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HYDRAULIC CHARACTERISTICS OF BENTONITE CAKE FABRICATED ON CUTOFF WALLS

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Abstract—Bentonite cake is usually formed on the excavated trench surface that is supported by the bentonite slurry during construction of slurry cutoff walls. The lower hydraulic conductivity of bentonite cakes formed during construction of slurry cutoff walls in comparison to backfill materials provides an additional benefit. In the present study, the hydraulic conductivities of bentonite cakes made using three different bentonites were estimated using the modified fluid-loss test under various pressures. Both the hydraulic conductivities of bentonite cakes and cutoff-wall backfill are important in evaluating the *in situ* hydraulic performance of slurry cutoff-wall construction. Three bentonite slurry concentrations of 4, 6, and 8% were used to fabricate bentonite cakes that represent common field conditions. X-ray diffraction, cation exchange capacity, and swell-index data were collected to characterize the bentonites. Two modified methods for analyzing fluid-loss test results were used to estimate bentonite cake hydraulic conductivities. In addition, the viscosity as a function of time was measured to explain the sealing capacities of the bentonite slurries. The bentonite-cake hydraulic conductivities ranged from 2.15×10^{-11} m/s to 2.88×10^{-10} m/s, which were 10 to 500 times lower than the cutoff wall backfill design. Experimental results for 4 and 6% bentonite slurries were relatively similar, but the 8% slurries were noticeably different. Calculated bentonite-cake thickness and stress distribution indicated that the local void ratio and hydraulic conductivity may vary across the cake thickness. The considerably lower bentonite-cake hydraulic conductivities compared to the cutoff wall backfill design show its significance in slurry cutoff-wall construction practices.

Key Words—Bentonite Cake, Bentonite Slurry, Cutoff Wall, Hydraulic Conductivity, Modified Fluid-loss Test, Viscosity.

INTRODUCTION

Bentonite slurries have been used to prevent the collapse of trenches, which are excavated for vertical cutoff walls. The stability of trench excavation is maintained by lateral pressure exerted by the slurry. The formation of a bentonite cake during the construction of vertical cutoff walls was observed and reported by Xanthakos (1979), Filz *et al.* (1997), Henry *et al.* (1998), Britton *et al.* (2004), and Soroush and Soroush (2005). Bentonite slurry penetrates into the soil cutoff wall due to the potential difference between slurry water and soil pore water. If the void spaces in the soil are sufficiently small compared to slurry particles, a bentonite cake will be formed by bentonite particles retained on the excavation surface. On the other hand, if the soil particles are coarse, the suspended silt and fine particles in the slurry may be retained within the soil matrix and the bentonite cake will form on the layer of retained silt and fine particles (Xanthakos, 1979; Filz *et al.*, 1997).

The bentonite cake plays an important role in stabilizing excavation surfaces (Xanthakos, 1979; Filz *et al.*, 1997; Henry *et al.*, 1998). The location and low hydraulic conductivity of the bentonite cake have a significant influence on the overall hydraulic performance of the vertical cutoff wall. Controlling lateral groundwater spread using less permeable bentonite-cake layers could enhance cutoff-wall performance. Bentonite cake is a relatively impervious membrane which alters the boundary condition at the cutoff wall. Choi and Daniel (2006b) and Nguyen *et al.* (2010a, 2010b) recommended bentonite cake for evaluation of *in situ* hydraulic conductivities of vertical cutoff walls.

The US ACE (2010) suggested that the actual hydraulic conductivity of the slurry wall depends on both the bentonite cake formed on the sides of the wall and the soil-bentonite backfill. The contributions of both components depend on the hydraulic conductivity and thickness of the two components. For conservative design purposes, however, the US ACE (2010) recommended that the hydraulic conductivity of the slurry wall be based on the soil-bentonite backfill only. The equivalent hydraulic conductivity of the cutoff wall and bentonite cake combination is, therefore, crucial in assessing the hydraulic performance of cutoff wall construction. The equivalent hydraulic conductivity of the combination can be calculated from the separate hydraulic conductivities of backfill material and bentonite cake. The separate hydraulic conductivities of

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backfill material and bentonite cake can be measured directly in the laboratory. Typically, the designed hydraulic conductivity of a cutoff-wall backfill is either 1×10^{-8} or 1×10^{-9} m/s depending on regulations.

The laboratory-measured hydraulic conductivity of bentonite cake might differ from conductivity values measured in the bentonite cake formed on a vertical cutoff wall excavation surface. A fluid-loss test is conducted to evaluate the fluid-loss properties of a clay layer deposited on a filter paper at a particular applied pressure. The bentonite-cake hydraulic conductivity can then be determined using a fluid-loss measurement (ASTM D 5891, 2002). The fluid-loss test was modified from the API (American Petroleum Institute) RP 13B-1 (1990) method.

Several research studies have developed methods to evaluate hydraulic conductivity from API filter-press test results (Barvenik and Ayres, 1987; Grube, 1992; Heslin *et al.*, 1997; Henry *et al.*, 1998; Filz *et al.*, 2001). These methods have either test-procedure complexities or calculation limitations. Among these methods, the Filz *et al.* (2001) method requires dry-bentonite layer placement in a filter-press cell which may result in large variations in bentonite thickness and the method takes 24 to 48 h to obtain test results. The Henry *et al.* (1998) method was based on the Nash (1974) formula for bentonite-cake formation in a slurry trench and is as follows:

$$k_c = \frac{\gamma_w (1 - n_s) V^2}{2 t p_0 A^2 (n_s - n_c)} \qquad (1)$$

where k_c = hydraulic conductivity of bentonite cake, γ_w = unit weight of water, n_s = porosity of slurry, V = volume of filtrate flow over time t, p_0 = vertical stress applied to slurry, A = cross-sectional area of bentonite cake, and n_c = porosity of bentonite cake. The drawback of the Henry *et al.* (1998) method is that the slurry porosity should be estimated from measuring the water content of slurry, which can result in a large variation in the calculated hydraulic conductivity (Chung, 2004; Chung and Daniel, 2008).

The modified fluid-loss test developed by Chung and Daniel (2008) seems to be a reliable method to evaluate the hydraulic conductivity of the bentonite cake. This method is based on the cake-filtration theory (Rushton *et al.*, 2000). However, the Chung and Daniel (2008) method ignored the filter-medium resistance, which prevents a precise description of the filtration process. In the present study, the Ruth (1935) approach, which has been used widely in the filtration industry, is also applied to calculate the hydraulic conductivity of a bentonite cake. The Ruth (1935) method takes into account the filter-medium resistance that is disregarded in the Chung and Daniel (2008) method. Therefore, the modified fluid-loss test (Chung and Daniel, 2008), combined with the Ruth (1935) approach, provides a more reliable approach to characterize the hydraulic property of the bentonite cake, which, in turn, facilitates the estimation of actual hydraulic conductivity of the slurry-wall construction along with a measure of the hydraulic conductivity of soil-bentonite backfill. Estimation of bentonite-cake hydraulic conductivity provides an insight into the bentonite-cake effect during slurry-wall construction.

MATERIALS AND METHODS

Materials

The Tixoton, Bentonil GTC4, and DY-100S bentonites, which are typical bentonites used to stabilize excavation surfaces, were used in this study. The Tixoton and Bentonil GTC4 bentonites were obtained from Sud-Chemie® Korea Co., and the DY-100S bentonite was provided by Dong Yang® Bentonite Industry Co. According to Sud-Chemie®, Bentonil GTC4 and Tixoton are used widely in applications of support and stabilization of trenches (http://www.sud-chemie.com/scmcms/web/page_en_6199.htm). DY-100S is used widely in South Korea for applications such as stabilization of trenches, soil sealing, drilling, *etc.* In addition, these bentonites have been used throughout South Korea for stabilization of trenches and soil sealing in many construction sites. Tixoton and Bentonil GTC4 bentonites are carboxymethyl cellulose (CMC) polymer-treated bentonites. The DY-100S bentonite was not treated with polymer. Tixoton and Bentonil GTC4 contain 0.2% and 0.3% CMC, respectively. X-ray diffraction (XRD) patterns of the bentonites (Table 1) were obtained with a Rigaku Geigerflex

Table 1. Mineral composition (wt.%) of bentonites, by XRD test analysis.

Mineral composition	Qtz	Pl	K-f	Hbl	Cal	Mnt	Op	Py	Syl
Bentonite type									
Tixoton	1.0	2.2	6.0	–	–	85.0	3.3	–	2.5
Bentonil-GTC4	2.0	5.3	6.0	1.5	0.4	83.0	0.5	0.2	1.1
DY-100S	4.4	18.7	–	–	3.4	62.9	0.6	3.3	6.7

* Qtz: Quartz, Pl: Plagioclase, K-f: K-feldspar, Hbl: Hornblende, Cal: Calcite, Mnt: Montmorillonite, Op: Opal, Py: Pyrite, Syl: Sylvite.

2301 diffractometer using CuKα radiation at 30 kV and 15 mA with a Ni-filter. The scan speed was 2º2θ/min for the range 2–40º2θ. The mineral compositions were quantified using *Siroquant* version 2.5. The XRD analyses indicated similar montmorillonite contents of 85.0% for Tixoton and 83.0% for Bentonil GTC4, both greater than the 62.9% content of DY-100S (Table 1). The larger montmorillonite content suggested that Tixoton and Bentonil GTC4 would have a greater swelling potential and thus better sealing capacities than DY-100S. The bentonite cation exchange capacities (CECs) (Table 2) were determined using the methylene blue (MB) spot test method (ASTM C837, 2009). During the course of the MB spot test, the bentonite slurry was prepared by mixing 2 g of dried bentonite with 300 mL of distilled water and stirred until the slurry was uniformly dispersed. The pH of the slurry was fixed in the range between 2.5 to 3.8 by adding sulfuric acid. Five ml of the MB solution was added to the slurry, and the mixture was stirred for 1 to 2 min. A drop of the mixture was placed on the edge of the filter paper. The end point is indicated by the formation of a light blue halo around the drop. The addition of MB solution to the mixture was continued in 1.0 mL increments with 1 to 2 min of stirring after each addition, then testing, until the end point was reached. After the end point was reached, the mixture was stirred for 2 min and retested. The MB index (*i.e.* CEC) was calculated as follows:

$$MBI = \frac{E \times V}{W} \times 100 \tag{2}$$

where: MBI = methylene blue index for the clay (meq/100 g clay), E = MB concentration (meq/mL), V = volume of methylene blue solution required for the titration (mL), and W = mass of dry material (g).

Swell indexes (Table 2) were determined using the ASTM method D5890 (2006). To perform these tests, a 2 g sample of dried and finely ground bentonite clay was dispersed into a 100 mL graduated cylinder in 0.1 g increments. A minimum 10 min interval was required between each 0.1 g of bentonite to allow the clay particles to hydrate fully from the bottom of the cylinder. These steps were repeated until the entire 2 g sample had been added to the cylinder. The sample was then covered and protected from disturbances for a period of 16–24 h, at which time the level of the settled and swollen clay was recorded to the nearest 0.5 mL. The swell index values were consistent with the estimated montmorillonite contents in that DY-100S with the smallest montmorillonite content had the smallest swell index. Slurry bentonite contents of 4, 6, and 8% by weight, which are values commonly used in construction practice, were used in this study.

Table 2. CEC and swell-index test results.

Bentonite sample	Tixoton	Bentonil-GTC4	DY-100S
CEC (meq/100 g)	75	78	64
Swell index (mL/2 g)	26.3	27.5	23.8

Modified fluid-loss test procedure

As discussed previously, the conventional fluid-loss test (ASTM D5891, 2002; API RP 13B-1, 1990) was inappropriate for estimating the hydraulic conductivity of a saturated bentonite cake (Chung, 2004; Chung and Daniel, 2008). Improvements have been made in order to evaluate reliably the hydraulic conductivity of bentonite cake using the API filter-press test as an aid (Henry *et al.*, 1998; Filz *et al.*, 2001; Chung, 2004; Chung and Daniel, 2008). Among those methods, the Chung and Daniel (2008) method is one of the most reliable approaches for measuring bentonite-cake hydraulic conductivity. Those authors developed a modified fluid-loss test based on filtration theory to estimate bentonite-cake hydraulic conductivity. Filtrate flow rates and bentonite-cake water contents were measured and analyzed to calculate the hydraulic conductivity and void ratio profile. A modified fluid-loss test of a bentonite cake deposited from a slurry onto filter paper allowed estimation of the hydraulic conductivity. The modified fluid-loss test followed rigorously the procedure described by ASTM D5891 (2002) except for filtrate-measurement intervals and overall applied pressures.

Chung and Daniel (2008) applied pressures of 69, 139, 207, 345, 483, and 690 kPa, but in the present study, pressures of 70, 140, 210, 350, 480, and 690 kPa were used. These are typical pressures that occur during the formation of bentonite cake. In the modified fluid-loss test (Figure 1), five or six filtrate volumes were measured within a certain time period, typically 1 h. The pressure inside the cell must be kept constant. After collection of the filtrate, the bentonite cake was detached carefully from the filter paper to measure water content after removal of the slurry suspension at the top of the cake. The average void ratio of fully saturated bentonite cake was calculated from the measured water content and the specific gravity of the solids. The relations between filtration time and bentonite-cake void ratio were used to calculate the hydraulic conductivity.

Viscosity of various bentonite concentration slurries

Bentonite slurries are usually thixotropic, non-Newtonian fluids, which means that the slurries coagulate when undisturbed and return to the liquid state when agitated. This process can be repeated over and over. In this study, bentonite slurry thixotropy was characterized by measuring slurry viscosity. After curing for 16 h, the bentonite slurries were stirred in a mixer for 5 min to simulate ready-to-use slurries in the field. The bentonite slurry viscosities at 25ºC were then measured continuously using an A & D® SV-10 sine-wave vibro

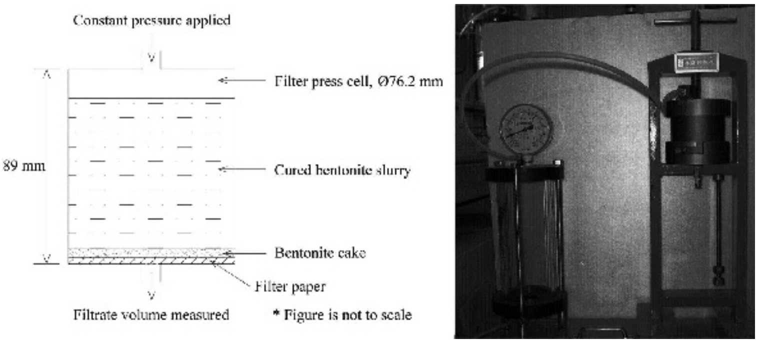

Figure 1. Fluid-loss test equipment. Ø = diameter.

viscometer (A & D Company, Ltd., Tokyo, Japan) for 6 h. The DY-100S bentonite has a plagioclase content of 18.7%, which is the highest among the three bentonites and this may hinder sensor vibration of the A & D® SV-10 sine-wave vibro viscometer due to larger friction. Thus, the viscosity of DY-100S slurry can be greater than the other bentonites even though the montmorillonite content is lowest. Bentonite slurry viscosity generally increased with increased slurry concentration. The viscosities ranged from 0.13 to 0.67 Poise for 4% slurries, 0.67 to 2.27 Poise for 6% slurries, and 1.84 to 9.05 Poise for 8% slurries. The Tixoton slurry viscosity generally increased with time, but the Bentonil GTC4 slurry viscosity remained almost unchanged after a slight initial increase. The DY-100S slurry clearly showed a minimum viscosity at a certain time (Figure 2), which can be attributed to the fact that it was not polymer-treated. The polymer-treated bentonites can form inter-particle bonds between the polymer and clay particles (Heller and Keren, 2002). The CMC polymer is a viscosity modifier that can increase clay-suspension viscosity (Xanthakos, 1979; Caenn and Chilligar, 1996; Heller and Keren, 2002; Akther *et al.* 2007, 2008).

APPLICATION OF FILTRATION THEORY

The modified fluid-loss test can reproduce bentonite cake-formation practices in vertical cutoff-wall construction. The test slurry that was used is the same type as used in construction. The test applied pressures corresponding to the possible pressures exerted during bentonite-cake formation in a vertical cutoff wall. Based on the phenomena that occur during bentonite cake formation, mathematical descriptions of bentonite cake formation can be derived using cake filtration theory (Rushton *et al.*, 2000). Cake filtration theory is based on fundamental relationships between the pressure drop and the flow rate of fluid passing through filter media (Darcy, 1856). The pressure drop is directly proportional to the fluid-flow rate. Filtration in a bentonite cake occurs by bridging over surface pores within filter media (*i.e.* cloth, septum, soil, or filter paper). The bridging particles prevent clogging of the medium with fine particles. However, fine particles could migrate into the filter medium pores before bridging occurs. In this case,

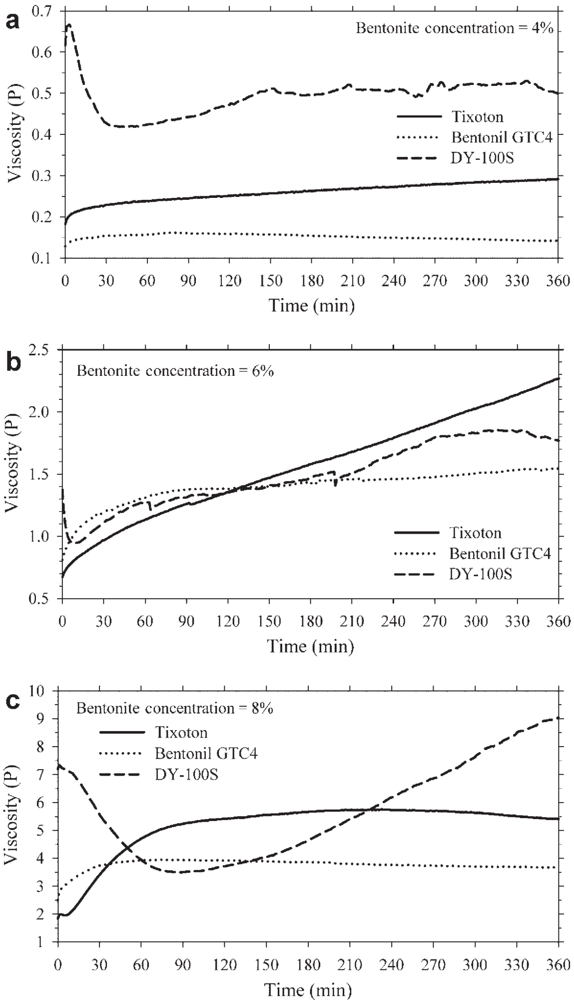

Figure 2. Viscosity-time relations beteween Tixoton, Bentonil GTC4, and DY-100S bentonite slurries for (a) 4%, (b) 6%, and (c) 8% concentration slurry at 25°C

the filter medium permeability is impaired and the pressure drop across the filter medium becomes significant (Beeson and Wright, 1952; Krueger and Vogel, 1954; Darley and Gray, 1988). The cake-filtration equation was presented by Rushton *et al.* (2000) as follows:

$$\frac{dV}{dt} = \frac{A^2 p_0}{\mu c V \alpha} \tag{3}$$

where V = filtrate volume, t = filtration time, A = filtering area, p_0 = pressure drop (= air pressure + hydraulic pressure = applied overall pressure), μ = liquid viscosity, c = mass of a dry bentonite cake deposited per unit volume of filtrate, and α = specific resistance of the bentonite cake. For the compressible cake filtration, the mass of a dry bentonite cake deposited per unit volume of filtrate, c, is expressed as follows:

$$c = \frac{s\rho}{1 - sm} \tag{4}$$

where s = mass fraction of solids in the slurry feed, ρ = liquid density, and m = cake moisture ratio. The cake moisture ratio, m, is expressed as follows:

$$m = \frac{\text{Mass of wet cake}}{\text{Mass of dry cake}} = 1 + \frac{(1 - C)}{C}\frac{\rho}{\rho_s} \tag{5}$$

where C = cake volume fraction concentration ($C = 1 - n$, n = porosity of the bentonite cake) and ρ_s = solid density.

The specific resistance, α, is defined as follows:

$$\alpha = \frac{1}{kC\rho_s} \tag{6}$$

where k = intrinsic permeability of the bentonite cake. The specific resistance is proportional to the reciprocal of the intrinsic permeability. For the bentonite cake, the hydraulic conductivity, k_c, can be calculated from the intrinsic permeability as follows:

$$k_c = \frac{k\gamma_w}{\mu} \tag{7}$$

In equation 3, the pressure drop is the summation of pressure drops through both the filter medium and the bentonite cake. Applying Darcy's law, the general cake-filtration equation was obtained as follows:

$$p_0 = \frac{\mu c \alpha V}{A^2}\frac{dV}{dt} + \frac{\mu R_m}{A}\frac{dV}{dt} \tag{8}$$

where $R_m = L_m/k_m$ (L_m = filter medium thickness; k_m = intrinsic permeability of the filter medium). The first term on the right hand side of equation 8 is the pressure drop through the bentonite cake. The second term is the pressure drop through the filter medium.

The modified fluid-loss test (Chung and Daniel, 2008) was conducted under constant pressure throughout the filtration process. Under these conditions, equation 8 can be rearranged and integrated as follows:

$$\int_0^t dt = \frac{\mu c \alpha}{A^2 p_0}\int_0^V V\,dV + \frac{\mu R_m}{A p_0}\int_0^V dV \tag{9}$$

After integration and rearrangement, the following equation, known as the linearized parabolic rate law, is obtained:

$$\frac{t}{V} = \frac{\mu c \alpha}{2A^2 p_0}V + \frac{\mu R_m}{A p_0} \tag{10}$$

From experimental data of t/V *vs.* V, the slope and intercept of equation 10 can be obtained. As suggested by Ruth (1935), the hydraulic conductivity of bentonite cake (or the specific resistance) can be estimated from the slope of the t/V *vs.* V plot. The slope is denoted here as θ (*i.e.* $\theta = \frac{\mu c \alpha}{2A^2 p_0}$). The value of the intercept can be used to estimate the hydraulic conductivity of the filter medium (or the medium resistance). The hydraulic conductivity of the bentonite cake is derived from the slope as follows:

$$k_c = \frac{\gamma_w s \rho}{2A^2 p_0 C \rho_s \left(1 - s\left(1 + \frac{1-C}{C}\frac{\rho}{\rho_s}\right)\right)\theta} \tag{11}$$

In the Chung and Daniel (2008) method, filter medium resistance to filtrate flow was disregarded. This assumption is acceptable if medium resistance is considerably smaller than bentonite-cake resistance. Filter paper is the filter medium in the present experiment. However, in practice, filter-medium permeability can be impaired by fine particle migration into filter medium pores. Therefore, as mentioned above, the pressure drop across the filter medium can become significant. Based on the assumption that the filter medium has no resistance, Chung and Daniel (2008) derived a linear relationship between p_0t/V and V as follows:

$$\frac{\rho_0 t}{V} = \frac{\beta\gamma_w}{2A^2 k_c}V \tag{12}$$

where p_0 = applied overall pressure, and β = ratio of the volume of bentonite cake to the filtrate volume, which is obtained from a mass balance of the solid and liquid entering the filtering system. β is determined as follows:

$$\beta = \frac{s\rho}{(1 - s)C\rho_s - s(1 - C)\rho} \tag{13}$$

From experimental results of p_0t/V *vs.* V, the slope of equation 12 can be obtained and is denoted here as ϕ (*i.e.* $\phi = \frac{\beta\gamma_w}{2A^2 k_c}$). The hydraulic conductivity of the bentonite cake is then calculated as follows:

$$k_c = \frac{\beta\gamma_w}{2A^2\varphi} \tag{14}$$

In the present study, both the Ruth (1935) and Chung and Daniel (2008) methods were adopted to evaluate the hydraulic conductivity of bentonite cake. In addition, Chung and Daniel (2008) also provided the bentonite cake effective stress equation as follows:

$$\sigma'_z = p_0 \left(1 - \frac{z}{L}\right)^{1/(1-\eta)} \tag{15}$$

where σ'_z = effective stress at depth z in the bentonite cake, L = thickness of the bentonite cake, and η = slope of the log k − log p_0 plot, where log p_0 is the abscissa.

In addition, the bentonite-cake thickness can be calculated as follows:

$$L = \frac{\beta V}{A} \tag{16}$$

Equation 16 is based on the linear relationship between cake volume and filtrate volume (Rushton *et al.*, 2000). In addition to direct measurement, bentonite-cake thickness can be estimated indirectly from filtrate volume and the bentonite cake volume to filtrate volume ratio.

RESULTS AND DISCUSSION

Reported hydraulic conductivities of bentonite cake are in the range 3×10^{-11} m/s to 2×10^{-10} m/s (Henry *et al.*, 1998) for applied overall pressures that ranged from 7.9 kPa to 104.9 kPa, respectively. Chung and Daniel (2008) reported a 8.16×10^{-12} m/s to 3.51×10^{-10} m/s range for applied overall pressures that ranged from 69 to 690 kPa, respectively, for Barakade, CG50, and Bentomat ST bentonites. However, all of the studies noted above used only 6% bentonite slurries. In the present study, modified fluid-loss test results were summarized for Tixoton, Bentonil GTC4, and DY-100S bentonites using 4%, 6%, and 8% slurries. The p_0t/V *vs.* V graph using the Chung and Daniel (2008) method and the t/V *vs.* V graph using the Ruth (1935) method for 6% Tixoton at 70, 140, 210, 350, 480, and 690 kPa were constructed (Figure 3a,b). Modified fluid-loss test results were analyzed in the p_0t/V *vs.* V and t/V *vs.* V plots (Figures 4a–c, 5a–c, 6a–c, and 7a–c). The p_0t/V *vs.* V graph (Figure 3a) by the Chung and Daniel (2008) method was assumed to pass through the graph origin. On the other hand, the t/V *vs.* V plot (Figure 3b) intercepted the t/V axis in the Ruth (1935) method. In the Chung and Daniel (2008) method, the p_0t/V graph slope increased when overall pressure was increased. On the contrary, the t/V *vs.* V graph slope in the Ruth (1935) method decreased when overall pressure increased because θ was normalized to the overall applied pressure (p_0). With large overall pressures, negative intercepts were observed in t/V *vs.* V graphs.

The bentonite-cake void ratio tended to decrease when the overall pressure increased (Figure 4a–c). The overall 70 kPa pressure was not large enough to cause any filtrate flow for the 8% slurries. At the same overall pressure, Tixoton bentonite cakes had smaller void ratios than Bentonil GTC4 or DY-100S bentonite cakes for 4%, 6%, and 8% slurries. The bentonite-cake void ratios ranged from 9.0 to 17.0 and decreased with increased slurry concentrations. The DY-100S bentonite-cake void ratio was almost unchanged throughout the overall 140 to 690 kPa pressure range for an 8% slurry. Because DY-100S was not treated with CMC and its montmorillonite content was small, the degree of flocculation of the DY-100S slurry was large The greater the degree of flocculation, the greater the interparticle attractive forces, and thus the more rigid the interparticle structure of bentonite cake and the greater its resistance to pressure (Darley and Gray, 1988). At the slurry concentration of 8%, the degree of flocculation of the DY-100S slurry may be high enough to form a rigid bentonite cake structure that is not deformed under the applied pressures. The slurry concentrations of 4% and 6% may not be high enough to result in a degree of flocculation that can form a rigid bentonite cake structure. Bentonil GTC4 bentonite cakes had void ratios that were sensitive to changes in slurry concentra-

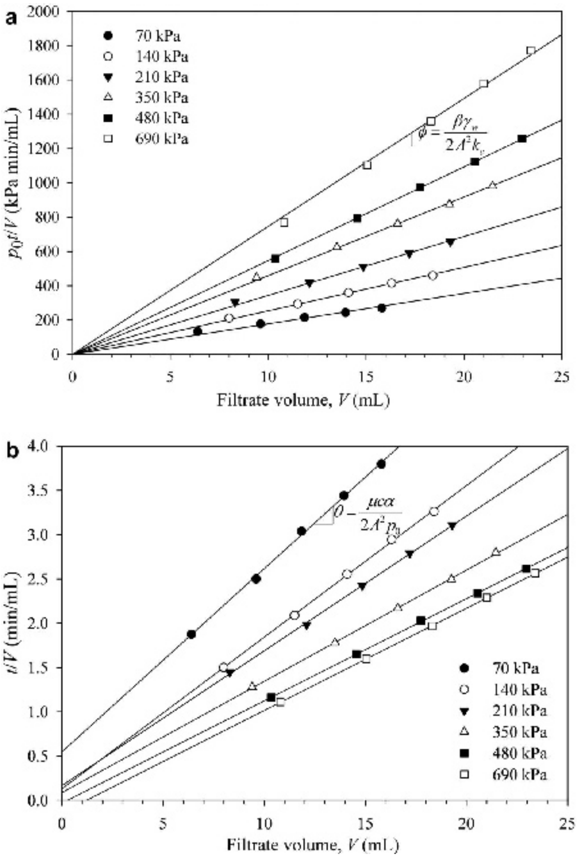

Figure 3. (a) p_0t/V *vs.* V and (b) t/V *vs.* V graphs from a modified fluid-loss test for a 6% concentration slurry of Tixoton.

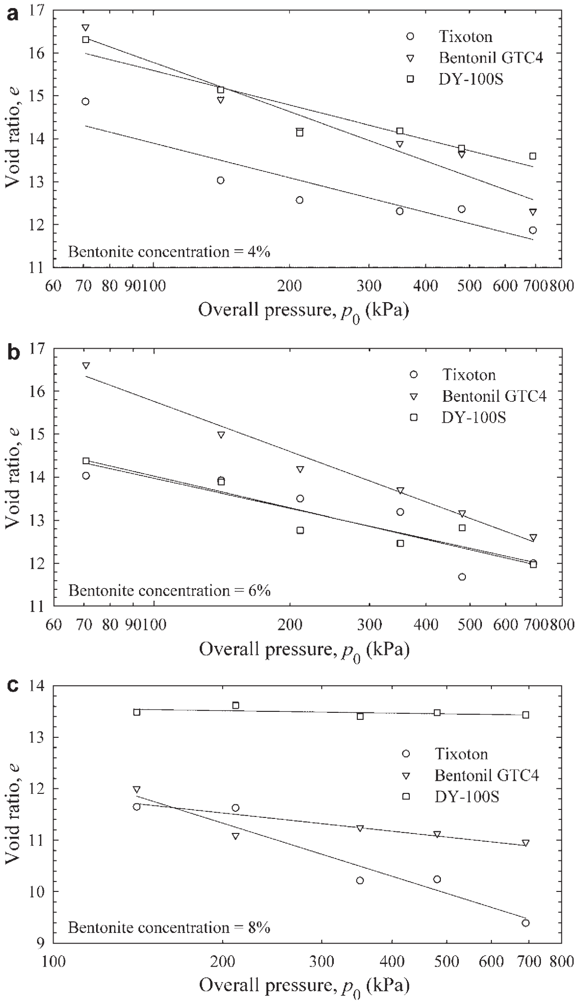

Figure 4. Void ratio-overall pressure relations between Tixoton, Bentonil GTC4, and DY-100S bentonite cakes formed by: (a) 4%, (b) 6%, and (c) 8% concentration slurry

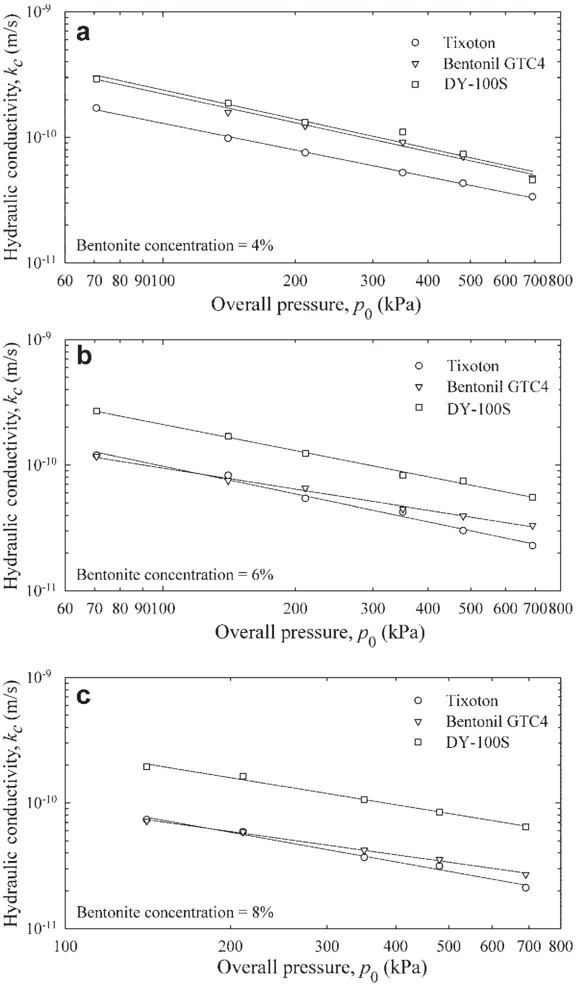

Figure 5. Hydraulic conductivity-overall pressure relations between Tixoton, Bentonil GTC4, and DY-100S bentonite cakes for (a) 4%, (b) 6%, and (c) 8% concentration slurry by the Chung and Daniel (2008) method.

tion. Almost no significant difference was observed in the void ratio/overall pressure relationships for the 4% and 6% Tixoton and Bentonil GTC4 slurries. Because the interface between the slurry and bentonite cake is unclear, great care should be taken in measurements because bentonite-cake void ratio measurements can be susceptible to error. A blower can be used to blow off the remaining slurry on the top surface of the bentonite cake which is the interface between the slurry and bentonite cake during the test.

The relationships between hydraulic conductivity and overall pressure for Tixoton, Bentonil GTC4, and DY-100S bentonite cakes using the Chung and Daniel (2008) method (Figure 5a–c) and the Ruth (1935) method (Figures 6a–c) were very similar. The Chung and Daniel (2008) method overestimated slightly the hydraulic conductivity of bentonite cake because the method does not account for medium resistance. The difference between the two methods was small because the filter-paper medium used in the present study had negligible resistance to filtrate flow. However, if a soil layer were used as filter medium instead of filter paper, the Ruth (1935) method should be used to account for soil-layer resistance to filtrate flow. The bentonite-cake hydraulic conductivity decreased when the overall pressure was increased. In addition, the greater slurry concentration reduced hydraulic conductivity. The bentonite-cake hydraulic conductivities ranged from 2.77×10^{-11} to 2.88×10^{-10} m/s for 4% slurries, 2.15×10^{-11} to 2.57×10^{-10} m/s for 6% slurries, and 2.17×10^{-11} to 2.09×10^{-10} m/s for the 8% slurries. The bentonite-cake hydraulic conductivities in the present study were 10 to 500 times lower than the cutoff wall backfill design, which is typically 1×10^{-8} or 1×10^{-9} m/s depending on regulations. The DY-100S bentonite-cake hydraulic conductivities were highest and almost double that of the Tixoton bentonite cakes throughout the overall

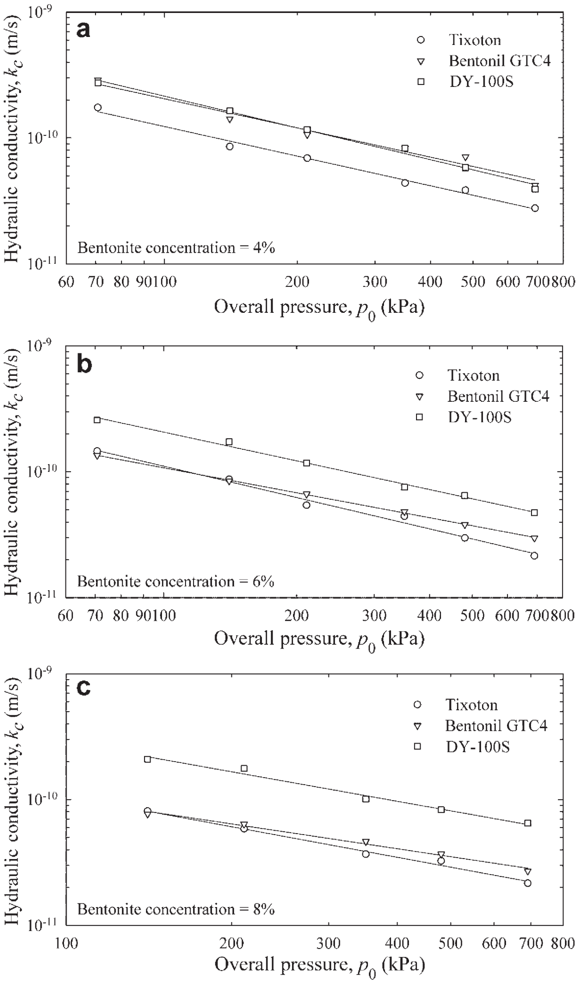

Figure 6. Hydraulic conductivity-overall pressure relations between Tixoton, Bentonil GTC4, and DY-100S bentonite cakes for (a) 4%, (b) 6%, and (c) 8% concentration slurry by the Ruth (1935) method.

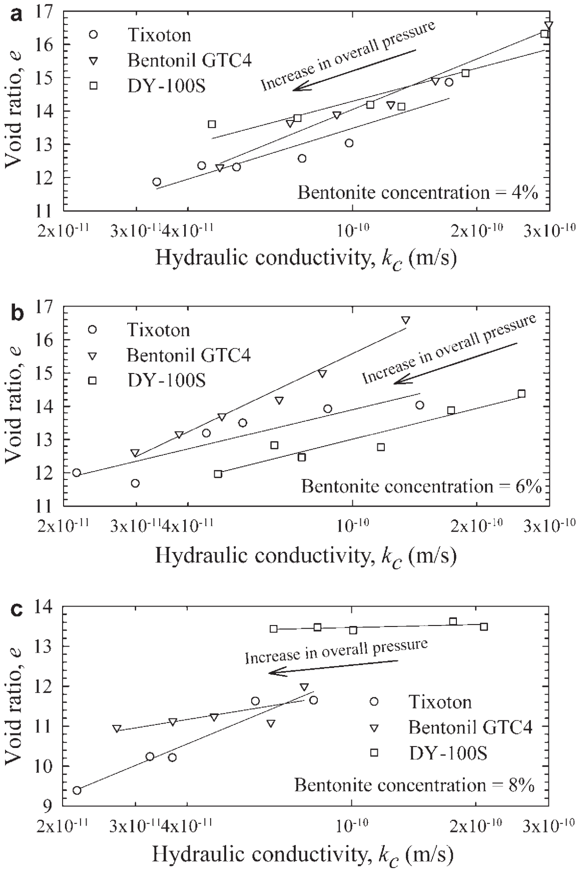

Figure 7. Void ratio-hydraulic conductivity relations of Tixoton, Bentonil GTC4, and DY-100S bentonite cakes for: (a) 4%, (b) 6%, and (c) 8% concentration slurry

pressure range. As discussed above, DY-100S was not treated with CMC, had the smallest montmorillonite content, and the lower sealing capacity resulted in the highest hydraulic conductivity. The hydraulic conductivities of Bentonil GTC4 bentonite cake were affected by slurry-feed solids concentration. The hydraulic conductivities of Bentonil GTC4 bentonite cake were almost equal to that of the DY-100S bentonite cakes for the 4% slurry, but decreased to that of the Tixoton bentonite cake for the 6% and 8% slurries.

Hydraulic conductivity was proportional to the void ratio of the bentonite cake; due to the similarity of the results from the two methods, only the Ruth (1935) method results were plotted (Figure 7a–c). Tixoton, Bentonil GTC4, and DY-100S bentonite-cake hydraulic conductivities had a similar range to values reported in other studies (Henry *et al.*, 1998; Chung and Daniel, 2008). The C_k parameter is defined as follows:

$$C_{\mathrm{k}} = \frac{\Delta e}{\Delta \log k_{\mathrm{c}}} \tag{17}$$

The Tixoton, Bentonil GTC4, and DY-100S bentonite cake C_k (hydraulic conductivity ratio) values were dramatically different for the bentonite 8% slurries (Table 3). In addition, small differences were observed in the void ratio/hydraulic conductivity relationships for the 4% and 6% Tixoton and Bentonil GTC4 slurries. A sharp change in the dispersion/flocculation state also occurs at a certain slurry concentration. The specific concentration was called the cutoff concentration by Hutchinson *et al.* (1974), Xanthakos (1979), and Xanthakos *et al.* (1994). Hutchinson *et al.* (1974) performed conventional fluid-loss tests and found that total fluid-loss was reduced sharply above a cutoff slurry concentration of ~4.5%. Olsta *et al.* (2004) reported no apparent correlation between the bentonite free swell index and hydraulic conductivity.

As mentioned above, the saturated hydraulic conductivity of a porous medium for a specific fluid was calculated from the medium intrinsic permeability, unit

Table 3. Bentonite cake C_k (hydraulic conductivity ratio) values.

Bentonite concentration	4%	6%	8%
Tixoton	3.51	2.97	4.28
Bentonil GTC4	5.01	5.90	1.68
DY-100S	3.12	3.09	0.24

weight, and fluid viscosity. The bentonite-cake intrinsic permeability was affected by applied pressure and bentonite slurry characteristics. From measured bentonite slurry viscosities, Tixoton and Bentonil GTC4 slurries generally coagulated immediately after mixing (*i.e.* viscosity increased during measurement) due to the CMC. The long-chain CMC molecules orient in the applied force or flow direction and impart a pseudo plastic behavior to the system. This characteristic enables CMC to flow toward voids and effectively seal the cake, thus sealing capacity is improved and cake permeability is decreased (Xanthakos, 1979). In contrast, the DY-100S bentonite slurry took a certain time to coagulate after mixing. Viscosity decreased rapidly initially and then increased after a minimum value was reached (Figure 2) because DY-100S was not polymer-treated. The DY-100S slurry fluid loss was greatest and the corresponding DY-100S bentonite-cake hydraulic conductivity was also highest.

As an example, effective stress and hydraulic pressure distributions in Bentonil GTC4 bentonite cakes were calculated (Figure 8) using equation 15 proposed by Chung and Daniel (2008). This effective stress distribution may produce a void ratio variation in the bentonite cake because the cake is very compressible (Filz *et al.*, 2001). The local hydraulic conductivity, therefore, may vary across the cake thickness. However, these distributions do not change with increased bentonite-cake thickness, and hence the average porosity of bentonite cake remains constant with time (Darley and Gray, 1988).

Bentonite-cake thickness generally increased with time; and thickness was calculated using equation 16 and plotted against overall pressure after 1 h filtration and test completion (Figure 9a–c). Tixoton bentonite-cake thickness was smallest and less affected by slurry concentration. The DY-100S bentonite-cake thickness was largest and increased with increased slurry concentration. These results might be explained by the reasoning of Xanthakos (1979) where flocculated slurry (*i.e.* DY-100S) sediments of the same concentration were more voluminous than dispersed slurries because the flocs in a flocculated slurry settled and piled up without breaking and retaining the voids (*i.e.* the floc particles cannot adjust position). Almost no change occurred in the Bentonil GTC4 cake thickness with increases in slurry concentration. Compared to the measured bentonite-cake thickness, the calculated bentonite-cake thickness (Figure 10) using filtrate volume was generally overestimated due to the spurt-loss effect. At the start of a fluid-loss test, a spurt occurs before the proper filtration begins (Darley and Gray, 1988). Therefore, the collected filtrate volume already includes the spurt loss and the calculated bentonite-cake thickness should be overestimated accordingly. Bentonite-cake thicknesses measured and calculated in this study were in good agreement with the 3–5 mm range reported by D'Appolonia (1980) and Britton (2001).

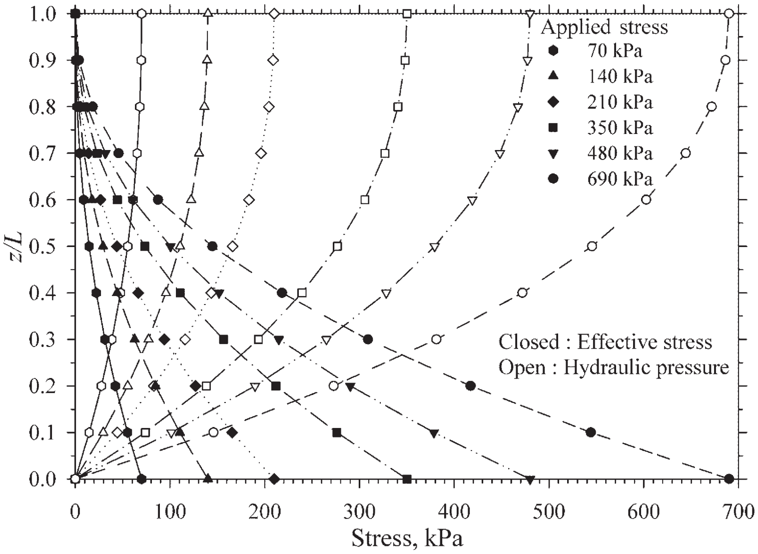

Figure 8. Stress distribution in bentonite cakes formed by 6% Bentonil GTC4 slurry under different overall stresses. z: depth of a certain point in the bentonite cake; L: thickness of the bentonite cake.

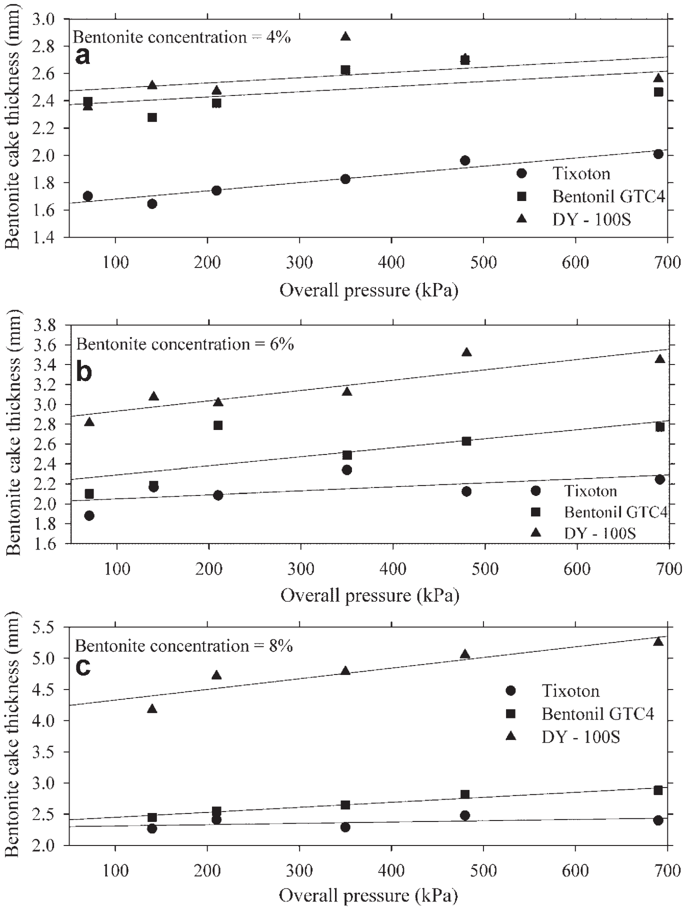

Figure 9. Thickness-overall pressure relations between Tixoton, Bentonil GTC4, and DY-100S bentonite cakes for (a) 4%, (b) 6%, and (c) 8% concentration slurry.

SUMMARY AND CONCLUSIONS

The modified fluid-loss test (Chung and Daniel, 2008) was employed to estimate the hydraulic conductivity of bentonite cakes formed during slurry cutoff wall construction. Polymer (CMC)-treated Tixoton and Bentonil GTC4 bentonites and untreated DY-100S bentonites were examined in the present study. The Ruth (1935) method, which includes filter-medium resistance, was used to estimate hydraulic conductivities for comparison with the Chung and Daniel (2008) method. Viscosities were measured on 4%, 6%, and 8% slurries of the three bentonites and used to evaluate sealing capacity. The findings of this study are summarized as follows:

(1) The Ruth (1935) and Chung and Daniel (2008) method results were almost identical when filter paper was used as the medium because the flow resistance of filter paper is negligible. This shows that the modified fluid-loss test can be used conveniently to estimate bentonite-cake hydraulic conductivities. The Ruth (1935) method should be used to evaluate bentonite-cake hydraulic conductivity if a real filter medium with non-negligible resistance, such as soil, is examined.

(2) The bentonite-cake hydraulic conductivities ranged from 2.15×10^{-11} m/s to 2.88×10^{-10} m/s, which agree with the ranges reported by Henry *et al.* (1998) and Chung and Daniel (2008). The bentonite-cake hydraulic conductivities in this study were 10 to 500 times lower than the cutoff wall backfill design, which is typically either 1×10^{-8} or 1×10^{-9} m/s depending on regulations. The DY-100S bentonite-cake hydraulic conductivities were almost double the Tixoton bentonite-cake hydraulic conductivities throughout the overall pressure range. The Tixoton bentonite-cake hydraulic conductivities were the lowest of the three bentonites.

(3) The viscosity/time relationships for the bentonite slurries can explain the modified fluid-loss test results. Due to the CMC-polymer content, the Tixoton and Bentonil GTC4 slurries generally coagulated immediately after mixing. The untreated DY-100S slurry had a low sealing capacity because coagulation required a longer time after mixing. Therefore, DY-100S slurry

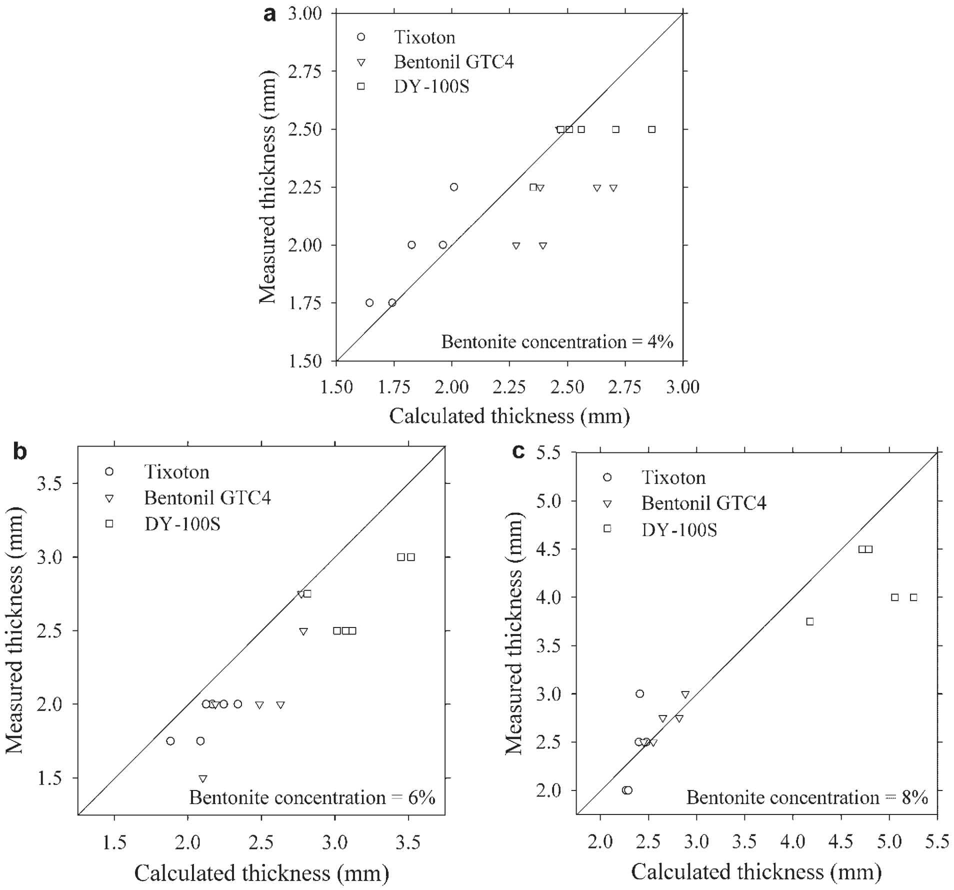

Figure 10. Measured thickness *vs*. calculated thickness of Tixoton, Bentonil GTC4, and DY-100S bentonite cakes for: (a) 4%, (b) 6%, and (c) 8% concentration slurry.

fluid losses were greatest and the corresponding bentonite-cake hydraulic conductivities were also highest, indicating the beneficial effects of CMC on filtration characteristics.

(4) Measured and calculated bentonite-cake thicknesses and stress distributions were similar to values reported by D'Appolonia (1980) and Britton (2001). The DY-100S untreated bentonite-cake thickness was largest. Compared to the measured bentonite-cake thicknesses, the values calculated using collected filtrate volume were overestimated due to the spurt-loss effect. Measured hydraulic conductivities of bentonite cakes and backfill material can be used to calculate the equivalent hydraulic conductivity of cutoff walls for use in cutoff-wall performance evaluations. The hydraulic conductivity, thickness, and porosity of bentonite cake will be needed in future studies for slurry cutoff-wall contaminant-transport analyses.

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