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Research paper

Phosphate-amended sand/Ca-bentonite mixtures as slurry trench wall backfills: Assessment of workability, compressibility and hydraulic conductivity

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ABSTRACT

In regions and countries where sodium bentonite is scarce, the resourceful calcium bentonite can be considered as an alternative material for soil-bentonite slurry trench walls. However, the lower swelling capacity of calcium bentonite as compared to Na-bentonite may result in the unacceptable high hydraulic conductivity of the sand/calcium bentonite backfills, and, therefore, amendment of calcium bentonite is necessary. However, studies on the feasibility of using amended calcium bentonite for soil bentonite backfills are limited. This study investigates the feasibility of using sodium hexametaphosphate amended calcium bentonite for the backfill material through a comprehensive laboratory investigation. First, a series of viscosity, density and filtrate loss tests are conducted using bentonite-tap water slurries with different amounts of phosphate to determine the optimal amendment dosage. Subsequently, the Atterberg limits and free swell index are evaluated for the amended/un-amended calcium bentonite and backfills, which consist of sand and amended/un-amended calcium bentonite. Finally, slump, oedometer tests and flexible-wall hydraulic conductivity tests are conducted on the backfills. The results indicate that the slurry with 20% calcium bentonite amended by 2% phosphate results in the target slurry, and the optimum phosphate dosage for amended calcium bentonite is found to be 2%. The phosphate amendment causes an increase of 1.21 times in the liquid limit, and an increase of 1.40 times in the free swell index of the amended bentonite relative to those of the un-amended bentonite. The sand/calcium bentonite backfill changes from non-plasticity to plasticity after the amendment. The amended backfill displays two times higher swell index value and one order of magnitude lower consolidation coefficient value than the un-amended backfill. The hydraulic conductivity of un-amended backfills containing 15% to 25% un-amended bentonite is greater than the commonly targeted value of 10^{-9} m/s for slurry trench walls. In contrast, the hydraulic conductivity of the amended backfill with 15% to 25% amended bentonite varies from 8.3×10^{-10} m/s to 2.7×10^{-10} m/s, which is lower than 10^{-9} m/s. In addition, the amended backfills containing 20% and 25% amended calcium bentonite have nearly the same magnitude of hydraulic conductivity as the conventional sand/sodium bentonite backfill. This study demonstrates that phosphate is a promising amendment for achieving low hydraulic conductivity of sand/calcium bentonite backfills for soil-bentonite slurry trench walls.

1. Introduction

Soil-bentonite (SB) slurry trench walls, composed of sodium bentonite (Na-bentonite) with superior swelling capacity, are used extensively as engineered barriers to control migration of contaminants in polluted groundwater (Evans, 1993; Sharma and Reddy, 2004; Malusis et al., 2011; Scalia et al., 2014). The hydraulic conductivity (*k*) is an important parameter for the clayey soil system (Valipour, 2012a, 2012b; Mahdizadeh Khasraghi et al., 2015; Valipour and Sefidkouhi, 2015), and *k* of the backfills in slurry trench walls is commonly recommended to be $<10^{-9}$ m/s (Malusis and McKeehan, 2013; Bohnhoff and Shackelford, 2014a; Fan et al., 2014). Deposits of calcium bentonite (Ca-bentonite) are much more abundant relative to the Na-bentonite all over the world (Murray, 2002, 2003). As a consequence, in regions and counties (e.g., China and India) where high quality Na-bentonite is scarce, commonly available Ca-bentonite is considered as an appropriate alternate material for use (Du et al., 2015a, 2015b; Shen et al., 2014; Wu et al., 2015; Xue et al., 2013). However, Ca-bentonite exhibits a lower swelling capacity compared to Na-bentonite, which may lead to an unacceptably high *k* in both the bentonite and the sand/Ca-bentonite

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backfill (Kenney et al., 1992). Thus, modification is required to make Ca-bentonite usable for backfills of SB slurry trench walls. For example, if two soluble polyelectrolyte polymers are used to amend activated Ca-bentonite, the *k* of the amended bentonite is found to be lower than the un-amended one (Razakamanantsoa et al., 2012). In addition, Yang et al. (2014) and Du et al. (2016) evaluate the effects of three types of phosphate dispersants on the dispersivity of clayey soil/Ca-bentonite backfill exposed to concentrated lead (Pb) solutions, and the results indicate that sodium hexametaphosphate (SHMP) is a promising amendment that improves the contaminant containment properties of the clayey soil/Ca-bentonite backfills.

SHMP is a commonly used dispersant in the particle size analysis of soil conducted in a laboratory. Lambe (1954) indicates that a trace amount (i.e., 1%) of phosphate may be sufficient to improve engineering properties such as dispersivity, hydraulic conductivity, liquid limit, and compressibility of the soils. Adebowale et al. (2006) study the effectiveness of using phosphate as an amendment to enhance the dispersivity of kaolin and bentonite in sewage and found that the addition of phosphate improves the sorption capacity of kaolin to heavy metals. Moreover, phosphate helps maintain the dispersivity of kaolin-bentonite mixtures in lead solutions (Du et al., 2016). These previous studies suggest that phosphate has a great potential to be used as an amendment to reduce the *k* of the sand/Ca-bentonite backfills and improve the containment performance of the backfills. However, most of the previous studies focus on the *k* of the amended Na-bentonite materials (Malusis et al., 2009; Shackelford et al., 2010; Bohnhoff and Shackelford, 2014a; Scalia et al., 2014); whereas there is limited research that investigates the *k* of amended sand/Ca-bentonite backfills, especially measuring it directly by conducting triaxial (or flexible-wall) hydraulic conductivity tests.

The objectives of this study are to (1) assess the optimum SHMP dosage of the amended Ca-bentonite based on viscosity, density, and filtrate loss tests using slurries with different SHMP dosages; (2) evaluate the index properties of both amended/un-amended Ca-bentonite and amended/un-amended sand/Ca-bentonite backfills based on liquid limit and free swell tests; (3) investigate the effects of SHMP amendment on consolidation behavior of the sand/Ca-bentonite backfill; and (4) optimize the amended Ca-bentonite content for backfill based on the hydraulic conductivity test results. The results of this study are useful for optimizing the SHMP dosage to amend Ca-bentonite and facilitate the application of SHMP amended bentonite in slurry trench walls.

2. Materials and methods

2.1. Sand and calcium bentonite

The model SB backfills are prepared using sand (Three River sand from a quarry in Beloit, Wisconsin, USA) and one of two powdered bentonites: (1) natural Ca-bentonite (CaB) (Panther Creek® 200, CETCO, IL, USA), and (2) SHMP amended Ca-bentonite (SHMP-CaB). The sand is chosen to model a typical in-situ sandy aquifer where the SB slurry trench wall would be constructed. The CETCO CaB is used rather than a typical CaB available in China because all the tests are conducted at the University of Illinois at Chicago, IL, USA. According to preliminary tests, the liquid limit of the Ca-bentonite is close to 100% and is lower than that of the China CaB used in Du et al. (2016), which has approximately 300% of the liquid limit. Therefore, the type of CaB selected for this study represents a low quality CaB that requires amendment for use in slurry trench walls. The specific gravity, free swell index, and pH of the CaB are measured as 2.31, 6.6 mL/2 g, and 8.8 according to the ASTM D854 (2010), ASTM D5890 (2011), and ASTM D4972 (2007), respectively. The liquid limit and plasticity index of the CaB are determined according to ASTM D4318 (2010), and the values are found to be 102.3% and 55%, respectively. Thus, the CaB is classified as a high plasticity silty to clayey soil (MH/CH) as per ASTM D2487 (2011). The grain size distributions of the sand and CaB are determined according to ASTM D422-63 (2007) and the results are presented in Fig. 1.

2.2. Phosphate dispersant and amended Ca-bentonite

The SHMP is chosen as amendment because it is more effective in dispersing Ca-bentonite than the other phosphate dispersants according to previous studies (Yang et al., 2014; Du et al., 2016). The fine granular SHMP used in this research is obtained from Humboldt Manufacturing Co., Elgin, Illinois, USA. The SHMP-CaB is prepared by the following procedure: First, granular SHMP is dissolved in distilled water (2.0 times of liquid limit of the CaB) using a magnetic stirrer (Fisher Scientific, Pittsburgh, Pennsylvania, USA). Subsequently, the SHMP solution is mixed with the CaB at a 2% SHMP-to-dry bentonite weight ratio. To make sure that the SHMP is mixed homogeneously with the CaB, a high-speed blender is used to mix the SHMP solution/CaB mixture for 30 min. The blended mixture is then poured into a beaker, sealed with plastic film and hydrated for 24 h at 20 °C room temperature. Then the hydrated mixture is mixed in a blender for another 10 min. Finally, the wet mixture is oven dried at 105 °C, ground by mortar and pestle and sieved through No. 200 standard sieve. Preliminary tests show that this type of amendment (i.e., oven drying-grinding method) has approximately the same engineering properties to the direct mixing CaB with SHMP in terms of liquid limit and compressibility. This study only presents the results of oven-drying-grinding method. The specific gravity, free swell index, and pH of the amended CaB are measured as 2.42, 9.0 mL/2 g, and 7.9, respectively, while the liquid limit and plasticity index are 123.8% and 74.3%, respectively, and in consequence the amended CaB is classified as fat or high plasticity clay (CH).

2.3. Slurries

The bentonite-tap water slurries, with 15 to 30% by weight ratio of either CaB or SHMP-CaB to the slurry, are prepared in order to evaluate the optimum bentonite content for use in backfill. First, the slurries are mixed in high-speed blender for 5 min, and then sealed in a beaker and allowed to hydrate for 24 h. The slurries are subjected to another 5 min remixing, then tested for viscosity, density, filtrate loss, and pH values. The density and viscosity tests of the slurries are conducted using a Model 140 mud balance and a Model 201 Marsh funnel viscometer (both from Fann Instrument Company, Houston, Texas) following the American Petroleum Institute (API) recommended specification 13B-1 (API, 2003). The filtrate loss of the slurries is measured in a SERIES 300 API filter press (Fann Instrument Company, Houston, Texas)

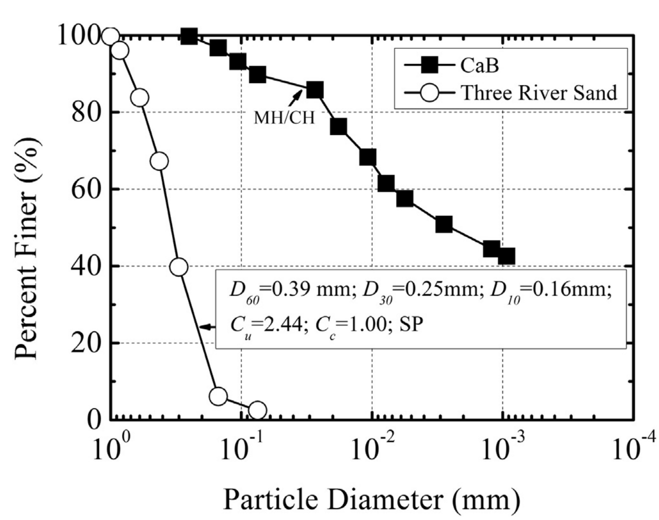

Fig. 1. Grain size distribution of CaB and Three River sand.