Evaluation of Hydraulic Conductivity of Bentonite Filter Cake Using Modified Fluid Loss Test

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SYNOPSIS: The mixture of bentonite powder and water is generally used to maintain the stability of excavation surface during the construction of vertical cutoff walls. The filter cake on the sidewall surface is the result of filtration of slurry into the adjacent soil formation. The filter cake is believed to have a very low hydraulic conductivity compared to that of the cutoff wall. This paper evaluates hydraulic conductivities of bentonite filter cakes set up with three types of bentonites under various pressure levels. A modified fluid loss test was employed in this experiment. Theory of filtration process was reviewed to explain the procedure in the present experiment. Hydraulic conductivity of the filter cakes with consideration of the filter medium resistance was evaluated. The results of the experiment with two calculation methods and discussion are presented to show the efficiency of the modified fluid loss test.

Key words: hydraulic conductivity, bentonite, filter cake, filtration, cutoff wall, modified fluid loss test.

1. Introduction

Formation of bentonite filter cake during the construction of vertical cutoff walls has been observed and reported by several researchers (Filz et al. 1997, Henry et al. 1998, and Britton et al. 2004). Bentonite-water slurries have been used to effectively maintain the stability of the trench excavations, which are constructed for vertical cutoff walls. The stability of trench excavations is maintained by the lateral pressure exerted by the slurry. Besides, there will be a filtration of slurry into the soil formation due to the difference between the slurry pressure and the pore water pressure. If the void spaces in the soil are small enough, a filter cake will be formed by bentonite particles retained on the excavation surface. On the other hand, if the soil particles are coarser, the suspended silt and fine sand particles in the slurry will be possibly retained in the soil matrix and the filter cake will sequentially be formed on the layer of retained silt and fine sand particles (Filz et al. 1997).

The filter cake plays an important role in stabilizing excavation surfaces with the use of bentonite-water slurries. In addition, the very low hydraulic conductivity and location of the filter cake significantly influence the performance of the cutoff wall. It could enhance the cutoff wall performance to control lateral spreading of ground water with less permeable filter cake layers. The filter cake is believed to be a relatively impervious membrane altering the boundary condition of the cutoff wall unexpectedly.

The equivalent hydraulic conductivity of the combination of cutoff wall and filter cakes can be calculated if the hydraulic conductivities of the backfill material and of filter cake itself are known. This scheme provides a method to estimate the hydraulic conductivity of the complete construction of vertical cutoff wall with consideration of filter cakes. The hydraulic conductivities of the backfill material and of the filter cake can be measured directly in the laboratory.

Therefore, there is a concern of measuring the hydraulic conductivity of the bentonite filter cake, which is formed on the excavation surface in a vertical cutoff wall. A fluid loss test is to evaluate fluid loss properties of a clay mineral layer deposited on a filter paper at a certain applied pressure. Then the hydraulic conductivity of the bentonite filter cake can be obtained from the measurement of fluid loss (ASTM D 5891 - 2002). It should be noted that the fluid loss test is modified from the filter press test specified in API RP 13B-1 (1990).

The modified fluid loss test proposed by Chung (2004) is a reliable method to evaluate the hydraulic conductivity of bentonite filter cake. This method was based on the cake filtration theory that can be found in Rushton et al. (2000). The theory of cake filtration process was reviewed to explain the applicability of the modified fluid loss test. The authors also attempted to perform a calculation of the hydraulic conductivity of bentonite filter cake with consideration of filter medium resistance using Ruth's suggestion (1935).

2. Cake filtration theory

The fluid loss test can reproduce the practical condition of filter cake formation in the construction of vertical cutoff wall. The slurry used in the test is the same type as being used in the construction. The applied pressures in the test correspond to those that are possibly exerted during filter cake formation in a vertical cutoff wall.

Based on the phenomena occurring in the formation of filter cake, mathematical descriptions of the filter cake formation discussed in subsequent sections can be found in Rushton et al. (2000). The cake filtration theory is based on the fundamental relationship between the pressure drop and flow rate of liquid passing through filter media (Darcy 1856). The pressure loss is directly proportional to the flow rate of the fluid. Filtration resulting in a filter cake occurs by a bridging mechanism over the surface pores within a filter medium (cloth, septum or filter paper). This helps to prevent the medium from clogging with fine particles. Neglecting the resistance of filter medium (in this study, the filter medium is the filter paper), the mathematical description begins with the relationship between the filtrate flow rate and pressure drop as follows:

$$\frac{\Delta P}{L} = \frac{\mu}{kA}\frac{dV}{dt} \tag{1}$$

where ΔP = pressure drop = air pressure + hydraulic pressure = applied overall pressure

L = thickness of the filter cake

μ = liquid viscosity

k = intrinsic permeability of the filter cake

A = filter area

V = filtrate volume

t = filtration time

For the filter cake, the intrinsic permeability can be translated into the hydraulic conductivity (k_c) as follows:

$$k = k_c \frac{\mu}{\gamma_w} \tag{2}$$

where γ_w = unit weight of water

The cake thickness increases due to the deposition of solids at the previously formed filter cake surface. The change in cake thickness is accompanied by changes in the fluid flow rate and pressure differential as filtration time increases. Material displaying constant cake concentration is incompressible and this type of filtration is called incompressible cake filtration. For an incompressible filtration, filter cake volume increases linearly by a constant amount for each unit volume of suspension filtered because the cake concentration remains constant. However, when filtering at a constant pressure, the rate of cake deposition will not be constant because new elements of filter cake increases the total resistance to the passage of filtrate from the new cake layer. The cake thickness at any instant in time is as follows:

$$L = \frac{\beta V}{A} \tag{3}$$

where β = constant of proportionality
V = filtrate volume
A = filter area

Substituting Equation (3) into Equation (1), the cake filtration equation becomes:

$$\frac{dV}{dt} = \frac{A^2 \Delta P k}{\beta V \mu} \tag{4}$$

Chung (2004) used the Equation (4) for calculating the hydraulic conductivity of the filter cake in his study. The ratio of the volume of filter cake to the filtrate volume (β) is obtained by means of a mass balance of the solid and liquid entering the filter system.

$$\beta = \frac{s\rho}{(1-s)C\rho_s - s(1-C)\rho} \tag{5}$$

where s = mass fraction of solids in the slurry (around 6% for the bentonite slurries in this study)
ρ = liquid density
C = cake volume fraction concentration (C = 1 n, n = porosity of the filter cake)
ρ_s = solid density

For convenience, a specific resistance (α) is established to combine the cake' s intrinsic permeability, cake volume fraction concentration and solid density, which will all be constants for an incompressible filtration.

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

In addition, a variable to combine the cake thickness, solid density and cake volume fraction concentration is also introduced as follows:

$$w = LC\rho_s \tag{7}$$

w is the mass of dry solids deposited per unit area.

From Equations (6) and (7), the relationship between the thickness and the intrinsic permeability of the filter cake is as follows:

$$\frac{L}{k} = \alpha w \tag{8}$$

Multiplying both the numerator and denominator of Equation (4) by $C\rho_s$ to have:

$$\frac{dV}{dt} = \left(\frac{A}{\beta V C\rho_s}\right)\left(\frac{kC\rho_s}{1}\right)\left(\frac{A\Delta P}{\mu}\right) \tag{9}$$

From $L=\beta V/A$, this gives:

$$\frac{dV}{dt} = \left(\frac{1}{LC\rho_s}\right)\left(\frac{kC\rho_s}{1}\right)\frac{A\Delta P}{\mu} \tag{10}$$

Substituting w and α leads to:

$$\frac{dV}{dt} = \frac{A\Delta P}{\mu w\alpha} \tag{11}$$

The above equation is the differential equation for cake filtration. It should be noted that Equation (11) is another form of cake filtration having the same nature of Equation (4).

If only the cake resistance (R_c) is considered in Darcy' s law, where R_c = L/k:

$$\Delta P = \mu R_c \frac{dV}{dt}\frac{1}{A} \tag{12}$$

then overall resistance to filtration increases due to an increase in the cake thickness.

From the definition of density and some mathematical operations, the concentration by volume fraction is defined as follows:

$$C = \frac{\text{Volume solid in cake}}{\text{Volume solid in cake + Volume liquid in cake}} = \left(1 + \frac{(1-C_w)\rho_s}{C_w\rho}\right)^{-1} \tag{13}$$

Concentration in terms of mass of solids per unit volume of liquid is as follows:

$$C_{wvl} = \frac{\text{Mass solids in slurry}}{\text{Volume liquid in slurry}} = \frac{s\rho}{1-s} \tag{14}$$

It is assumed that w can be obtained from C_{wvl} as follows:

$$w = C_{wvl}\frac{V}{A} \tag{15}$$

However, this ignores the liquid retained in the filter cake. The assumption results in an underestimation of the value of w. The error is small so long as the slurry concentration is low.

For a more rigorous treatment of the dry mass of cake per unit filter area, it is usual to consider the cake moisture ratio (m), which is defined as:

$$m = \frac{\text{Mass of wet cake}}{\text{Mass of dry cake}} = \frac{CAL\rho_s + (1-C)AL\rho}{CAL\rho_s} = 1 + \frac{(1-C)}{C}\frac{\rho}{\rho_s} \tag{16}$$

Therefore, w becomes:

$$w = \frac{\beta VC\rho_s}{A} = \left(\frac{s\rho}{1-sm}\right)\frac{V}{A} \tag{17}$$

If m = 1, Equation (17) reduces to Equation (15). Both equations are of a similar form:

$$w = c\frac{V}{A} \tag{18}$$

where c is either:

$$c = C_{wvl} \tag{19}$$

or:

$$c = \frac{s\rho}{1-sm} \tag{20}$$

The term c is the mass of dry cake deposited per unit volume of filtrate. C_{wvl} and s are the concentration terms of the slurry, and c is constant for incompressible cake filtration. However, it should be kept in mind that the bentonite filter cake is very compressible in reality. Therefore, m is no longer constant and Equation (20) will vary in the case compressible cake filtration. Equation

(18) will be used for further treatment of the variable w. The choice of which equation to be used for c depends on the compressibility of filter cake.

Substituting Equation (18) into Equation (11) yields:

$$\frac{dV}{dt} = \frac{A^2 \Delta P}{\mu c V \alpha} \tag{21}$$

In deriving the above equation, the pressure loss due to the flow of filtrate through the filter medium, which is the filter paper in this study, has been neglected. This assumption can be removed by assuming that the pressure drop in the medium (ΔP_m) can be added to the pressure drop over the filter cake (ΔP_c). The total pressure drop will be expressed as follows:

$$\Delta P = \Delta P_c + \Delta P_m \tag{22}$$

Applying Darcy' s law, the general cake filtration equation is obtained as follows:

$$\Delta P = \frac{\mu c \alpha}{A^2} V \frac{dV}{dt} + \frac{\mu}{A} R_m \frac{dV}{dt} \tag{23}$$

where R_m = L_m/k_m, L_m = filter medium thickness, and k_m = intrinsic permeability of the filter medium.

The modified fluid loss test (Chung 2004) is conducted under the condition of constant pressure throughout the filtration process. Under these conditions, Equation (23) can be rearranged and integrated as follows:

$$\int_0^t dt = \frac{\mu c \alpha}{A^2 \Delta P} \int_0^V V dV + \frac{\mu R_m}{A \Delta P} \int_0^V dV \tag{24}$$

After integration and rearrangement, the following equation, known as the linearized parabolic rate law, results in:

$$\frac{t}{V} = \frac{\mu c \alpha}{2A^2 \Delta P} V + \frac{\mu R_m}{A \Delta P} \tag{25}$$

Equation (25) is a straight line, where t/V is the dependent and V is the independent variable. From experimental data points of t/V against V, the slope and intercept of Equation (25) can be obtained (Ruth 1935). From the obtained slopes, the hydraulic conductivity of bentonite filter cake (or the specific resistance) can be estimated. The value of the intercept can be used for estimating the hydraulic conductivity of the filter medium (or the medium resistance). The hydraulic conductivity of the filter cake is derived from Equation (26) as follows:

$$k_c = \frac{\gamma_w s \rho}{2A^2 \Delta P C \rho_s \left(1 - s\left(1 + \frac{1-C}{C}\frac{\rho}{\rho_s}\right)\right) \times (\text{Value of obtained slope})} \tag{26}$$

In Chung' s method, the resistance of the filter medium to the flow of filtrate was neglected. However, this can be acceptable if the medium resistance is considerably small compared to that of the filter cake. In this paper, the authors used both the methods proposed by Ruth (1935) and Chung (2004) to evaluate the hydraulic conductivity of bentonite filter cakes.

3. Test setup and procedure

The free swell test (ASTM D5890-1995) and conventional fluid loss test (ASTM D5891-2002, API RP 13B-1-1990) are not reliable to estimate the hydraulic conductivity of saturated bentonite (Chung 2004). Improvements have been made in order to obtain a more reliable value of hydraulic conductivity of bentonite filter cake with the aid of the API filter press test (Henry et al. 1998, Filz et al. 2001, Chung 2004). Henry et al. (1998) used the equation suggested by Nash (1974) to calculate the hydraulic conductivity from the result of the API filter press test. Chung (2004) developed a modified fluid loss test based on the filtration theory to estimate the hydraulic conductivity of bentonite filter cake. The rate of filtrate flow and water content of filter cake are measured and analyzed to calculate the hydraulic conductivity and void ratio of the filter cake. The modified fluid loss test allows an evaluation of hydraulic conductivity of bentonite filter cake deposited on a filter paper more than 6% solids slurry of bentonite in a range of pressures from 69 kPa to 690 kPa. The modified fluid loss test follows rigorously the procedure described in ASTM D5891 except for the filtrate measuring intervals and overall pressure applied.

A ball-milled bentonite sample of 22.5 g is mixed with the 350 mL of liquid solution in a mixer for 20 minutes to form a 6% (by weight) bentonite slurry. The slurry is cured for 16 hours. The cured slurry is then stirred in the mixer for 5 minutes to disperse the suspension before being poured into the filter press cell, which is then pressurized to the desired pressure up to 690 kPa. Tests are performed under the application of different pressures ranging from 69 kPa to 690 kPa. Chung (2004) used the pressures of 69, 138, 207, 345, 483, and 690 kPa. In this experiment, the authors used the pressures of 70, 140, 210, 350, 480, and 690 kPa. These values are the typical values of pressures occurring in the formation of filter cake in practice.

In the modified fluid loss test, 5 or 6 filtrate volumes are measured within a certain period of time (typically one hour). The pressure inside the cell must be maintained constant. The bentonite filter cake is carefully detached from the filter paper to measure water content after removing slurry suspension at the top of the cake. The average void ratio of the filter cake is calculated from the measured water content and the specific gravity of solids with the assumption of complete saturation. The filtrate-time relation and the void ratio of filter cake are used to calculate the hydraulic conductivity of filter cake.

The bentonites used in this experiment were Tixoton and Bentonil GTC4 from Sud-Chemie Korea Co., and DY 100S from DY Bentonite Industry Co. These are the typical types of bentonites for stabilizing the excavation surface.

4. Results and comparison

The hydraulic conductivities of filter cakes were reported to be in the range of $3x10^{-11}$ m/s to $2x10^{-10}$ m/s (Henry et al. 1998) for the formation pressures ranging from 7.9 kPa to 104.9 kPa. In Chung (2004), that range is from $7x10^{-12}$ m/s to $4x10^{-10}$ m/s for the formation pressures ranging from 69 kPa to 690 kPa with three types of bentonites including Barakade, CG50 and Bentomat ST. In this paper, the following figures show the results of the modified fluid loss test performed with three types of bentonites: Tixoton, Bentonil GTC4, and DY 100S.

Figures 1 and 2 show an example of the $p_o t/V$ V graph for Chung's method (p_o is the applied overall pressure, i.e. ΔP in the previous section of cake filtration theory) and t/V V graph for Ruth's method of the bentonite Tixoton under six different pressures. Figures 3 to 6 present the results of the modified fluid loss test after interpreting $p_o t/V$ V and t/V V graphs.

It is noted that the $p_o t/V$ V graph in the Chung's method is assumed to pass through the origin of the graph. On the other hand, the t/V V graph intercepted the axis of t/V in Ruth's method. In the Chung's method, the slope of the $p_o t/V$ V graph increases when the overall pressure increases. On the contrary, the slope of the t/V V graph in Ruth's method decreases when the overall pressure increases in the Ruth's method. With the large overall pressures, negative intercepts can be observed in the t/V V graph. In those cases, the medium resistance (the resistance of filter paper herein) is assumed to be zero since it is too small compared to that of the filter cake.

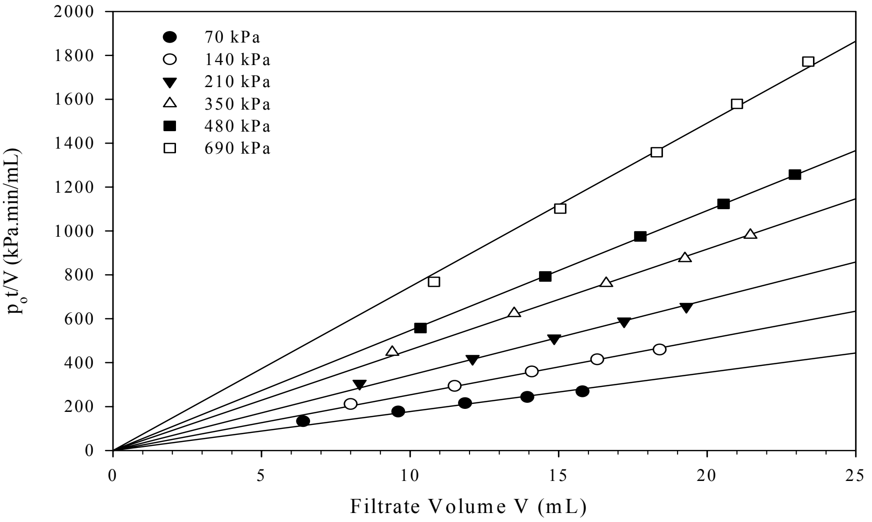

Figure 1. $p_o t/V$ V graph from modified fluid loss test for Tixoton

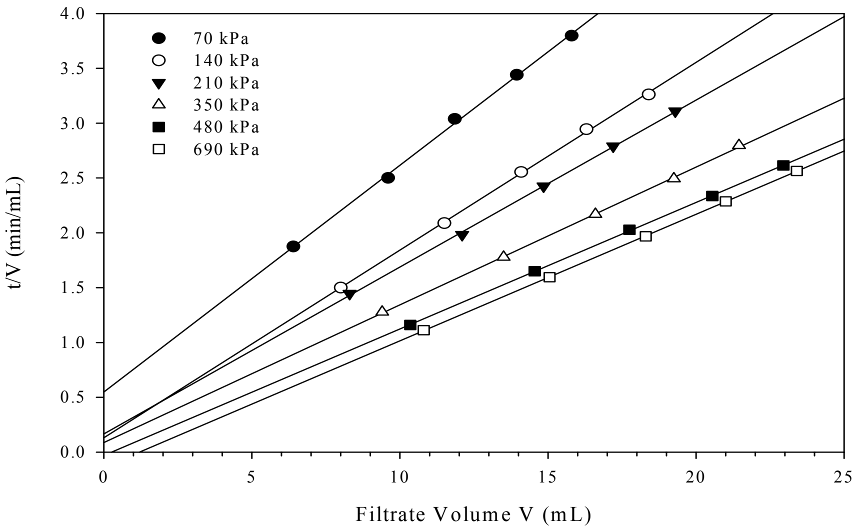

Figure 2. t/V V graph from modified fluid loss test for Tixoton

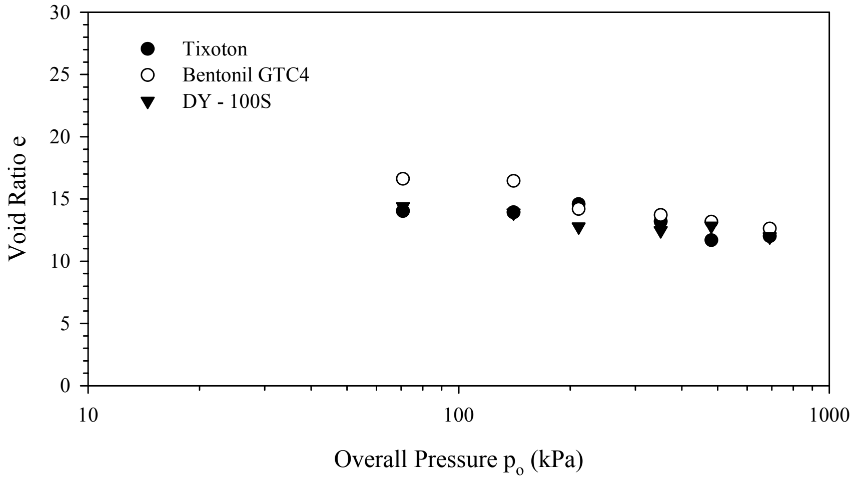

Figure 3. Void ratio overall pressure relation of Tixoton, Bentonil GTC4, and DY 100S

Figure 3 shows that the void ratio of filter cake tends to decrease when the overall pressure increases. At the same overall pressure, the filter cakes of Tixoton and DY 100S have the smaller void ratios than does the filter cake of Bentonil GTC4. It should be noticed that the measurement of void ratio of the filter cake is very susceptible to error because this value is usually large. Therefore, great care should be taken when measuring the void ratio of filter cake.

Figures 4 and 5 show very similar results between Chung's method and Ruth's method even though Chung's method did not consider the medium resistance. This can be explained by the negligible resistance of filter paper to the flow of filtrate. However, if a soil layer is used as a filter medium instead of the filter paper, the Ruth's method should be used to consider the resistance of the soil layer to the filtrate flow. It is easy to observe that the hydraulic conductivity of the filter cake decreases when the overall pressure increases in both methods. Both methods yield a clearly decreasing trend of results of hydraulic conductivities over the range of overall pressures. The hydraulic conductivities of the DY 100S filter cakes are almost double the hydraulic conductivities of the Tixoton filter cakes throughout the range of overall pressures. The hydraulic conductivities of the Bentonil GTC4 filter cakes are slightly higher than those of the Tixoton filter cakes throughout the range of overall pressures.

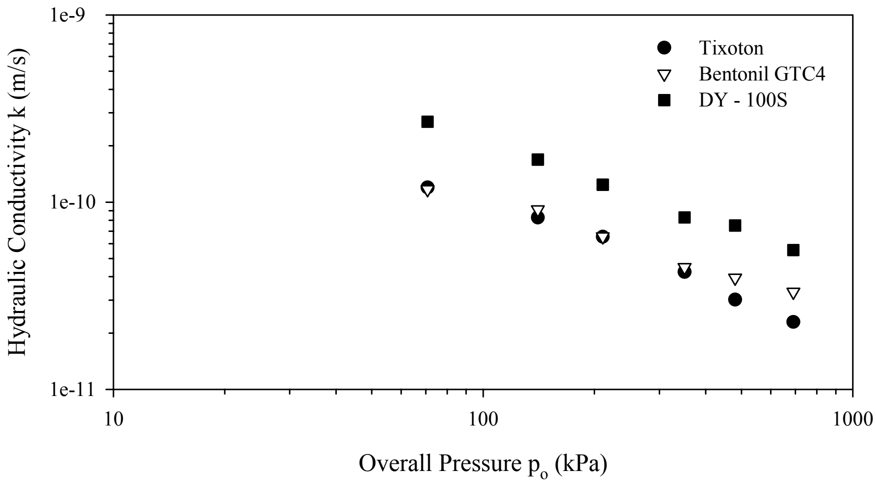

Figure 4. Hydraulic conductivity overall pressure relation
of Tixoton, Bentonil GTC4, and DY 100S by Chung's method

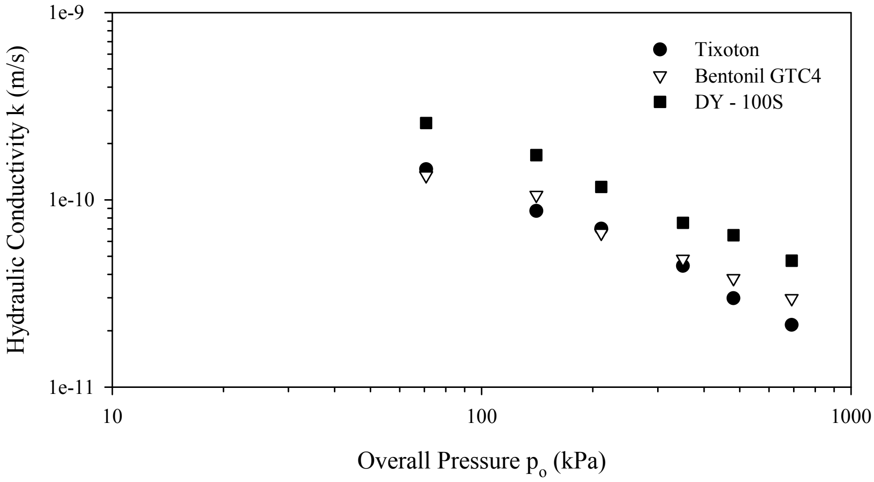

Figure 5. Hydraulic conductivity overall pressure relation of Tixoton, Bentonil GTC4, and DY 100S by Ruth' s method

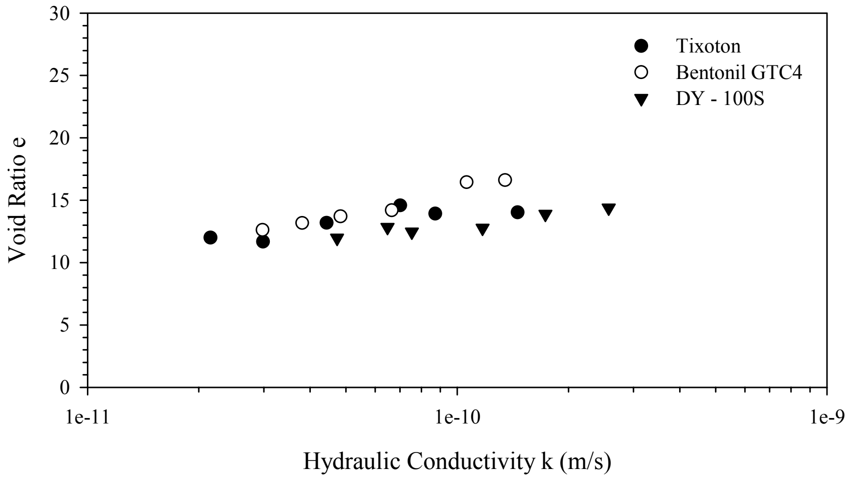

Figure 6. Void ratio - hydraulic conductivity relation of Tixoton, Bentonil GTC4, and DY 100S

Figure 6 shows that the hydraulic conductivity of the fitler cake is proportional to the void ratio of the filter cake. Due to the similarity of the results from the two methods, the result of Ruth' s method was plotted in Figure 6. The hydraulic conductivities of the filter cakes of Tixoton, Bentonil GTC4, and DY 100S are plotted in the similar range reported in other works (Henry et al. 1998 and Chung 2004).

5. Summary and conclusions

The modified fluid loss test (Chung 2004) was employed to estimate the hydraulic conductivity of filter cake. Three types of bentonite, i.e. Tixoton, Bentonil GTC4, and DY 100S, were used in this experiment. The Ruth' s method (1935), which considers the resistance of the filter medium, is used to estimate the hydraulic conductivities along with Chung' s method. The results from the two methods were almost identical in the case of using a filter paper. This shows that the modified fluid loss test can be reliably used for estimating the hydraulic conductivity of filter cake. The range of hydraulic conductivities of the three bentonites is from $2x10^{-11}$ m/s to $2.6x10^{-10}$ m/s. This range is very similar to the ranges reported by Henry et al. (1998) and Chung (2004). The hydraulic conductivities of DY 100S filter cakes are almost double the hydraulic conductivities of Tixoton filter cakes throughout the range of overall pressures. The Tixoton filter cakes have the lowest hydraulic conductivities among three types of bentonite filter cakes. The authors suggest that the Ruth' s method should be used for calculating the hydraulic conductivity of the filter cake if a soil layer is used as a filter medium.

Acknowledgement

The current research was partially supported by Korea Research Foundation Grant No. D00477 and by Small and Medium Business Administration R&D fund.

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