



## Research paper

## Modified bentonites for soil-bentonite cutoff wall applications with hard mix water

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## ABSTRACT

The influence of mix water hardness and bentonite type on the quality of bentonite slurry and hydraulic performance of soil-bentonite backfill mixtures was investigated through slurry quality testing and flexible-wall hydraulic conductivity ( $k$ ) testing of soil-bentonite backfill specimens. A conventional sodium bentonite (NG) and two types of modified bentonite, HYPER clay (HC) and multiswellable bentonite (MSB), were used to prepare the slurries and backfills. Slurries were prepared with mix waters containing  $\text{CaCl}_2$  concentrations ( $C_M$ ) ranging from 0.5 to 25 mM (hardness,  $H_M = 50\text{--}2500$  mg/L as  $\text{CaCO}_3$ ), and backfills with similar total bentonite contents (5.5–5.9%) were prepared by combining dry sand-bentonite mixtures with the slurries in a benchtop mixer. Backfill specimens were permeated using  $\text{CaCl}_2$  solutions with concentrations,  $C_p$ , ranging from 0.5 to 50 mM. The results of the slurry testing showed that the impact of the mix water on slurry quality parameters (Marsh viscosity, filtrate loss, and bleed) was dependent upon  $C_M$ , bentonite type, and bentonite content. For  $C_M \leq 5$  mM ( $H_M \leq 500$  mg/L), slurry containing 5% NG exhibited adequate viscosity, filtrate loss, and bleed. However, NG contents of 7% and 12% were required to obtain adequate viscosity, filtrate loss, and bleed for  $C_M = 10$  mM ( $H_M = 1000$  mg/L) and 25 mM ( $H_M = 2500$  mg/L), respectively, whereas adequate slurry properties were obtained for  $C_M = 10$  mM using lower percentages (5–6%) of HC or MSB. In terms of backfill  $k$ , the specimens containing HC amended with polyanionic cellulose appeared to be the most resilient against hard mix water. The  $k$  of backfill specimens containing NG generally exceeded  $10^{-9}$  m/s when prepared using slurry with  $C_M = 10$  mM and exceeded  $10^{-8}$  m/s when prepared using slurry with  $C_M = 25$  mM. In contrast, HC backfill specimens prepared using slurry with  $C_M = 10$  or 25 mM exhibited  $k$  ranging from  $4 \times 10^{-11}$  to  $5 \times 10^{-10}$  m/s. Overall,  $C_M$  had greater influence on backfill  $k$  relative to  $C_p$  for the range of  $C_p$  considered in this study.

## 1. Introduction

Soil-bentonite vertical barriers backfilled with bentonite admixed soil can be used to control the migration of pollutants in groundwater. The most common installation method for these barriers is the slurry trench method in which a trench is excavated and simultaneously filled with bentonite slurry (typically 4–7% bentonite by weight) to prevent trench collapse (D'Appolonia and Ryan, 1979; Evans, 1993). The trench spoils are then mixed with slurry and additional dry bentonite (if needed) to create a high-slump backfill with the required low hydraulic conductivity,  $k$  (typically  $k \leq 10^{-9}$  m/s). The backfill is placed in the trench, displacing the stabilizing slurry, to form the final barrier system.

Sodium bentonite, or bentonite containing predominantly Na-montmorillonite, is generally preferred for use in soil-bentonite barriers

due to its high osmotic swell capacity. Osmotic swell of the bentonite in the slurry is necessary for the slurry to exhibit the high viscosity and low filtrate loss needed to maintain trench stability prior to backfilling (US EPA, 1984). In addition, osmotic swell enables the bentonite in the backfill to plug the voids within the soil matrix, resulting in only a small fraction of bentonite (typically 1–6% by dry weight, depending on the native soil composition) needed for the backfill to exhibit the required  $k$ . However, osmotic swell can be inhibited when bentonite comes into contact with electrolyte solutions, particularly those that contain appreciable concentrations of multivalent cations (Shackelford et al., 2000; Jo et al., 2001, 2005; Kolstad et al., 2004; Lee and Shackelford, 2005b; Katsumi et al., 2008; Scalia and Benson, 2010, 2011), which can negatively impact both the slurry and the backfill.

In vertical barrier applications, the initial state of swell of the

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**Table 1**  
Selected properties of the bentonites tested in this study.

Property	Reference	Material				
		NG	MSB	HC + 8%VWR	HC + 2%PAC	HC + 8%PAC
Soil classification	ASTM, 2011a	CH	CH	CH	CH	CH
Liquid limit (%)	ASTM, 2017	583	547	916	747	891
Plasticity index (%)	ASTM, 2017	530	502	801	647	772
DIW swell index (mL/2 g) <sup>a</sup>	ASTM, 2006	35	28.5	43	43	51
Montmorillonite content (%)	<sup>b</sup>	69	74	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Cation exchange capacity, CEC (cmol <sub>c</sub> /kg)	<sup>c</sup>	83.4	49.8	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Exchangeable metals: (cmol <sub>c</sub> /kg)	<sup>c</sup>			<sup>d</sup>	<sup>d</sup>	<sup>d</sup>
Ca		4.9	7.7			
Mg		8.8	6.1			
Na		73.4	33.3			
K		1.1	0.5			
Sum		88.2	47.6			

<sup>a</sup> Measured in deionized water.

<sup>b</sup> Based on energy dispersive x-ray diffraction analysis performed by Mineralogy, Inc. (Tulsa, OK).

<sup>c</sup> Procedures given by Shackelford and Redmond (1995).

<sup>d</sup> Not measured. All HC clays were prepared with NG as base clay.

bentonite is established during construction, as the bentonite hydrates during the slurry and backfill mixing processes. Thus, the influence of electrolyte exposure on the swelling of the bentonite during hydration is dependent on the quality of the water used to mix the slurry (herein referred to as *mix water*). For example, hard mix water (i.e., water containing high concentrations of divalent metal cations such as Ca<sup>2+</sup> and Mg<sup>2+</sup>) can interfere with bentonite swell during hydration, which can yield inadequate slurry viscosity, excessive filtrate loss, and/or sedimentation of the bentonite from the slurry (i.e., bleed) (Xanthakos, 1979; D'Appolonia, 1982; US EPA, 1984; Evans, 1993; Suckling et al., 2011; Norris, 2016; Replogle, 2016; Replogle and Malusis, 2017). Moreover, hard mix water may impact the swelling of any dry bentonite added to the backfill, potentially compromising the backfill *k* before the barrier is put into service. After construction, increases in backfill *k* may occur over time due to reversal of bentonite swell upon contact with metal cations in site groundwater (Malusis and McKeehan, 2013; Norris, 2016; Replogle, 2016; Di Emidio et al., 2017). However, Malusis and McKeehan (2013) reported only modest (two- to four-fold) increases in *k* for sandy backfill specimens (bentonite content = 5.7%) prepared using relatively soft mix water (hardness = 49.5 mg/L as CaCO<sub>3</sub>) and permeated with CaCl<sub>2</sub> solutions having concentrations of 50–1000 mM (hardness = 5000 to 100,000 mg/L as CaCO<sub>3</sub>). These results suggest that even backfills that rely on a high bentonite content to exhibit the desired *k* can be reasonably resilient when subjected to aggressive divalent solutions, provided that the bentonite is able to undergo osmotic swell upon hydration during slurry and backfill mixing.

As a result of the above considerations, specifications for slurry trench construction often limit the mix water hardness to a maximum of 50 ppm (i.e., 50 mg/L as CaCO<sub>3</sub>) as recommended by the US EPA (1984) and the US Army Corps of Engineers (USACE, 1986) and. Ryan and Day (2003) note that a mix water hardness limit of 50 ppm may be difficult to meet, even with a potable water source, and may be unnecessarily restrictive. However, the existing literature regarding the influence of mix water hardness on slurry and backfill quality is limited. Replogle and Malusis (2017) reported that adequate viscosity, filtrate loss, and bleed can be obtained for sodium bentonite slurries prepared from mix waters with hardness up to 1000 ppm by increasing the bentonite content from 5% to 6 or 7%, but did not consider the subsequent impact of the hard mix water on the *k* of backfills prepared with these slurries. Other studies have been conducted to investigate the use of chemically modified bentonites for improving the resilience of soil-bentonite backfills subjected to electrolyte solutions (e.g., Malusis et al., 2010; Bohnhoff, 2012; Bohnhoff et al., 2013; Malusis and McKeehan,

2013; Malusis and Di Emidio, 2014), but these studies did not investigate the influence of hard mix water.

Therefore, the purpose of this study is to investigate the influence of both mix water hardness and bentonite type on the stability of slurry and the hydraulic conductivity of soil-bentonite backfill mixtures. In addition to sodium bentonite, two types of chemically modified bentonite are considered in the study, viz., HYPER clay (HC; see Di Emidio et al., 2015) and multiswellable bentonite (MSB; see Onikata et al., 1996). Both HC and MSB have been developed for improved resilience in electrolyte solutions and have been shown to be potentially viable alternatives to sodium bentonite in cutoff wall applications (Malusis and McKeehan, 2013; Malusis and Di Emidio, 2014; Norris, 2016; Di Emidio et al., 2017). The testing program and results presented herein represent a range of site preparation and water conditions that could be encountered at vertical barrier installations.

## 2. Materials and methods

### 2.1. Bentonites

The sodium bentonite used in this study, referred to as NaturalGel® (NG), was obtained from Wyo-Ben, Inc. (Billings, MT) and is the same sodium bentonite used in other recent studies on soil-bentonite backfill behavior (e.g., Yeo, 2003; Yeo et al., 2005; Malusis et al., 2009, 2010, 2011; Hong et al., 2012; Malusis and McKeehan, 2013; Malusis and Di Emidio, 2014). As shown in Table 1, the NG contained approximately 70% montmorillonite and exhibited a cation exchange capacity (CEC) of 83.4 cmol<sub>c</sub>/kg, with Na occupying approximately 80% of the exchange sites.

MSB (Hojun Corp., Japan) is created by amending sodium bentonite with propylene carbonate. The amendment is intended to develop hydrogen bonds within the hydration shells of the interlayer cations which results in a greater expansion of the interlayer spacing between silica sheets of the clay. This amendment has been shown to allow osmotic swelling even in the presence of strong electrolyte solutions, including sea water (Onikata et al., 1996, 1999; Katsumi et al., 2008). The MSB used in this study contained 25% propylene carbonate and was the same MSB as that used in the study by Mazzieri et al. (2010) and Malusis and McKeehan (2013). As shown in Table 1, MSB contains a comparable percentage of montmorillonite but a lower CEC relative to NG. The lower CEC is attributed primarily to a dilution effect resulting from the addition of propylene carbonate, i.e., the propylene carbonate contributes 25% of the mass of MSB but does not contribute to the CEC (Malusis and McKeehan, 2013).

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