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Research paper

Measurement of hydraulic properties of bentonite cake formation deposited on base soil medium

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ABSTRACT

Bentonite cake and filter cake on the surface of porous media result from the filtration of stabilizing slurry into the adjacent porous formation. This paper provides measurements of hydraulic conductivities of bentonite cake formed on Korean standard sand under various pressure levels. Two types of bentonite (Tixoton and Bentonil GTC4) were used to create the slurries with three different concentrations (4, 6, and 8% by weight). An estimation of the hydraulic conductivity of the bentonite cake based on the filtration theory was carried out. The range of hydraulic conductivities of the bentonite cake was from 2.1×10^{-11} m/s to 5.7×10^{-10} m/s. The hydraulic conductivity of the bentonite cake deposited on Korean standard sand were compared with that of the bentonite cake deposited on filter paper to show the effect of the filter medium. The slurry concentration of 6% seems to be a value that most stimulates the effect of the filter medium on the permeability of the Bentonil GTC4 bentonite cake. In addition, a simple approach was developed to characterize the hydraulic properties of the filter cake, which has usually been confused with the bentonite cake in recently published literature.

1. Introduction

Two different terminologies referring to the relatively impermeable layers that are formed during the infiltration of slurry into the adjacent soil formation are widely and indistinguishably used. The two terminologies are "filter cake" and "bentonite cake". Fig. 1 shows how the filter cake and bentonite cake are formed on the surface of porous media. The slurry enters the pores due to the pressure difference and, during this process, the hydrated bentonite particles begin to occupy the void space of the soil matrix (see Fig. 1(a)). More hydrated bentonite particles subsequently accumulate in the pores, and a tightly packed layer of hydrated bentonite particles and soil particles is formed, commonly called filter cake (see Fig. 1(b)). The filter cake layer is then covered by a compacted layer of hydrated bentonite particles, called bentonite cake (see Fig. 1(c)). At this stage, the excavated wall face becomes relatively impermeable and resists further penetration of slurry (Xanthakos, 1979). The low hydraulic conductivity of the bentonite cake and filter cake has been frequently used in a variety of industries such as slurry trench walls, slurry-shield TBMs (Tunnel Boring Machines), drilling mud for oilwells, and liquid clarification.

The formation and properties of the bentonite cake have been previously studied by Nash (1974), Xanthakos (1979), D'Appolonia (1980), Filz et al. (1997), Henry et al. (1998), Britton et al. (2004), Soroush and Soroush (2005), Chung and Daniel (2008), and Nguyen et al. (2012). Mechanisms for bentonite cake formation are governed by the gradation of the adjacent soil formation and the gradation of particles in slurry if the slurry contains suspended soil particles (Xanthakos, 1979; Filz et al., 1997; Henry et al., 1998). In addition, Xanthakos (1979) reasoned that a potential difference between the slurry and excavated wall surface was created by electrochemical effects, generated by the interaction of slurry, groundwater, and soil, which stimulate bentonite particles to move vigorously toward the wall surface to form the bentonite cake.

The formation of the filter cake is governed by various factors such as the rheological properties of the slurry, the properties of the bentonite particles, the properties of the soil matrix, and the physicochemical interactions between the hydrated bentonite particles and the soil particles (Stamatakis and Tien (1991); Sorensen et al. (1996); Sherwood and Meeten (1997); Tien et al. (1997); Meeten (2000); Chen and Hsiau (2009)). The filter cake formation due to the penetration of bentonite slurry into the adjacent soil formation is usually ignored. In this study, the formation and properties of the filter cake will be presented.

The bentonite cake plays an important role in stabilizing excavated surfaces (Xanthakos, 1979; Filz et al., 1997; Henry et al., 1998). Moreover, the bentonite cake may remain intact on the trench surface even after the subsequent backfilling stage with the soil–bentonite mixture. In such cases, characteristics of the bentonite cake can influence the performance of the slurry walls. The very low hydraulic conductivity and location of the bentonite cake could enhance the slurry wall

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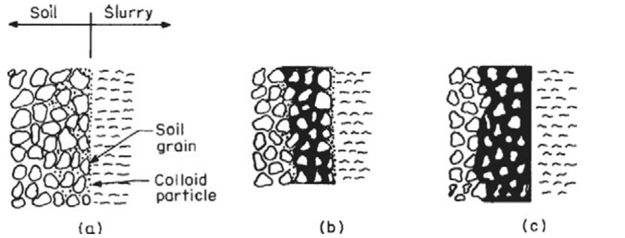

Fig. 1. Cake formation on slurry wall. (a) Penetration of bentonite slurry into soil formation; (b) formation of filter cake; (c) formation of bentonite cake (after Xanthakos, 1979).

performance to control lateral spreading of ground water. The equivalent hydraulic conductivity of a combination of the slurry wall and bentonite cake is therefore crucial to assess the in situ hydraulic performance of the slurry wall construction. US ACE (2010) also suggested that the actual hydraulic conductivity of the slurry wall is dependent on both the bentonite cake formed on the sides of the wall and the soil–bentonite backfill. The contributions of both components are dependent on the hydraulic conductivity and thickness of the two components. For design purposes, however, US ACE (2010) recommended that the hydraulic conductivity of the slurry wall be based only on the soil–bentonite backfill. In addition, Choi and Daniel (2006) and Nguyen et al. (2010, 2011, 2013) suggested using the slug test with consideration of bentonite cake to evaluate the in situ hydraulic conductivities of vertical cutoff walls.

While the hydraulic conductivities of the backfill material can be measured in the laboratory with samples taken directly from the field, it is almost unfeasible to collect the bentonite cake samples from the field for the permeability test. Therefore, there is an apparent concern about measuring the hydraulic conductivity of the bentonite cake that is formed on the excavation surface in a slurry trench wall, in the laboratory. The Chung and Daniel (2008) method seems to be a reliable approach to measure the hydraulic conductivity of the bentonite cake. Chung and Daniel (2008) developed the modified fluid loss test based on the filtration theory to estimate the hydraulic conductivity of bentonite cake. The rate of filtrate flow and water content of the bentonite cake are measured and analyzed to calculate the hydraulic conductivity of the bentonite cake. The modified fluid loss test allows an evaluation of hydraulic conductivity of bentonite cake deposited on a filter paper from bentonite slurry in the applied pressure range of from 69 kPa to 690 kPa.

As a development for the modified fluid loss test, in this study, the filter paper is replaced with a layer of real soil medium (i.e., Korean standard sand, also known as Joomoonjin standard sand) in order to resemble the in-situ condition to form bentonite cake. The hydraulic conductivity of the bentonite cake deposited on the sand is then estimated employing the Ruth (1935) method. The Ruth (1935) method, which has been popularly used in the filtration industry, takes into account the filter medium resistance (i.e., in this case, the filter medium is the layer of Korean standard sand) that is disregarded in the Chung and Daniel (2008) method in describing the filtration process. The obtained values are compared with those of the bentonite cake deposited on filter paper, which were reported in Nguyen et al. (2012). The modified fluid loss test (Chung and Daniel, 2008) used with a layer of Korean standard sand provides an approach to measure the hydraulic conductivity of the bentonite cake and filter cake, which, in turn, facilitates the estimation of the actual hydraulic conductivity of the entire slurry wall construction.

2. Test setup, procedure, and materials

The modified fluid loss test conforms to the procedure described in ASTM D5891 (2002) except for the filtrate measuring interval and applied overall pressure. In this experiment, the authors used the pressures of 70, 140, 210, 350, 480, and 690 kPa. Fig. 2 shows the schematic of the main part of the fluid loss test equipment. In the modified fluid loss test, 5 or 6 filtrate volumes are measured within a certain period of time (typically 2 h in this study). After collecting the filtrate volumes, the bentonite cake is carefully detached from the surface of the sand layer to measure water content after removing the slurry suspension at the top of the cake. The average void ratio of the bentonite cake is calculated from the measured water content and the specific gravity of bentonite solids with the assumption of complete saturation. The filtrate–time relation and the void ratio of bentonite cake are then used to calculate its hydraulic conductivity.

The bentonites used in this experiment were Tixoton, and Bentonil GTC4 from Sud-Chemie Korea Co., Ltd. They are the typical types of bentonites used for stabilizing the excavation surface (Sud-Chemie website, 2011). Tixoton and Bentonil GTC4 are pre-treated bentonites or polymer bearing bentonites (i.e., bentonites contain carboxymethyl cellulose (CMC)) according to the supplier's report. Tixoton and Bentonil GTC4 contain 0.2% and 0.3% CMC by weight, respectively. X-ray diffraction (XRD) patterns of Tixoton and Bentonil GTC4 were obtained with a Rigaku Geigerflex 2301 diffractometer using Cu-Kα radiation at 30 kV and 15 mA using a Ni-filter. The scan speed was fixed to be 2°2θ/min for range from 2 to 40°. The mineral compositions were quantified using Siroquant version 2.5. The XRD analyses indicate similar montmorillonite contents of 85.0% for Tixoton and 83.0% for Bentonil GTC4 as shown in Table 1. Conforming to ASTM D5890 (2006), the swell indexes (mL/2 g) are measured to be 26.3 for Tixoton and 27.5 for Bentonil GTC4. Cation exchange capacities (CECs) of the bentonites were determined using the methylene blue (MB) spot test method (ASTM C837, 2009). The CECs are measured to be 75 for Tixoton and 78 for Bentonil GTC4. The bentonite contents of the slurries considered in this experiment are 4, 6, and 8% by weight, which are commonly applied in construction practice.

The sand used in this study is Korean standard sand taken from Joomoonjin, Korea. The particle size distribution of the sand is shown in Fig. 3. The Korean standard sand is placed in the filter press cell using a rodding and tapping procedure. The relative density of the sand is in the range of 60 to 70%. The thickness of the sand layer in the filter press cell is 5 cm. The sand layer is saturated by slowly percolating water up from the bottom of the cell. The slurry is then poured into the cell using a deflector to avoid disturbing the sand. The D_{15} size of the Korean standard sand is 0.32 mm which is in the range reported by Sherard et al. (1984) and Henry et al. (1998) as the particle size of filter medium satisfying the filtering criterion.

3. Method of calculation

The mathematical descriptions of the bentonite cake formation are summarized and presented in Rushton et al. (2000). The phenomena

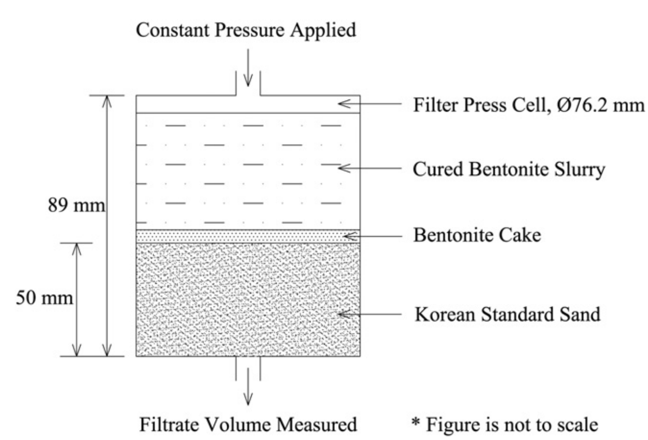

Fig. 2. Schematic of fluid loss test with Korean standard sand.