0.5 | 1.1 | 0.2 |
| Sum | | 47.6 | 88.2 | 80.6 |
| Soluble metals (mg/kg)[d,e] | | | | |
| Ca | | 1,323 | 46.1 | 440.9 |
| Mg | | 862.8 | 15.3 | 109.4 |
| Na | | 1,747 | 2,042 | 2,575 |
| K | | <39 | 58.4 | 39.1 |
| Soil pH | ASTM D4972[b] | 8.1 | 8.7 | 9.7 |

[a]Measured using tap water (pH = 6.6; EC = 22.2 mS/m).
[b]Measured using distilled water (pH = 8.3, EC = 0.067 mS/m).
[c]Based on energy dispersive x-ray analysis performed by Mineralogy, Inc. (Tulsa, OK).
[d]Performed by the Colorado State University Soil Testing Laboratory (Fort Collins, CO).
[e]Procedures given by Shackelford and Redmond (1995).



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$CaCl_2$ solutions (i.e., 10-, 50-, 200-, 500-, and 1,000-mM $CaCl_2$) prepared by dissolving anhydrous $CaCl_2$ pellets (Fisher Scientific, Fair Lawn, NJ) in DW (pH = 8.3, EC = 0.067 mS/m). Relevant properties of the permeant liquids are summarized in Table 2. The $CaCl_2$ solutions were chosen based on the common use of $CaCl_2$ for evaluating the influence of multivalent cations on $k$ of bentonite-rich soils (Stern and Shackelford 1998; Shackelford et al. 2000; Jo et al. 2005; Lee and Shackelford 2005a,b). Although contaminated groundwater may contain a variety of different multivalent cations, the influence of such cations on chemical compatibility of bentonite-rich barriers does not appear to be sensitive to the particular cation species. For example, Jo et al. (2001) and Kolstad et al. (2004) showed that the species of cation for several different divalent cations [$Ca^{2+}$, $Mg^{2+}$, zinc ($Zn^{2+}$), and copper ($Cu^{2+}$)], at a given concentration, generally had no effect on free swell or hydraulic conductivity of a GCL. Jo et al. (2001) also reported that $k$ for GCL specimens permeated with solutions containing trivalent lanthanum ($La^{3+}$) were only slightly greater (i.e., less than 2×) relative to $k$ for GCL specimens permeated with solutions containing divalent cations ($Ca^{2+}$, $Mg^{2+}$, $Zn^{2+}$, or $Cu^{2+}$).

The influence of $CaCl_2$ concentration (5 to 1,000 mM) on the swell index (ASTM D5890) of each bentonite is illustrated in Fig. 1. Although the swell indexes for all three clays decreased with increasing $CaCl_2$ concentration ($C$) over the range $10 \leq C \leq 1{,}000$ mM, the MSB exhibited a higher swell index relative to both NG and SW101 for all concentrations within this range. Interestingly, the swell index for MSB in DW (i.e., $C = 0$ in Fig. 1) was lower than the swell indexes for MSB in the 5- and 10-mM $CaCl_2$ solutions. According to Katsumi et al. (2008), a lower swell index in DW may occur because the low wettability of bentonite in DW prevents the bentonite from fully swelling within the 24-h testing period of ASTM D5890. However, because all of the swell tests in this study were conducted using 24-h test durations, additional testing is needed to further investigate this possibility.

### Model Backfill Preparation

Bentonite-water slurries (5% bentonite by weight) were prepared by blending the bentonite with tap water for 5 min in a Hamilton Beach (Washington, NC) seven-speed blender at the highest operating speed, simulating a colloidal shear mixer used in the field. Separate slurries were prepared using each of the three bentonites (MSB, NG, and SW101). Also, a small amount (0.3% by weight) of lignosulfate thinner (Spersene CF, M-I SWACO, Houston, TX) was added to the SW101 slurry to reduce the viscosity (Malusis et al. 2010). The slurries were allowed to hydrate for a minimum of 24 h before use. After hydration, the average Marsh viscosities of the MSB, NG, and SW101 slurries were 38, 40, and 51 s, respectively. Model SB backfills then were prepared by amending the mortar sand with dry bentonite (MSB, NG, or SW101 at 3 or 4% by dry weight) and combining the dry sand-bentonite mixtures with slurry containing the same bentonite type in a Hobart (Troy, OH) Model N50 benchtop mixer. Slurry was added until a slump [ASTM C143, ASTM (2009)] of 125 ± 12.5 mm (5 ± 0.5 in) was measured for each backfill, in accordance with typical slump requirements for SB backfill (Evans 1993).

The final mixture proportions and measured slumps for each backfill are shown in Table 3. After addition of slurry to achieve the target slump, the total bentonite contents (by dry weight) in the backfills prepared using a 3% dry bentonite amendment were either 4.5% (MSB-1) or 4.6% (NG-1 and SW101–1), whereas the total bentonite contents in the backfills prepared using a 4% dry bentonite amendment were either 5.6% (MSB-2) or 5.7% (NG-2). The slight differences in total bentonite content for backfills prepared using the same percentage of dry bentonite amendment are because of the slightly different amounts of slurry added to the backfills, as reflected by the slight differences in gravimetric water content ($w$) of the backfills. As shown in Table 3, the backfill containing 4.6% SW101 (i.e., backfill SW101–1) was the only backfill prepared with SW101 in this study, because this backfill proved to be sufficient for achieving a hydraulic conductivity to water of $\leq 10^{-9}$ m/s (see Results and Discussion).

### Hydraulic Conductivity Testing

Flexible-wall $k$ tests were conducted on specimens of each model backfill in accordance with Method C (falling headwater-rising tailwater method) of ASTM D5084 (ASTM 2010). The testing procedures and apparatus were the same as those described by Malusis et al. (2009), and involved the use of a custom-fabricated, acrylic

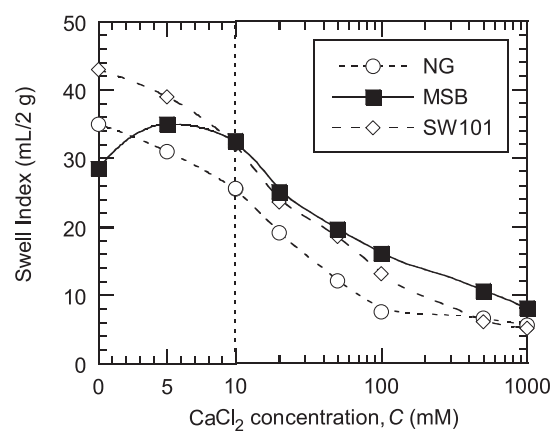


**Fig. 1.** Swell index of NG, MSB, and SW101 as a function of $CaCl_2$ concentration

**Table 2.** Relevant Properties of Permeant Liquids Used in Study

| Permeant liquid | $CaCl_2$ concentration (mM) | $Ca^{2+}$ concentration (mg/L)[a] | Absolute viscosity, $\mu$ (mPa·s)[b] | Unit weight, $\gamma$ (kN/m$^3$)[c] | EC (mS/m)[d] |
|---|---|---|---|---|---|
| Tap water | — | 19.8 | 1.01 | 9.81 | 22.2 |
| $CaCl_2$ Solutions | 10 | 381 | 1.01 | 9.81 | 240 |
| | 50 | 1,857 | 1.02 | 9.84 | 1,050 |
| | 200 | 7,449 | 1.07 | 9.92 | 3,680 |
| | 500 | 18,526 | 1.17 | 10.1 | 8,180 |
| | 1,000 | 36,628 | 1.35 | 10.4 | 14,160 |

[a]Measured using Dionex (Sunnyvale, CA) ICS-1500 ion chromatograph.
[b]Values at 20°C (Wahab and Mahiuddin 2001).
[c]Values computed based on $CaCl_2$ specific gravity of 2.15.
[d]Measured using a Thermo Fisher Scientific (Watham, MA) Model 162A bench EC meter.



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cylinder (length = 71 mm, diameter = 71 mm) placed around the flexible membrane to provide lateral support for the backfill before consolidation. Each specimen was consolidated under back pressure at an effective confining stress, $\sigma'$, of 34.5 kPa (5 psi) for approximately 48 h before permeation was initiated.

Three to five replicate specimens of each backfill listed in Table 3 were permeated with tap water to establish a baseline hydraulic conductivity to water, $k_w$. The specimens were permeated until ASTM D5084 termination criteria were achieved, that is, (1) the ratio of the outflow rate to the inflow rate was between 0.75 and 1.25 for four consecutive measurements, and (2) the hydraulic conductivity was steady, as defined by four or more consecutive $k_w$ measurements within 25% of the mean and no significant upward or downward trend in a plot of $k_w$ versus time. A hydraulic gradient of $\leq 30$ was maintained during each test.

For those backfills that consistently exhibited a final $k_w$ of $\leq 10^{-9}$ m/s, the permeant liquid was changed from tap water to a $CaCl_2$ solution (10, 50, 200, 500, or 1,000 mM), and the tests were continued. These tests are subsequently referred to herein as two-stage tests. In addition to the two-stage tests, one-stage tests were conducted on separate specimens of these same backfills in which the $CaCl_2$ solution (50, 200, 500, or 1,000 mM) was introduced immediately after the consolidation period. The objective of conducting both one- and two-stage tests was to assess the potential for a first exposure effect, in which specimens permeated with water before a chemical solution exhibit a lower $k$ relative to that of specimens permeated directly with the same chemical solution (Shackelford 1994; Lee and Shackelford 2005b).

In all of the one- and two-stage tests, permeation with $CaCl_2$ solutions was continued until each of the following termination criteria were achieved: (1) the aforementioned ASTM D5084 termination criteria were established (i.e., inflow/outflow balance and steady $k$); and (2) the ratio of effluent to influent EC was within the range $1.0 \pm 0.05$. The ASTM D5084 criteria are considered appropriate for representing short-term conditions, whereas the EC ratio criterion is a practical criterion for ensuring that final hydraulic conductivities are reasonably representative of long-term conditions in which chemical equilibrium has been achieved in the test specimens, that is, chemical reactions between the permeant liquid and the bentonite are complete (Jo et al. 2005). In addition, a second chemical equilibrium criterion based on the ratio of effluent Ca concentration, $[Ca^{2+}]_e$, to influent Ca concentration, $[Ca^{2+}]_i$, or $[Ca^{2+}]_e/[Ca^{2+}]_i$, equal to $1.0 \pm 0.05$ was employed in most of the tests to evaluate potential differences in $k$ at Ca equilibrium relative to $k$ at EC equilibrium. In these tests, $[Ca^{2+}]_e$ was measured using a Dionex (Sunnyvale, CA) ICS-1500 ion chromatograph. These termination criteria are consistent with those defined in ASTM D7100 (ASTM 2011), the current standard for compatibility testing of soils, except that ASTM D7100 requires that the ratio of influent-to-effluent characteristics be within $1.0 \pm 0.1$. Thus, the EC and $[Ca^{2+}]$ ratio criteria used herein are more stringent than those required by ASTM D7100. The ASTM D7100 standard also includes a criterion that a minimum of two pore volumes of flow (PVF) be passed through test specimens before termination. The PVF criterion was not formally utilized as a termination criterion in this study, but nonetheless was achieved in all but one of the tests.

## Results and Discussion

The results of the 31 hydraulic conductivity tests conducted in this study are summarized in Table 4. The testing program included 21 tests in which specimens were permeated with tap water to assess the suitability of the backfills for achieving $k_w \leq 10^{-9}$ m/s. Fifteen of these tests were continued as two-stage tests for evaluating $k$ to the $CaCl_2$ solutions. Two-stage $k$ tests were conducted on replicate specimens containing 5.6% MSB, 5.7% NG, and 4.6% SW101. Each replicate specimen of a given backfill was permeated with a different $CaCl_2$ solution (i.e., 10, 50, 200, 500, or 1,000 mM) in the second stage. The remaining 10 tests were one-stage tests in which specimens were permeated directly with 50-, 200-, 500-, or 1,000-mM $CaCl_2$.

The results in Table 4 include final hydraulic conductivities to water, $k_{fw}$, final hydraulic conductivities to $CaCl_2$ solution, $k_{fc}$, values of the ratio $k_{fc}/k_{fw}$ (two-stage tests only), and the test durations (time and PVF) for each stage. Also, final intrinsic permeabilities to $CaCl_2$ solution, $K_{fc}$, and to water, $K_{fw}$, are included in Table 4, along with values of the ratio $K_{fc}/K_{fw}$ (two-stage tests only). Intrinsic permeability, $K$, differs from $k$ in that changes in $K$ are caused solely by changes in fabric (e.g., clay shrinkage), whereas changes in $k$ may occur due to changes in $K$ and changes in viscosity ($\mu$) and unit weight ($\gamma$) of the permeant liquid. The relationship between $K$ and $k$ is given as follows (Shackelford 1994):

$$K = k\frac{\mu}{\gamma} \tag{1}$$

Therefore, $K_{fc}/K_{fw}$ may be expressed in terms of $k_{fc}/k_{fw}$ as follows (Shackelford et al. 2000):

$$\frac{K_{fc}}{K_{fw}} = \frac{k_{fc}}{k_{fw}}\frac{\mu_c}{\mu_w}\frac{\gamma_w}{\gamma_c} \tag{2}$$

where the subscripts $c$ and $w$ represent the chemical solution and water, respectively. Based on Eqs. (2), $K_{fc}/K_{fw} \neq k_{fc}/k_{fw}$ for cases in which $\mu_c\gamma_w \neq \mu_w\gamma_c$. In such cases, $K_{fc}/K_{fw}$ is the more appropriate parameter relative to $k_{fc}/k_{fw}$ for evaluating the effect of liquid-soil interactions. The $K_{fc}$ and $K_{fw}$ values in Table 4 were computed using the values of $\mu$ and $\gamma$ for the tap water and $CaCl_2$ solutions in Table 2. The differences between $K_{fc}/K_{fw}$ and $k_{fc}/k_{fw}$ were small (<5%) for $CaCl_2$ concentrations $\leq 200$ mM. However, $K_{fc}/K_{fw}$ values for 500-mM $CaCl_2$ and 1,000-mM $CaCl_2$ were higher than the corresponding $k_{fc}/k_{fw}$ by 12 and 26%, respectively.

**Table 3.** Compositions and Physical Properties of Model Soil-Bentonite Backfill Mixtures Prepared using MSB, NG, and SW101

| Bentonite type | Backfill ID | Dry bentonite amendment (dry wt. %) | Total bentonite content[a] (dry wt. %) | Sand content (dry wt. %) | Gravimetric water content, $w$ (%) | Mean slump[b] (mm) |
|---|---|---|---|---|---|---|
| MSB | MSB-1 | 3 | 4.5 | 95.5 | 38.5 | 127 |
| | MSB-2 | 4 | 5.6 | 94.4 | 40.0 | 128 |
| NG | NG-1 | 3 | 4.6 | 95.4 | 40.0 | 115 |
| | NG-2 | 4 | 5.7 | 94.3 | 43.0 | 114 |
| SW101 | SW101–1 | 3 | 4.6 | 95.4 | 39.9 | 120 |

[a]Dry bentonite amendment plus bentonite from slurry.

[b]Based on a minimum of two replicates.



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**Table 4.** Results of Flexible-Wall Hydraulic Conductivity Tests on Consolidated SB Backfill Specimens ($\sigma' = 34.5$ kPa)

| | | Tap water ($w$) | | | | $CaCl_2$ solution ($c$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Test duration | | | | | Test duration | | | |
| Backfill | $e_f$ | $k_{fw}$ (m/s) | $K_{fw}$ ($m^2$) | $t$ (days) | PVF | C (mM) | $k_{fc}$ (m/s) | $K_{fc}$ ($m^2$) | $t$ (days) | PVF | $k_{fc}/k_{fw}$ | $K_{fc}/K_{fw}$ |
| 4.6% NG | 0.92 | $1.4 \times 10^{-9}$ | $1.4 \times 10^{-16}$ | 13.8 | 1.16 | — | — | — | — | — | — | — |
| | 0.90 | $5.5 \times 10^{-10}$ | $5.7 \times 10^{-17}$ | 13.8 | 0.44 | — | — | — | — | — | — | — |
| | 0.85 | $5.8 \times 10^{-10}$ | $5.9 \times 10^{-17}$ | 13.8 | 0.44 | — | — | — | — | — | — | — |
| 4.5% MSB | 0.86 | $5.0 \times 10^{-9}$ | $5.2 \times 10^{-16}$ | 27.4 | 14.7 | — | — | — | — | — | — | — |
| | 0.86 | $1.3 \times 10^{-8}$ | $1.3 \times 10^{-15}$ | 10.2 | 8.13 | — | — | — | — | — | — | — |
| | 0.87 | $2.0 \times 10^{-9}$ | $2.1 \times 10^{-16}$ | 29.8 | 7.20 | — | — | — | — | — | — | — |
| 4.6% SW101 | 0.88 | $3.1 \times 10^{-10}$ | $3.2 \times 10^{-17}$ | 182 | 2.09 | 10 | $7.6 \times 10^{-10}$ | $7.8 \times 10^{-17}$ | 57.2 | 3.19 | 2.4 | 2.4 |
| | 0.84 | $2.5 \times 10^{-10}$ | $2.5 \times 10^{-17}$ | 141 | 1.29 | 50 | $1.1 \times 10^{-9}$ | $1.1 \times 10^{-16}$ | 102 | 4.28 | 4.3 | 4.3 |
| | 0.84 | $2.7 \times 10^{-10}$ | $2.7 \times 10^{-17}$ | 198 | 1.65 | 200 | $9.8 \times 10^{-10}$ | $1.1 \times 10^{-16}$ | 84.7 | 3.83 | 3.7 | 3.9 |
| | 0.85 | $4.4 \times 10^{-10}$ | $4.5 \times 10^{-17}$ | 209 | 2.69 | 500 | $1.1 \times 10^{-9}$ | $1.2 \times 10^{-16}$ | 68.0 | 3.51 | 2.5 | 2.8 |
| | 0.79 | $1.8 \times 10^{-10}$ | $1.8 \times 10^{-17}$ | 36.4 | 0.34 | 1,000 | $6.9 \times 10^{-10}$ | $9.0 \times 10^{-17}$ | 70.7 | 2.63 | 3.9 | 5.0 |
| | 0.88 | — | — | — | — | 50 | $7.7 \times 10^{-10}$ | $7.9 \times 10^{-17}$ | 208 | 5.77 | — | — |
| | 0.88 | — | — | — | — | 200 | $7.4 \times 10^{-10}$ | $8.0 \times 10^{-17}$ | 112 | 3.27 | — | — |
| | 0.84 | — | — | — | — | 500 | $7.2 \times 10^{-10}$ | $8.3 \times 10^{-17}$ | 143 | 4.75 | — | — |
| | 0.84 | — | — | — | — | 1,000 | $7.4 \times 10^{-10}$ | $9.7 \times 10^{-17}$ | 76.3 | 2.30 | — | — |
| 5.7% NG | 0.90 | $3.1 \times 10^{-10}$ | $3.2 \times 10^{-17}$ | 112 | 1.46 | 10 | $4.9 \times 10^{-10}$ | $5.0 \times 10^{-17}$ | 62.4 | 2.39 | 1.6 | 1.6 |
| | 0.94 | $2.7 \times 10^{-10}$ | $2.7 \times 10^{-17}$ | 28.8 | 0.39 | 50 | $6.9 \times 10^{-10}$ | $7.1 \times 10^{-17}$ | 92.4 | 2.73 | 2.6 | 2.6 |
| | 0.92 | $2.3 \times 10^{-10}$ | $2.3 \times 10^{-17}$ | 20.5 | 0.26 | 200 | $6.8 \times 10^{-10}$ | $7.4 \times 10^{-17}$ | 85.4 | 2.64 | 3.0 | 3.2 |
| | 0.84 | $2.8 \times 10^{-10}$ | $2.8 \times 10^{-17}$ | 29.2 | 0.41 | 500 | $7.5 \times 10^{-10}$ | $8.7 \times 10^{-17}$ | 94.2 | 2.17 | 2.7 | 3.1 |
| | 0.83 | $2.3 \times 10^{-10}$ | $2.4 \times 10^{-17}$ | 26.4 | 0.33 | 1,000 | $7.1 \times 10^{-10}$ | $9.3 \times 10^{-17}$ | 61.8 | 2.28 | 3.1 | 3.9 |
| | 0.86 | — | — | — | — | 50 | $7.0 \times 10^{-10}$ | $7.2 \times 10^{-17}$ | 91.3 | 2.52 | — | — |
| | 0.90 | — | — | — | — | 200 | $7.3 \times 10^{-10}$ | $8.1 \times 10^{-17}$ | 120 | 3.93 | — | — |
| | 0.88 | — | — | — | — | 500 | $7.1 \times 10^{-10}$ | $8.0 \times 10^{-17}$ | 83.2 | 2.75 | — | — |
| 5.6% MSB | 0.90 | $2.1 \times 10^{-10}$ | $2.2 \times 10^{-17}$ | 178 | 1.44 | 10 | $3.1 \times 10^{-10}$ | $3.2 \times 10^{-17}$ | 244 | 1.57 | 1.5 | 1.5 |
| | 0.87 | $2.2 \times 10^{-10}$ | $2.2 \times 10^{-17}$ | 18.5 | 0.21 | 50 | $4.2 \times 10^{-10}$ | $4.3 \times 10^{-17}$ | 121.9 | 2.40 | 1.9 | 1.9 |
| | 0.88 | $2.0 \times 10^{-10}$ | $2.1 \times 10^{-17}$ | 18.5 | 0.20 | 200 | $4.2 \times 10^{-10}$ | $4.5 \times 10^{-17}$ | 111.0 | 2.15 | 2.1 | 2.2 |
| | 0.85 | $3.1 \times 10^{-10}$ | $3.2 \times 10^{-17}$ | 65.3 | 1.19 | 500 | $5.8 \times 10^{-10}$ | $6.7 \times 10^{-17}$ | 85.6 | 2.53 | 1.8 | 2.1 |
| | 0.83 | $2.5 \times 10^{-10}$ | $2.6 \times 10^{-17}$ | 82.6 | 1.00 | 1,000 | $3.5 \times 10^{-10}$ | $4.6 \times 10^{-17}$ | 107.5 | 2.23 | 1.4 | 1.7 |
| | 0.89 | — | — | — | — | 50 | $4.4 \times 10^{-10}$ | $4.5 \times 10^{-17}$ | 206 | 4.12 | — | — |
| | 0.91 | — | — | — | — | 200 | $4.2 \times 10^{-10}$ | $4.5 \times 10^{-17}$ | 178 | 3.51 | — | — |
| | 0.84 | — | — | — | — | 500 | $4.6 \times 10^{-10}$ | $5.3 \times 10^{-17}$ | 101 | 2.27 | — | — |

Note: $e_f$ = final void ratio; $k_f$ = final hydraulic conductivity; $k_f$ = final intrinsic permeability; C = $CaCl_2$ concentration; PVF = pore volumes of flow.

### Hydraulic Conductivity to Water

As shown in Table 4, final hydraulic conductivities to water ($k_{fw}$) for one or more specimens of backfills containing 4.6% NG and 4.5% MSB were $> 10^{-9}$ m/s, whereas $k_{fw}$ for all specimens containing 4.6% SW101 were $< 10^{-9}$ m/s. The geometric mean $k_{fw}$ for replicate specimens of these three backfills, illustrated in Fig. 2, varied in the order: 4.6% SW101 ($3.1 \times 10^{-10}$ m/s) < 4.6% NG ($7.6 \times 10^{-10}$ m/s) < 4.5% MSB ($5.0 \times 10^{-9}$ m/s). These results are consistent with the results in Table 1, in that the DW swell index, LL, and CEC for the three bentonites varied in the order: SW101 > NG > MSB. However, increasing the NG or MSB content in the backfills by approximately one percentage point caused a significant decrease in $k_{fw}$, such that $k_{fw}$ for all replicate specimens containing 5.6% MSB and 5.7% NG were within the range $2.0 \times 10^{-10} \leq k_{fw} \leq 3.1 \times 10^{-10}$ m/s. This range of $k_{fw}$ is well below the typical regulatory limit of $10^{-9}$ m/s and was similar to the range of $k_{fw}$ for specimens containing 4.6% SW101 (i.e., $1.8 \times 10^{-10} \leq k_{fw} \leq 4.4 \times 10^{-10}$ m/s). Thus, the backfills containing 5.6% MSB, 5.7% NG, and 4.6% SW101 were chosen for testing with the $CaCl_2$ solutions.

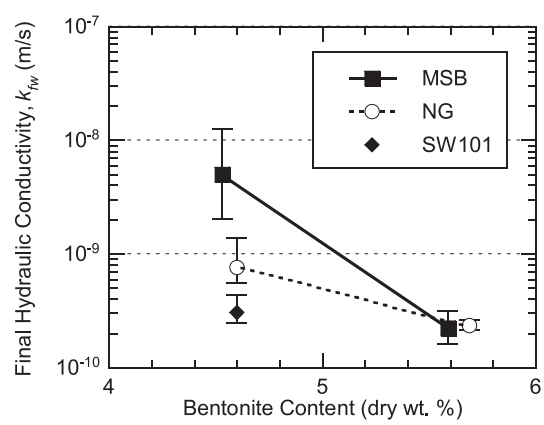


**Fig. 2.** Final values of hydraulic conductivity to tap water, $k_{fw}$, for SB backfill specimens as a function of bentonite content (plotted values represent geometric mean $k_{fw}$ values for replicate specimens; error bars encompass range of measured $k_{fw}$ for each set of replicates)

### Hydraulic Conductivity to $CaCl_2$ Solutions

Hydraulic conductivities measured during both the one- and two-stage tests are plotted as a function of PVF in Fig. 3. All of the one- and two-stage specimens exhibited increases in $k$ upon permeation with the $CaCl_2$ solutions. These increases in $k$ are because of increases in $K$ resulting from suppressed osmotic swelling of the



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bentonite fraction, as reflected by the results in Table 4, which show that $K_{fc}/K_{fw} \geq k_{fc}/k_{fw} > 1$ for the two-stage specimens. However, the increases are modest (i.e., $<5\times$) in all cases, regardless of $CaCl_2$ concentration or bentonite type. Also, similar final $k$ ($k_{fc}$) values were obtained for one- and two-stage specimens of the same backfill permeated with the same $CaCl_2$ solution. These findings are discussed in greater detail in the following.

Although most of the tests were conducted without incident, an unexpected compressor shutdown occurred during the two-stage tests on the three specimens permeated with 10-mM $CaCl_2$. This shutdown is believed to be responsible for the slight increase in $k$ of the specimens upon restart [Figs. 3(a), (f), and (k)]. However, ASTM D5084 and EC ratio termination criteria had already been achieved for these specimens at the time of the shutdown. Therefore, the $k_{fc}$ values listed in Table 4 for these three specimens are those measured immediately before the shutdown.

### Assessment of Bentonite Type

As shown in Table 4, the 5.6% MSB specimens consistently exhibited a lower $k_{fc}$ relative to the 5.7% NG specimens and 4.6% SW101 specimens permeated with the same $CaCl_2$ solution. Also, $K_{fc}/K_{fw}$ for the two-stage specimens of 5.6% MSB ranged from 1.5 to 2.2, whereas $K_{fc}/K_{fw}$ for the two-stage specimens of 5.7% NG and 4.6% SW101 ranged from 1.6 to 3.9 and 2.8 to 5.0, respectively. This range of $K_{fc}/K_{fw}$ for the 5.6% MSB specimens was lower than the $K_{fc}/K_{fw}$ measured for any one of the two-stage specimens of 5.7% NG and 4.6% SW101, except for the 5.7% NG specimen permeated with the most dilute (10 mM) $CaCl_2$ solution (i.e., $K_{fc}/K_{fw} = 1.6$). Thus, the results show that the backfill containing MSB was the most resilient of the three backfills tested in the study.

The lower values of $K_{fc}/K_{fw}$ for the backfill containing MSB are consistent with the results in Fig. 1, in that MSB exhibited the highest swell index of the three bentonites for a given $CaCl_2$ concentration in the range of 10 mM $\leq C \leq$ 1,000 mM. However, swell index was not a fully reliable indicator of the influence of $CaCl_2$ concentration or bentonite type on $K_{fc}/K_{fw}$ in this study. For example, although the swell indexes for all three bentonites decreased with increasing $CaCl_2$ concentration, the relationship between $K_{fc}/K_{fw}$ and $CaCl_2$ concentration was not as consistent. Also, $K_{fc}/K_{fw}$ for the 4.6% SW101 specimens were higher than those for the 5.7% NG specimens for all $CaCl_2$ concentrations, except 500 mM, despite the fact that SW101 exhibited similar or higher indexes relative to NG for a given $CaCl_2$ concentration. Variability in the correlation between $K_{fc}/K_{fw}$ and bentonite swell index could be because of inherent variability in the properties of replicate test specimens, as illustrated, at least in part, by the differences in $k_{fw}$ and final void ratio ($e_f$) among the replicate specimens (Table 4). As such, replicate tests

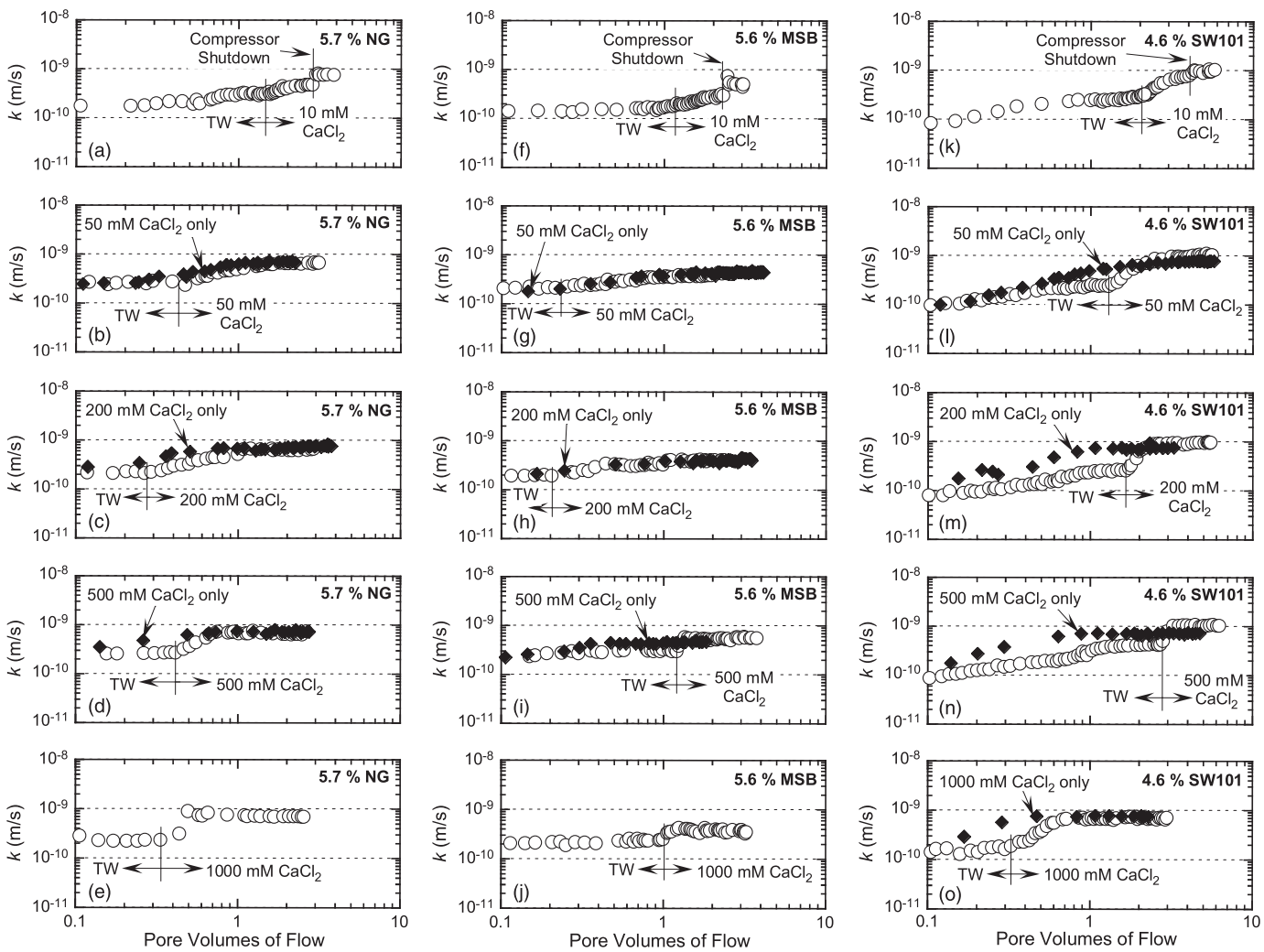


**Fig. 3.** Hydraulic conductivity ($k$) versus pore volumes of flow in one-stage (shaded diamonds) and two-stage (open circles) flexible-wall tests on SB backfill specimens containing (a–e) 5.7% NG; (f–j) 5.6% MSB; (k–o) 4.6% SW101; TW = tap water



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for each $CaCl_2$ concentration are recommended in future studies to better elucidate the influence of specimen variability on $K_{fc}/K_{fw}$.

Notwithstanding the differences in $K_{fc}/K_{fw}$ among the three backfills, all of the two-stage test specimens exhibited $K_{fc}/K_{fw} \leq 5.0$ regardless of $CaCl_2$ concentration or bentonite type. These increases in $K$ are modest relative to those exhibited by other types of bentonite-rich barriers in similar studies. For example, the $K_{fc}/K_{fw}$ values in Table 4 are plotted in Fig. 4 along with $K_{fc}/K_{fw}$ values from two-stage, flexible-wall tests performed on specimens of a GCL containing 100% granular Na bentonite (Shackelford et al. 2000; Lee and Shackelford 2005b) and a compacted sand-attapulgite-bentonite (S-A-B) mixture containing 10% attapulgite and 10% powdered Na bentonite (Stern and Shackelford 1998). The S-A-B specimen was permeated with tap water followed by a 500-mM $CaCl_2$ solution, whereas the GCL specimens were permeated with deionized water followed by 5- to 100-mM $CaCl_2$ solutions (Lee and Shackelford 2005b) or a saturated (6,700 mM) $CaCl_2$ solution (Shackelford et al. 2000). The $K_{fc}/K_{fw}$ for the compacted S-A-B specimen ($K_{fc}/K_{fw} = 7.0$) was two to three times higher than the $K_{fc}/K_{fw}$ values for the backfill specimens permeated with the same $CaCl_2$ solution (500 mM). Likewise, the $K_{fc}/K_{fw}$ values for the GCL specimens were higher (at a given $CaCl_2$ concentration) than those for the backfill specimens and increased by more than an order of magnitude (i.e., from $K_{fc}/K_{fw} \approx 2.5$ to $K_{fc}/K_{fw} \approx 100$) with increasing $CaCl_2$ concentrations from 10 to 6,700 mM.

The greater resilience of the backfill specimens relative to the GCL specimens and the compacted S-A-B specimen in Fig. 4 cannot be attributed to the use of treated bentonite in the backfills, because one of the three backfills contained untreated Na bentonite (i.e., 5.7% NG). In addition, the effective confining stresses, $\sigma'$, of 23.5 and 18 kPa employed in the GCL studies by Lee and Shackelford (2005b) and Shackelford et al. (2000), respectively, were only slightly lower than the $\sigma'$ of 34.5 kPa used in this study and by Stern and Shackelford (1998). Rather, the differences in $K_{fc}/K_{fw}$ among the various barrier types in Fig. 4 are most likely because of the differences in bentonite content, with a higher bentonite content corresponding to greater plasticity and swell capacity of the barrier material. For example, although Atterberg limits for the backfills were not measured as part of this study, Malusis et al. (2009) reported an LL of 27.0% for a model SB backfill comprised of 5.8% NG and the same mortar sand used in this study. In contrast, LL values of 74.0 and 589% were reported for the S-A-B mixture (Stern and Shackelford 1998) and the GCL bentonite (Lee and Shackelford 2005a), respectively. Based on these LL values, the S-A-B and GCL specimens would be expected to exhibit greater increases in $K$ because of chemical interactions that suppress osmotic swell of the bentonite.

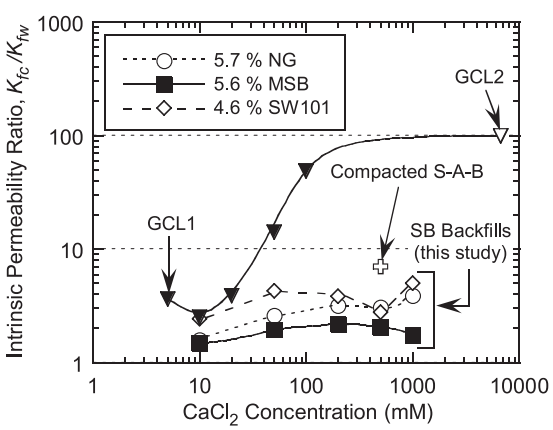


**Fig. 4.** Comparison of intrinsic permeability ratios ($K_{fc}/K_{fw}$) for the SB backfills in this study with those for granular bentonite GCLs (GCL1: Lee and Shackelford 2005b; GCL2: Shackelford et al. 2000) and a compacted S-A-B mixture containing 10% attapulgite and 10% bentonite (Stern and Shackelford 1998)

## Assessment of First Exposure

Differences in $k_{fc}$ for the one-stage backfill specimens relative to the two-stage backfill specimens were compared based on the first exposure ratio (FER), which represents the ratio of the hydraulic conductivity of a specimen permeated initially with a chemical solution relative to the hydraulic conductivity of a separate specimen permeated with the same chemical solution after permeation with water (Stern and Shackelford 1998; Lee and Shackelford 2005b), or

$$\text{FER} = \frac{k_{fc1}}{k_{fc2}} = \frac{K_{fc1}}{K_{fc2}} \tag{3}$$

where the subscripts 1 and 2 represent one- and two-stage tests, respectively. As shown by Eqs. (3), FER computed based on $K_{fc}$ is equivalent to FER computed based on $k_{fc}$.

Values of FER for the backfills are compared against those for the aforementioned GCL (Shackelford et al. 2000; Lee and Shackelford 2005b) and compacted S-A-B mixture (Stern and Shackelford 1998) in Fig. 5. All FER values for the backfills were within the range $0.7 \leq \text{FER} \leq 1.1$, regardless of $CaCl_2$ concentration, indicating that permeation with tap water before introducing the $CaCl_2$ solutions had no significant effect on $k_{fc}$. Likewise, the order of permeation had no adverse impact on $k_{fc}$ of the GCL specimens permeated with solutions containing $\leq 50$ mM $CaCl_2$. In contrast, the order of permeation had a slight impact on $k_{fc}$ of the GCL specimens permeated with 100-mM $CaCl_2$ (FER = 3) and a significant impact on the compacted S-A-B specimen permeated with 500-mM $CaCl_2$ (FER = 20) and the GCL specimen permeated with 6,700-mM $CaCl_2$ (FER $\approx$ 160).

Differences in the impact of first exposure among the different barrier types in Fig. 5 are attributed to differences in the state of

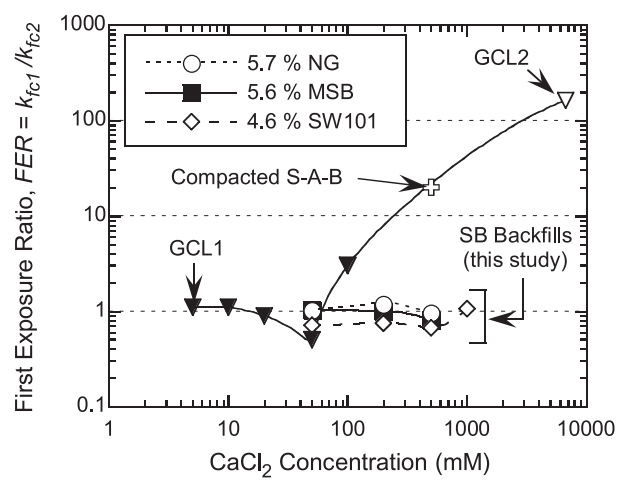


**Fig. 5.** Comparison of FER values for SB backfills in this study with those for granular bentonite GCLs (data for GCL1 from Lee and Shackelford 2005b; data for GCL2 from Shackelford et al. 2000) and a compacted S-A-B mixture containing 10% attapulgite and 10% bentonite (data from Stern and Shackelford 1998); note: $k_{fc1}$ and $k_{fc2}$ represent $k_{fc}$ values from one- and two-stage tests, respectively



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bentonite hydration and extent of osmotic swelling achieved in the test specimens at the onset of permeation with the $CaCl_2$ solutions. The high initial moisture contents of the backfills ($w > 38.5\%$; Table 3), in combination with the high-shear mixing energy imparted to the slurry, created conditions in which the bentonite fraction was fully prehydrated and had undergone osmotic swell before specimen preparation. This premise is supported by the measured $k$ profiles in Fig. 3, which show that (1) $k$ values for all of the backfill specimens were immediately low at the start of permeation, and (2) $k$ for the two-stage backfill specimens either remained steady or increased slightly with increasing PVF before becoming steady during the tap water permeation stage. The latter observation, in particular, indicates that permeation of the backfill specimens with tap water before introducing the $CaCl_2$ solutions provided no benefit in terms of additional osmotic swelling beyond that which occurred during backfill preparation. Therefore, the absence of a first exposure effect (i.e., FER $\approx 1$) for the backfills in this study is reasonable on the basis that the bentonite fractions in the one-stage specimens and the two-stage specimens were in similar states of osmotic swell at the onset of permeation with the $CaCl_2$ solutions.

In contrast to the preceding, the S-A-B specimens were only partially hydrated, and the GCL specimens were unhydrated, before application of confining stress and permeation of the specimens. The $k$ values for the two-stage S-A-B and GCL specimens decreased substantially (by an order of magnitude or more) during the water permeation stage (Stern and Shackelford 1998; Shackelford et al. 2000; Lee and Shackelford 2005b) because of osmotic swelling of the bentonite. Consequently, the state of swell in the two-stage S-A-B and GCL specimens at the onset of permeation with the $CaCl_2$ solutions was different from that in the corresponding one-stage specimens. This difference in the state of swell between one- and two-stage specimens is the primary factor giving rise to the potential for a first exposure effect (i.e., FER $> 1$). However, because Na bentonite is still able to undergo osmotic swell in $\leq$ 100-mM $CaCl_2$ solutions (Amorim et al. 2007), $k_{fc1}$ was no more than three times greater than $k_{fc2}$ for the GCL specimens permeated with $\leq$ 100-mM $CaCl_2$ solutions (i.e., FER $\leq 3$ in Fig. 5). Conversely, the Na bentonite in the one-stage S-A-B and GCL specimens permeated with $\geq$ 500-mM $CaCl_2$ likely had undergone only crystalline swell (i.e., interlayer expansion yielding a basal spacing of $\leq$ 20 Å; Amorim et al. 2007), resulting in FER $\geq 20$.

### Assessment of Termination Criteria

Values of $k_c$, EC ratio, and $[Ca^{2+}]$ ratio were monitored as a function of PVF to identify when each of the aforementioned termination criteria were achieved in each test (McKeehan 2010). The minimum PVF required to meet the termination criteria based on ASTM D5084 ($PVF_{5084}$), EC ratio ($PVF_{ec}$), and $[Ca^{2+}]$ ratio ($PVF_{ca}$) are listed along with the corresponding $k_c$ (i.e., $k_{c,5084}$, $k_{c,ec}$, and $k_{c,ca}$) in Table 5. Steady $k_c$ and inflow/outflow balance (based on ASTM D5084) were achieved in $< 2.25$ PVF in all tests, whereas up to 2.75 and 3.5 PVF were required to satisfy the criteria for the EC ratio and the $[Ca^{2+}]$ ratio, respectively. The PVF corresponding to each criterion followed the order $PVF_{5084} < PVF_{ec} \leq PVF_{ca}$ in most cases. Notable exceptions in this regard were the three two-stage tests in which the backfill specimens were permeated with 10-mM $CaCl_2$. The EC ratio criterion was achieved before the ASTM

**Table 5.** PVF and Hydraulic Conductivities to $CaCl_2$ Solution ($k_c$) Corresponding to Achievement of Termination Criteria Based on ASTM D5084, EC ratio, and $[Ca^{2+}]$ ratio

| | | | Termination criterion | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | ASTM D5084 | | | EC ratio | | | $[Ca^{2+}]$ ratio | | |
| Backfill | C (mM) | N | $PVF_{5084}$ | $k_{c,5084}$ (m/s) | $k_{fc}/k_{c,5084}$[a] | $PVF_{ec}$ | $k_{c,ec}$ (m/s) | $k_{fc}/k_{c,ec}$[a] | $PVF_{ca}$ | $k_{c,ca}$ (m/s) | $k_{fc}/k_{c,ca}$[a] |
| 4.6% SW101 | 10 | 2 | 1.75 | $7.6 \times 10^{-10}$ | 1.0 | 1.50 | $7.4 \times 10^{-10}$ | 1.0 | — | — | — |
| | 50 | 2 | 2.22 | $9.5 \times 10^{-10}$ | 1.1 | 2.11 | $9.3 \times 10^{-10}$ | 1.1 | 2.96 | $9.8 \times 10^{-10}$ | 1.1 |
| | 200 | 2 | 1.31 | $9.2 \times 10^{-10}$ | 1.1 | 1.78 | $9.4 \times 10^{-10}$ | 1.0 | 1.56 | $9.3 \times 10^{-10}$ | 1.0 |
| | 500 | 2 | 1.25 | $1.1 \times 10^{-9}$ | 1.0 | 2.30 | $1.0 \times 10^{-9}$ | 1.0 | 1.73 | $1.0 \times 10^{-9}$ | 1.0 |
| | 1,000 | 2 | 0.57 | $6.9 \times 10^{-10}$ | 1.0 | 2.61 | $6.9 \times 10^{-10}$ | 1.0 | — | — | — |
| | 50 | 1 | 2.05 | $5.9 \times 10^{-10}$ | 1.3 | 2.32 | $6.3 \times 10^{-10}$ | 1.2 | 3.44 | $7.2 \times 10^{-10}$ | 1.1 |
| | 200 | 1 | 1.68 | $7.2 \times 10^{-10}$ | 1.0 | 2.33 | $7.0 \times 10^{-10}$ | 1.1 | 2.79 | $7.5 \times 10^{-10}$ | 1.0 |
| | 500 | 1 | 1.69 | $7.0 \times 10^{-10}$ | 1.0 | 2.08 | $6.8 \times 10^{-10}$ | 1.1 | 2.34 | $6.7 \times 10^{-10}$ | 1.1 |
| | 1000 | 1 | 1.58 | $7.5 \times 10^{-10}$ | 1.0 | 2.08 | $7.6 \times 10^{-10}$ | 1.0 | 2.08 | $7.6 \times 10^{-10}$ | 1.0 |
| 5.7% NG | 10 | 2 | 1.37 | $4.9 \times 10^{-10}$ | 1.0 | 0.77 | $4.6 \times 10^{-10}$ | 1.1 | — | — | — |
| | 50 | 2 | 1.23 | $6.3 \times 10^{-10}$ | 1.1 | 1.81 | $6.7 \times 10^{-10}$ | 1.0 | 2.46 | $6.9 \times 10^{-10}$ | 1.0 |
| | 200 | 2 | 0.55 | $4.5 \times 10^{-10}$ | 1.5 | 2.38 | $6.3 \times 10^{-10}$ | 1.1 | — | — | — |
| | 500 | 2 | 0.52 | $7.2 \times 10^{-10}$ | 1.0 | 1.71 | $6.5 \times 10^{-10}$ | 1.2 | 1.47 | $6.6 \times 10^{-10}$ | 1.1 |
| | 1,000 | 2 | 0.53 | $7.7 \times 10^{-10}$ | 0.9 | 1.87 | $7.1 \times 10^{-10}$ | 1.0 | 2.02 | $7.1 \times 10^{-10}$ | 1.0 |
| | 50 | 1 | 1.31 | $6.5 \times 10^{-10}$ | 1.1 | 1.49 | $6.5 \times 10^{-10}$ | 1.1 | 2.25 | $6.9 \times 10^{-10}$ | 1.0 |
| | 200 | 1 | 1.10 | $6.7 \times 10^{-10}$ | 1.1 | 1.47 | $6.5 \times 10^{-10}$ | 1.1 | 1.95 | $6.7 \times 10^{-10}$ | 1.1 |
| | 500 | 1 | 1.25 | $7.0 \times 10^{-10}$ | 1.0 | 1.70 | $7.1 \times 10^{-10}$ | 1.0 | 1.50 | $7.0 \times 10^{-10}$ | 1.0 |
| 5.6% MSB | 10 | 2 | 0.58 | $2.8 \times 10^{-10}$ | 1.1 | 0.47 | $2.8 \times 10^{-10}$ | 1.1 | — | — | — |
| | 50 | 2 | 1.18 | $3.8 \times 10^{-10}$ | 1.1 | 2.06 | $4.5 \times 10^{-10}$ | 0.9 | — | — | — |
| | 200 | 2 | 0.36 | $3.4 \times 10^{-10}$ | 1.2 | 2.15 | $4.2 \times 10^{-10}$ | 1.0 | — | — | — |
| | 500 | 2 | 0.25 | $5.4 \times 10^{-10}$ | 1.1 | 1.98 | $5.9 \times 10^{-10}$ | 1.0 | 1.72 | $5.7 \times 10^{-10}$ | 1.0 |
| | 1,000 | 2 | 0.95 | $3.9 \times 10^{-10}$ | 0.9 | 2.23 | $3.5 \times 10^{-10}$ | 1.0 | 2.23 | $3.5 \times 10^{-10}$ | 1.0 |
| | 50 | 1 | 1.47 | $3.9 \times 10^{-10}$ | 1.1 | 1.80 | $4.2 \times 10^{-10}$ | 1.0 | 2.32 | $4.3 \times 10^{-10}$ | 1.0 |
| | 200 | 1 | 1.70 | $3.8 \times 10^{-10}$ | 1.1 | 1.76 | $3.8 \times 10^{-10}$ | 1.1 | 2.02 | $3.9 \times 10^{-10}$ | 1.1 |
| | 500 | 1 | 0.59 | $4.3 \times 10^{-10}$ | 1.1 | 2.27 | $4.6 \times 10^{-10}$ | 1.0 | 2.01 | $4.5 \times 10^{-10}$ | 1.0 |

Note: C = $CaCl_2$ concentration; N = number of stages in test.

[a]Based on $k_{fc}$ values in Table 4.



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D5084 criteria in these tests, likely because the $CaCl_2$ concentration of 10 mM was sufficiently dilute so that the contribution of $CaCl_2$ to the effluent EC could not be fully distinguished from the contribution of soluble salts leached from the specimens. Such conditions can result in premature determination of EC equilibrium with the permeant liquid (Shackelford et al. 1999).

Notwithstanding the previously noted exceptions, the results in Table 5 illustrate that longer test durations may be expected when termination criteria for the EC ratio and the $[Ca^{2+}]$ ratio are employed in chemical compatibility tests on SB backfills. In this study, an average of 1.2 PVF were required to satisfy ASTM D5084 criteria, whereas 1.9 and 2.2 PVF, on average, were required to satisfy the criteria for the EC ratio and the $[Ca^{2+}]$ ratio, respectively. These findings are consistent with the results of the study by Jo et al. (2005) on the long-term $k$ of GCL specimens permeated with $CaCl_2$ solutions, except that greater PVF typically were required in the GCL tests to meet these same criteria (3–25 PVF for the EC ratio and 3–159 PVF for the $[Ca^{2+}]$ ratio) because of the appreciably greater amount of bentonite in the GCL specimens.

The results in Table 5 also illustrate that $k_{c,5084}$, $k_{c,ec}$, and $k_{c,ca}$ were not appreciably different for a given backfill specimen, regardless of bentonite type or $CaCl_2$ concentration. Also, values of the ratio $k_{fc}/k_{c,5084}$ were $< 2$ in all cases (Fig. 6), illustrating that the short-term hydraulic conductivities based on ASTM D5084 were similar to the long-term hydraulic conductivities measured after satisfying the criteria for chemical equilibrium. Values of $k_{c,ec}$ and $k_{c,ca}$ differed slightly from $k_{c,5084}$ and were more comparable to $k_{fc}$ (i.e., $k_{fc}/k_{c,ec} \leq 1.2$ and $k_{fc}/k_{c,ca} \leq 1.1$). Nonetheless, use of only the ASTM D5084 termination criteria would have been sufficient in this study to obtain reasonable estimates of the long-term hydraulic conductivity of the backfills (i.e., within a factor of 2). Moreover, the minimal differences between $k_{c,ec}$ and $k_{c,ca}$ indicate that the $[Ca^{2+}]$ ratio criterion was unnecessary for the tests in this study.

## Conclusions

The results of this study indicate that MSB is a promising material for use in SB cutoff walls at sites with high concentrations of multivalent electrolytes in the groundwater. Backfill specimens containing fine sand and 5.6% MSB exhibited only minor ($\leq 2.2\times$) increases in hydraulic conductivity ($k$) or intrinsic permeability ($K$) upon permeation with 10–1,000 mM $CaCl_2$ solutions, outperforming similar backfill specimens containing either untreated Na bentonite or a SW101 bentonite. However, none of the backfill specimens in this study exhibited more than a five-fold increase in $k$ or $K$, regardless of $CaCl_2$ concentration or bentonite type. These increases were shown to be smaller than those reported for other types of bentonite-rich barriers with higher bentonite contents, including a compacted S-A-B mixture containing 10% Na bentonite and a GCL containing 100% Na bentonite.

In all cases, the final $k$ values for backfill specimens permeated with a given $CaCl_2$ solution after permeation with tap water (i.e., two-stage specimens) were similar to those for specimens of the same backfill permeated with only the $CaCl_2$ solution (i.e., one-stage specimens). These results indicated that the backfills were not susceptible to a first exposure effect in which values of $k$ to chemical solutions were influenced by prior permeation with water. The absence of a first exposure effect for SB backfills has not been demonstrated in any previous studies, but is reasonable on the basis that both the one- and two-stage specimens were fully prehydrated with water before permeation.

The chemical equilibrium criteria employed in this study generally resulted in longer test durations than were necessary to satisfy the termination criteria defined by ASTM D5084. In addition, the $k$ measured for a given specimen upon satisfying the ASTM D5084 criteria differed from the final $k$ by less than a factor of two in all cases, suggesting that reasonable estimates of long-term hydraulic conductivity for SB backfills can be obtained without achieving chemical equilibrium between the influent and effluent. However, if confirmation of chemical equilibrium is desired, the results of this study indicate that an EC ratio criterion of $1.0 \pm 0.05$ is satisfactory for this purpose and that monitoring of individual chemical constituents is unnecessary.

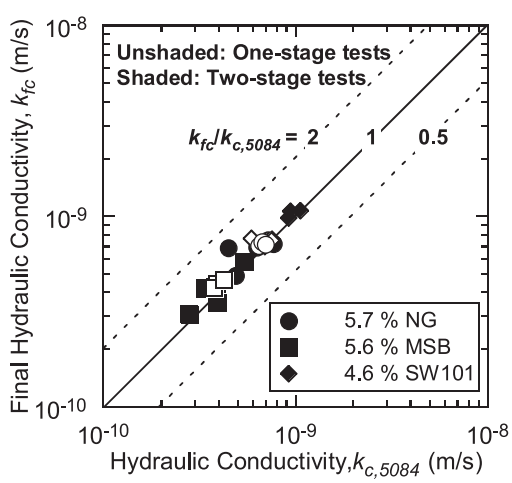


**Fig. 6.** Relationships between final hydraulic conductivities to $CaCl_2$ solution ($k_{fc}$) and hydraulic conductivities measured after achieving ASTM D5084 termination criteria ($k_{c,5084}$) for SB backfill specimens containing 5.7% NG, 5.6% MSB, and 4.6% SW101

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