Measurement of Hydraulic Conductivity in Oil Sand Tailings Slurries

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Abstract

Fine tails, the resulting fine waste from oil sand processing, undergoes large strain consolidation in tailings ponds. Its consolidation behavior must be analyzed using a large strain consolidation theory which requires the determination of the relationship between void ratio and hydraulic conductivity. Conventional measurement techniques are not suitable for fine tails and a special slurry consolidometer, with a clamping device to prevent seepage induced consolidation, was designed to determine the hydraulic conductivity of the fine tails and of nonsegregating fine tails - sand slurries.

A phenomena of hydraulic conductivity testing of slurries is that the flow velocity is not constant and decreases with time to a steady state value. Flow velocity, used to calculate hydraulic conductivity, was studied and it was determined that the steady state velocity should be used to estimate the field hydraulic conductivity. Hydraulic conductivity is also influenced by hydraulic gradient and bitumen content. It is shown that a low hydraulic gradient, less than 0.2, is necessary to counteract the effect of the bitumen and to represent tailings pond conditions. The hydraulic conductivity of fine tails - sand mixes is controlled by the fines void ratio, hence, fines content. The hydraulic conductivity of chemically amended nonsegregating tailings can be lower than that of fine tails. However, acid - lime or acid - fly ash amended nonsegregating tailings have similar hydraulic conductivity values in terms of fines void ratio. The hydraulic conductivity of nonsegregating tailings appears to be governed by fines content and by the nature of the fines aggregation caused by the chemical additive.

Key words: tailings, slurries, hydraulic conductivity, slurry consolidometer, nonsegregating tailings, oil sands

Introduction

In mining industries, the resulting waste stream is often in the form of a slurry. In oil sand processing the fine tails, essentially a mixture of fine sand, silt and clay size particles in water with a trace of bitumen, are confined in tailings ponds. To assess the effectiveness and feasibility of long range disposal plans for fine tails, an estimation of the consolidation rates and amounts is necessary. Since fine tails undergo large settlements during consolidation, it is necessary to use a large strain consolidation theory to analyze their consolidation behavior. The large strain consolidation theories are based on the hydraulic conductivity - void ratio relationship and effective stress - void ratio relationship (Gibson et al. 1967).

There are several methods of determining the hydraulic conductivity - void ratio relationship in the laboratory. Hydraulic conductivity of slurries can be determined either directly or indirectly. The direct method involves forcing a permeant through a specimen and monitoring the rate of flow, or the hydraulic head changes induced by it. Indirect methods of determining the hydraulic conductivity are done by inverting a consolidation theory and applying it to the data obtained from a consolidation test. The different testing methods (direct and indirect) are reviewed in this paper. Several problems have been encountered in the hydraulic conductivity measurement of fine tails due to its high water content and bitumen content.

The objective of this study is to establish a method for determining the hydraulic conductivity of fine tails. This paper describes the test apparatus used in this study and the testing procedure. Also discussed are the nature of the fine tails material and the influence of factors affecting the hydraulic conductivity of fine tails and fine tails - sand mixes: flow velocity, hydraulic gradient, fines content and bitumen content. Representative hydraulic conductivities for oil sand fine tails and for nonsegregating fine tails - sand mixes are determined. The factors affecting the hydraulic conductivity of nonsegregating tailings are also discussed.

Indirect methods of determining hydraulic conductivity

There are several kinds of consolidation tests available such as the step loading test, controlled gradient test, constant rate of deformation test, constant rate of loading test (Znidarcic et al. 1984) all of which use the inversion of a consolidation theory to determine the hydraulic conductivity. The most common method of indirectly determining the hydraulic conductivity is by inverting Terzaghi's theory. Olson and Daniel (1981) reported that for this method, the measured to back calculated hydraulic conductivity ratio ranged from 0.9 to 5. Lun and Parkin (1985) gave the possible reasons for such variations as the length of duration of the previous load increment, and the load ratio increment. Tavenas et al. (1983) indicated that the back calculated values underestimated the measured values up to 6 times, attributing such differences to the assumptions of Terzaghi's consolidation theory. The assumptions most often violated are constant hydraulic conductivity and constant compressibility. The study by Tavenas et al. (1983) concluded that indirect methods are unacceptable in determining the hydraulic conductivity of highly compressible natural clays.

Several authors have proposed the indirect measurement of hydraulic conductivity using finite strain consolidation theories (Tan et al. 1988; Znidarcic et al. 1986; Been and Sills 1981). All these studies suffer from the restrictive assumptions made to solve the equations limiting their applicability to problems where linear or constant material properties are a good approximation of real behavior. Therefore, only the direct measurement of hydraulic conductivity has been used in this study.

Direct methods of determining hydraulic conductivity

Constant head and falling head test

Traditionally, hydraulic conductivity testing of soils is conducted by using constant head or falling head methods in the laboratory. These two methods have been widely used in geotechnical laboratories owing to the simplicity and the availability of equipment at reasonable cost (Aiban and Znidarcic 1989). The constant head test is usually preferred for the hydraulic conductivity measurements of granular materials because the flow reaches the steady state rapidly and the test can be completed in a short period. However, it takes considerable time to complete a test with fine grained soils and, in such instances the falling head test is generally used (Olson and Daniel 1981).

Several disadvantages inherent to both constant and falling head tests have been discussed by Olsen et al. (1985), and Hardcastle and Mitchell (1974). In both methods, flow rates are obtained by conventional volume measurement techniques where the maximum resolution is of the order of 10^{-3} ml. For this resolution, accurate measurements of hydraulic conductivity of soil with low hydraulic conductivity can be achieved only if the imposed gradients are very high or the tests last for a long time (Alva-Hurtado and Selig 1981). If the burettes are replaced by capillary tubes in order to increase resolution, contamination of the tubes will lead to a non zero contact angle between the water and the glass which will affect the imposed gradient and produce erroneous results. (Olson and Daniel 1981).

The higher imposed gradients will usually produce a large variation of effective stress in the sample causing it to become less homogeneous (Aiban and Znidarcic 1989). In the falling head test, the hydraulic gradient changes continuously with time. Therefore, the falling head test is always done in a transitional state and the effective stress within the sample changes continuously which in turn changes the volume and, therefore, hydraulic conductivity. Analysis of the falling head test accounts for the changing gradients but the change in corresponding volume and hydraulic conductivity are usually ignored. Several modifications have been proposed for falling head tests such as the rising tail water test and the automatic falling head permeameter test but all use the same falling head test principle (Tan 1989; Daniel 1989).

Flow pump test

Olsen (1966) proposed the flow pump technique for measuring hydraulic conductivity of fine grained soils. In the flow pump test a known constant quantity of flow is forced through the sample by the pump and the corresponding pressure difference is measured by a differential pressure transducer, which is used to determine the hydraulic gradient. This is exactly the opposite concept of the conventional constant head test in which a known constant hydraulic gradient is imposed across the sample and the corresponding flow is measured. A pump with a very slow flow rate must be used (Olsen et al. 1985). Aiban and Znidarcic (1989) reported that the constant head test and flow pump test yield the same hydraulic conductivity values when the sample is tested under similar conditions.

Restricted flow test

Sills et al. (1986) proposed a restricted flow test which continuously determines hydraulic conductivity during consolidation and also had the provisions for a separate hydraulic conductivity measurement at the beginning or the end of a consolidation test. In the restricted flow test, the total stress increment is applied to one face of the sample and one way drainage is allowed from that face through a restrictor. Pore pressures at the drained and undrained faces of the sample are measured using transducers. The hydraulic gradient can be calculated using the sample height and the pore pressure difference at any time, and the flow rate can be obtained either by direct measurement or by calculation from the sample compression. The main difficulty of this approach is achieving an accurate measurement of the difference between the pore pressures on the undrained and drained faces. Initially, the two pore pressures are large (similar to the total stress) and pressure transducers that can monitor these will not provide an accurate measurement of the small difference between the pore pressures. A differential pressure transducer may be used to measure the difference directly.

Seepage test

In this test, the specimen is subjected to the seepage of water by the application of a constant head difference across the specimen, so that the pore pressure distribution within the specimen is measured at different points. The flow of water through the specimen is measured, and the test continues until steady state pore pressure readings are obtained. After the steady state condition is established, seepage is stopped and the specimen is then sliced to obtain the void ratio distribution in the sample. During the slicing of the specimen some rebound will occur and therefore the measured void ratios may be higher than those during the steady state condition and must be corrected with a material balance calculation. From the pore pressure distribution, the hydraulic gradient can be calculated, and by using the measured flow rate, the void ratio - hydraulic conductivity relationship can be obtained.

Hydraulic conductivity testing of fine tails slurries

In choosing a test procedure for this research, the fine grained nature of the fine tails placed restrictions on the method chosen. High hydraulic gradients, which occur during the falling head test, cause consolidation by the seepage forces and, hence, make this test undesirable. Also, time effects on flow velocity cannot be studied. The constant head test which was used allows for extremely small head drops and allows the study of time effects (Olsen et al.

1985). Though the flow pump test was considered, it could not be used because the flow rate in this study is in the range of 10^{-5} to 10^{-8} cm/s. In the tests discussed in this study, the initial sample heights were about 26 cm while the head differences applied across the sample were about 2 to 5 cm .

Although the constant head test is usually performed in oedometer and triaxial cells (Leroueil et al. 1992), a triaxial cell could not be used since the sample could not stand by itself because of the high initial water content of the fine tails. The standard oedometer cell cannot be used for fine tails because it undergoes large strains during consolidation and the small sample thickness used in the standard oedometer is not adequate for consolidation and hydraulic conductivity measurements. The slurry consolidometer was designed so that hydraulic conductivity measurements could be taken at different void ratios by consolidating the sample under load increments.

Testing Equipment

Figure 1 shows the experimental setup, with the slurry consolidometer about 30 cm in height and 20 cm in diameter. When performing hydraulic conductivity tests on fine tails slurries, the applied hydraulic gradients can cause consolidation during the test (Pane et al. 1983). To overcome this, a clamping device consisting of a horizontal steel bar fastened to two vertical frame rods, was set up to prevent consolidation. Two steel threaded rods were fastened to the top cap and were allowed to travel vertically through the steel bar through bored holes. To prevent any further movement at the end of a consolidation increment, the two rods are clamped to the steel bar. The LVDT was kept in place to monitor the exact location of the top cap throughout the process in order to prevent any occurrence of volume change during hydraulic conductivity testing. Flow in and out of the sample also is measured during hydraulic conductivity testing to ensure that there is no volume change of the sample.

This apparatus ensures that hydraulic gradients could be used up to the value that causes the seepage pressure to equal the previously applied stress (σ'), where the maximum head difference (Δh) for each increment is σ'/γ_w. Since the top cap is fixed in space and the soil beneath is consolidated under a stress σ', the soil will not further consolidate unless subjected to a stress (seepage pressure) greater than σ'.

It was possible to monitor the flow with horizontal burettes whose inside diameter was small enough to maintain a vertical meniscus because the flows were small (initially due to the low gradients and then due to low hydraulic conductivity). Burettes of the same size were used to monitor the inflow and outflow eliminating the need for meniscus correction. The burettes used were either 5 or 10 ml capacity depending on the flow, and a digital stopwatch was used for timing the flow during the test.

The type of fluid used in hydraulic conductivity tests can influence the measured hydraulic conductivity values. Budhu et al. (1990) have reported that when clay rich soils are saturated with an organic fluid the hydraulic conductivity measured with the organic fluid as permeant is greater than the measured hydraulic conductivity when the soil is saturated with water and water is the permeant. The permeant was selected to determine the hydraulic conductivity values consistent with those in the field. The tailings pond water was used as permeant for the fine tails and water collected during the consolidation test was used for nonsegregating tailings and fine tails - sand mixes for the hydraulic conductivity tests.

At the end of consolidation under each load increment, the top cap was fixed in place by means of the clamping system as previously described. The end of consolidation was determined by using the measured settlement with time and measured pore pressures with time. Once the desired height difference (hydraulic gradient) between the inflow and outflow burettes was set, the valves were opened and the flow rate was monitored. Knowing the surface area (A), volume of flow (ΔV), and time interval (t), the hydraulic conductivity (k) can be calculated from a rearrangement of Darcy's law

$$k = \frac{\Delta V}{i\, A\, t} \tag{1}$$

where, i is the hydraulic gradient equal to the hydraulic head difference (Δh) divided by the height of the sample. Several tests were done with different hydraulic gradients at each void ratio in order to check Darcy's law, after which the load was increased to the next load increment and the sample was allowed to further consolidate under the load increment. After the consolidation ceased, the procedure was repeated to measure the hydraulic conductivity at the new void ratio.

Test Materials

In northern Alberta, Canada, open pit mining to produce synthetic crude oil from oil sand is carried out in two large scale operations, by Syncrude Canada Ltd. and Suncor Inc. The waste tailings stream is composed of about 85% sand and 15% fines at solids contents from 40% to 60%. The tailings pond dykes and beaches are formed by the sand and some fines. Approximately one - half to two - thirds of the fines and most of the water flow into ponds to form fine tails deposits. Approximately 400 million cubic metres of fine tails are presently held in the tailings ponds. Since the grain size distribution, bitumen content, and mineralogy affect the hydraulic conductivity of fine tails, their material properties have to be characterized. The fine tails will be referred to as Syncrude fine tails or Suncor fine tails depending on their mine origin. In the oil sands industry, fines are defined as < 45 μm and this definition is used here. Silt size range is from 2 μm to 45 μm and clay size is < 2 μm.

In this study, the 20% and 25% initial solids content fine tails consist of about 3% fine grained sand, 42% silt and 55% of clay size particles, while the 30% initial solids content fine tails has 8% sand, 45% silt and 47% clay size particles. The sand content in the tailings pond increases with depth and solids content. The clay mineralogy of the fine tails reflects the average clay mineralogy of the clay - shale strata in the McMurray formation, which is dominated by kaolinite and illite clays. Smectite and vermiculite which come almost exclusively from the upper and the lower half of the formation respectively are present in small amounts and a trace of chlorite and mixed layer clays are also present in fine tails (Kasperski 1992). Dereniwski and Mimura (1993) reported that the fine tails are dominantly kaolinite (55 - 65%) and illite (30 - 40%) with minute traces of mixed layer clay minerals.

The bitumen content of the fine tails, based on the total mass of the fine tails, averages around 2% (MacKinnon and Sethi 1993). If the bitumen is calculated as a percent of the mass of the mineral solids, its content is 6.5%. The specific gravity of the fine tails varies between 2.1 and 2.5 due to varying amounts of bitumen which has a specific gravity of 1.03. If the bitumen content of the fine tails is known, the following equation can be used to calculate the specific gravity of the bulk fine tails,

$$[2] \qquad G_{FT} = \frac{1+b}{b/G_b + 1/G_s}$$

where, G_{FT} is specific gravity of fine tails, G_b is specific gravity of bitumen, G_s is specific gravity of mineral grains which is 2.65, and b is bitumen content. The average unit weight of fine tails is about 12 kN/m^3. Devenny (1993) reported that the liquid limit of fine tails ranges from 60% to 70% and the plasticity index varies from less than 30% to 40%. In this study, the liquid limit varied between 40% to 60% and plasticity index varied between 20% to 35%. The range in Atterberg limits reflects the effects of ionic concentration, clay mineralogy and bitumen content. The higher values in Atterberg limits probably indicate greater bitumen content and high clay contents.

The hydraulic conductivity tests were performed on fine tails samples with different initial solids content, which is the mass of solids divided by the total mass with bitumen considered as solids. The effect of hydraulic gradient was investigated in four slurry consolidometer tests with the fine tails at 20% initial solids content. The effect of bitumen was studied with fine tails of 10% initial solids (Bromwell Engineering Inc. 1983) and three slurry consolidometer tests were performed with 20%, 25% and 30% initial solids. In order to study the effects of the presence of sand in fine tails, three different fine tails - sand mixes were studied (Pollock 1988) (Table 1). The grain size distributions are shown in Figure 2. The Suncor nonsegregating tailings tests consisted of 14 slurry consolidometer tests on samples (initial solids contents of 40 to 65% and fines contents of 14 to 38%) in which sulfuric acid along with quick lime or fly ash were added in different amounts (Table 1). The Syncrude nonsegregating tailings tests consisted of five slurry consolidometer tests on quick lime added samples (initial solids contents of 52 to 56% and fines contents of 12 to 26%) (Table 1).

Evaluation of factors affecting the hydraulic conductivity of fine tails

Flow velocity variation with time

Typical measured flow velocities are shown in Figure 3 and Figure 4. The measured flow velocities were not constant, but decreased with time and then reached a steady state, the time dependent velocity phenomenon existing even at low void ratios (Figure 4). However, the drop in velocity from initial to steady state becomes less as the void ratio decreases. It would be expected that the drop in velocity would be less at low void ratios because little change in the specimen can occur during the hydraulic conductivity test. Several tests were run at certain gradients to check whether this transient phenomenon was repeatable, with Figure 5 showing the results of one such test, which shows its repeatability. It is interesting to note that even after hours of flow, the initial condition seems to be re-attainable after only a few minutes of no flow. The tests shown in Figure 5 were not extended to the steady state condition, but to a time sufficient to check for repeatability. The time between the tests varied from 5 to 10 minutes.

Olsen et al. (1985) also noted similar flow velocity changes in slurries and suggested that this initial transient response can be due to: i) undissolved air in the equipment and/or specimen; ii) compliance in the equipment; iii) the inertia that must be overcome in changing the velocity of the pore fluid from zero to its steady state value; and iv) time dependent changes in the volume or distribution of pore space in a specimen.

If there is undissolved air in the equipment or specimen, the flow velocity will: i) increase with time due to air going into solution and not blocking the pore throats; or ii) decrease with time because of the fluid filling the voids left by the air going into solution. However in this study, the measured inflow and outflow with time are similar (Figures 6 and 7), which indicate that no undissolved air could be present in the sample. The repeatability of the transient behavior also suggests that undissolved air was not present as it would have to reappear in the same voids after 5 min to 10 min of no flow. Therefore the transient behavior cannot be attributed to undissolved air in the specimen or in the equipment .

The effect of equipment compliance on the response time depends on both the rigidity of the equipment and the magnitude of the externally applied gradient. The slurry consolidometer was made of stainless steel with a 7.45 mm wall thickness and was calibrated with water pressure which showed there was no compliance effect on the measurements. The external gradient applied was generally less than 0.2 and at low void ratios it was less than 0.6, and applied heads were in the range of 2 to 5 cm across the sample. Such small pressures will have negligible volume change effects on the tubings connecting the burettes and consolidometer. Figures 6 and 7 (similar inflow and outflow with time) suggest that there is no volume change in the equipment. Therefore, the compliance of the equipment could not be accountable for the transient behavior.

Inertia effect can create a time lag between the inflow and outflow measurements because it must be overcome in changing the velocity of the pore fluid from zero to the steady state value. Figures 6 and 7 show that there was no time lag between the inflow and outflow. Therefore inertia effect could not be responsible for the transient behavior.

Therefore, it appears that time dependent changes in the volume of the specimen or in the distribution of pore space in the specimen must account for the transient behavior. The top cap was locked in place and the LVDT did not record any movement of the top cap which indicates that there was no volume change in the slurry consolidometer. The measured inflow and outflow (Figures 6 and 7) also show this. Volume change in the sample was prevented because the hydraulic conductivity testing imposed no additional effective stress in the specimen. Therefore, the transient behavior cannot be attributed to time dependent volume change of the specimen. It is concluded that time dependent changes in the distribution of pore space must account for the transient behavior as described below.

The repeatability of this behavior suggests that whatever is causing the decrease in flow velocity is triggered by seepage force and is reversible. In high void ratio slurries, particles can move under the seepage stress and rearrange the distribution of pore space. The ratio of initial flow velocity to steady state velocity for the fine tails is about 300 to 400 at void ratios around 6 and is about 20 at a void ratio of about 1.5 (Figure 8). The variation in this ratio is compatible with the possibility of movement of fine particles into pore throats between coarser particles, which would occur more readily at high void ratios. For nonsegregating tailings, the ratio of initial flow velocity to steady state flow velocity is much less than that of the fine tails (Figure 9). Since the fines in nonsegregating tailings are in a flocculated or aggregated state, movement is less than that in fine tails.

The bitumen in the fine tails might also account for the transient behavior. Although considered as a solid in calculations, the bitumen is not totally rigid and can deform under stress. This deformable quality of the bitumen could allow it to move to block the pore throats while being subject to a seepage stress. At low hydraulic gradients, the effect of bitumen content on the measured hydraulic conductivity is negligible, as explained later under the effect of bitumen content. This suggests that the transient behavior cannot completely be attributed to the bitumen.

The time to reach the steady state for fine tails varies between 30 min to 15 hr. The time increases with an increase in high void ratio or a decrease in hydraulic gradient. The repeatability of this transient behavior suggests that it only takes about 5 to 10 min to return to the original state. The hydraulic conductivity tests were performed with an upward flow. The upward seepage stress is much less than the downward gravity force of the particles and bitumen (1/10 of the mass of the particles and 1/4 of the mass of the bitumen) so that it takes a long time for them to move under seepage stress and little time under gravity to return to their original position. Therefore, the transient behavior must be due to time dependent movement of fine particles and, to a lesser extent, bitumen.

Since there is continuous upward flow in the tailings ponds, due to consolidation, fine particle and bitumen blocking of pore throats would be occurring and the tailings pond field hydraulic conductivity will be similar to laboratory steady state hydraulic conductivity. Therefore, the steady state flow velocity was used to determine the hydraulic conductivity. Olsen et al. (1985) report also, that for slurries, the steady state flow obeys Darcy's law with respect to a linear gradient - velocity relationship. The time to reach the steady state will vary with material and void ratio. For fine tails, it varied up to 15 hours and less for fine tails-sand mixes and nonsegregating tailings. Therefore, to obtain representative results, the flow velocity should be measured with time to determine the steady state velocity to use in hydraulic conductivity calculations.

Effect of Hydraulic gradient

The effect of hydraulic gradient was studied by performing hydraulic conductivity tests at different hydraulic gradients at each void ratio after each load increment (Figure 10). As the gradient increases, the hydraulic conductivity of fine tails decreases at any given void ratio. However, when tested under hydraulic gradients less than 0.2, all hydraulic conductivity tests gave similar values for hydraulic conductivity. The effect of hydraulic gradient is small for void ratios less than 1. It can be concluded that the hydraulic conductivity of the fine tails depends on the hydraulic gradient, as opposed to Darcy's law.

The influence of hydraulic gradient may be due to: i) deformation of bitumen into pore throats within the soil skeleton in response to the flow of water; or ii) fines migration under the applied gradient into pore throats. It was noted that the hydraulic conductivity at low gradients was the same before and after a higher gradient was applied on the sample. This indicates a recoverable mechanism in flow through fine tails. The bitumen globules can deform when the hydraulic gradient is applied and when the gradient is removed they can relax back to the original position. If fines collect in the pore throats, the recoverable mechanism will not occur.

The deformation of bitumen should be directly related to the applied hydraulic gradient. The higher the gradient, the larger the deformation of the bitumen and the smaller the hydraulic conductivity. At small hydraulic gradients ($i < 0.2$), the deformation of bitumen should be small and the effect of hydraulic gradient on the hydraulic conductivity measurements should be negligible. At small void ratios ($e < 1$), the effect of hydraulic gradient is minimal because the bitumen does not have much space to deform. Hydraulic conductivity of fine tails is about 2 to 3 times lower when the hydraulic gradient is increased from 0.2 to 1. Due to the influence of hydraulic gradient on hydraulic conductivity, it is necessary to perform hydraulic conductivity tests at the field hydraulic gradient (measured or expected) in order to obtain reliable hydraulic conductivity values for field predictions.

Effect of bitumen content

Slurry consolidometer tests were performed on bitumen removed fine tails in order to evaluate the effect of the bitumen on the consolidation properties (Bromwell Engineering Inc. 1983). Bitumen was removed by treating the sample with hydrogen peroxide. Figure 11 shows that the hydraulic conductivity of the bitumen removed fine tails is similar to the hydraulic conductivity of fine tails at a low hydraulic gradient. This reinforces the argument that the bitumen is causing the difference in hydraulic conductivity with different gradients.

The viscosity of the bitumen at different temperatures is shown in Table 2. The viscosity of water is about 1 mPa.s. The laboratory temperature is about 25°C. In the laboratory hydraulic conductivity tests, at a hydraulic gradient of 0.2, bitumen, as a continuous medium, could flow 6.6×10^{-7} cm in a day, that is, it would take about 45 years to travel 1 mm.

In the fine tails, bitumen exists as small globules. These globules can travel at the rate of water travel. In laboratory hydraulic conductivity tests, at a hydraulic gradient of 0.2, water can flow at the rate of about 3 mm per day. The globules can travel until they encounter a pore throat but because of their high viscosity cannot flow thorough the pore throat and hence will decrease the hydraulic conductivity.

The average temperature of the tailings in the Syncrude tailings pond is 11°C and that of Suncor tailings ponds is 17°C. Even though there is a temperature difference between laboratory and tailings ponds, the viscosities at both temperatures are very high (5×10^5 mPa.s at 25°C and 5.5×10^6 mPa.s at 11°C) and therefore the influence of temperature on the hydraulic conductivity is negligible.

The hydraulic conductivity of the bitumen removed fine tails is an upper bound for the hydraulic conductivity of the fine tails and was found to be independent of the hydraulic gradient. Figure 11 suggests that the hydraulic conductivity of fine tails decreases with an increase in bitumen content. When the hydraulic gradient is less than 0.2, bitumen has little influence on the hydraulic conductivity. When the void ratio approaches 1, the effect of bitumen becomes less. The bitumen removed fine tails showed the highest hydraulic conductivity values at any given void ratio which suggests that removing the bitumen from the fine tails will increase the hydraulic conductivity and, hence, increase the rate of consolidation.

Effect of initial solids content and clay content

The hydraulic conductivity of fine tails is shown to be dependent on the bitumen content and hydraulic gradient. Figure 12 shows the hydraulic conductivity - void ratio relationship of different fine tails samples with different initial solids contents from this study, Bromwell Engineering Inc. (1983), and Pollock (1988). All tests used a hydraulic gradient of approximately 0.2 to model the hydraulic gradient in the tailings pond which is 0.2 or less. The initial solids content did not affect the hydraulic conductivity and although the clay content of the fine tails varied between 47% and 55% it also did not have an effect. The hydraulic conductivity decreased by about four orders of magnitude when the void ratio decreased from 8 to 1. Several authors have used an e - log k relationship to describes the k variation for natural clays. However, for fine tails, the following power law describes the relationship.

[3] $k = 6.16 \times 10^{-9} \bullet e^{4.468}$

where k is hydraulic conductivity in cm/s and e is the void ratio. This relationship can be used in the prediction or analysis of the consolidation behavior of fine tails.

Hydraulic conductivity of fine tails - sand mixes

The effect of sand content on the fine tails was investigated by using three different mixes (Pollock 1988) with different solids contents and fines contents (Table 1) (Figure 13). Permeability trends appear from one mix to the next with respect to the sand - fines content (Figure 14). The hydraulic conductivity varies by several orders of magnitude at a given void ratio decreasing with increasing fines content. This suggests that the concentration of fines, not the sand, governs the hydraulic conductivity.

Figure 14 shows the variation of hydraulic conductivity in terms of fines void ratio. The fines void ratio (e_f) is defined as

$$[4] \qquad e_f = (e / f) \ (G_f / G_s)$$

where, G_s is specific gravity of solids, G_f is specific gravity of fines, f is fines content, and e is total void ratio. As all the data fall in the same range, this confirms the dependence of the hydraulic conductivity on the fines content. The influence of the sand on the hydraulic conductivity appears to be only as a filler, which decreases the fines concentration for a given volume. For this reason, hydraulic conductivity increases with increasing sand content in terms of total void ratio (Figure 13).

Hydraulic conductivity of nonsegregating tailings (NST)

Hydraulic conductivity of nonsegregating tailings were analyzed to study the influence of gel structure in fine tails on hydraulic conductivity. Nonsegregating tailings is a mixture of fine tails and tailings sand combined with a chemical additive used to make the mix nonsegregating. The additives used in this study were sulfuric acid, quick lime, fly ash and gypsum alone or in combination. Suncor nonsegregating tailings were formed using acid with quick lime or fly ash or gypsum alone, while Syncrude nonsegregating tailings were formed using quick lime. Suncor acid - lime/fly ash nonsegregating tailings show similar hydraulic conductivity values as the fine tails in terms of fines void ratio (Figure 15). Even with the addition of coagulants, the hydraulic conductivity is controlled by the fines, hence, by the fines void ratio. For Suncor gypsum nonsegregating tailings the hydraulic conductivity is only about one - third of the hydraulic conductivity of the fine tails (Figure 16). For Syncrude lime nonsegregating tailings, the hydraulic conductivity is only about one - fifth of that of fine tails (Figure 17). Mesri and Olsen (1971) reported that k is maximized when the flow channels consist of many small and relatively few large channels, with the flow occurring through all the channels. In nonsegregating tailings, there are probably a high number of large channels, and a number of small channels which are ineffective and disconnected. Therefore, the hydraulic conductivity may be similar or less than that of the fine tails in terms of fines void ratio.

The differences in hydraulic conductivity for the various nonsegregating tailings mixes indicates that the different chemical additives result in different gel structures and that the gel structure controls the hydraulic conductivity of the fines. This finding is important in the analyses of the hydraulic conductivity of fine tails. Modeling has shown that the hydraulic conductivity of the fine tails in the laboratory is different than the hydraulic conductivity of the fine tails in the field tailings pond. This difference in hydraulic conductivity would appear to be caused by a difference in the fine tails gel structure in the laboratory and field.

The hydraulic conductivity's dependence on the additives can be explained with help of coagulation chemistry as applied to water and waste water treatment. In fine tails the solids are much more concentrated than those in water or waste water. However, the chemical principles involved may not differ. The predominant mechanisms of aggregation or coagulation are: i) charge neutralization where the soluble hydrolysis species interact with the fine particles and, ii) sweep coagulation where neutral species dominate and precipitate as solids to enhance the aggregation. Sweep coagulation is favored in high pH values when alum is used as coagulant (Amirtharajah and O'Melia 1990). For fine tails which contain many chemical constituents the chemistry of coagulation is very complex. However, the addition of acid in conjunction with quick lime lowers the pH and may reduce sweep coagulation in favor of the charge neutralization mechanism. With the absence of acid in Syncrude lime nonsegregating tailings, sweep coagulation may be predominant. The sweep - flocs formed will lead to a reduced number of flow channels, resulting in lower hydraulic conductivity. Addition of gypsum does not introduce H^+ or OH^- ions into nonsegregating tailings to alter the pH, however, with the OH^- ions, Ca^{2+} ions can associate to slightly lower the pH. This would lead to a coagulation state which lies between the lime added nonsegregating tailings and the acid added nonsegregating tailings. In contrast, the addition of acid in Suncor acid - lime/fly ash nonsegregating tailings may maintain a balance between the two coagulation mechanisms to keep the hydraulic conductivity similar in terms of fines void ratio. However, further experiments are required to validate this principle.

Conclusions

In general, the void ratio - hydraulic conductivity relationship of oil sands fine tails is influenced by hydraulic gradient and bitumen content. A transient state exists in the flow through the fine tails in the laboratory during hydraulic conductivity testing which requires some time to decrease to a steady state. This drop in flow velocity during the transient state decreases with decreasing void ratio. This phenomena can be attributed to the reorientation of fine particles due to the seepage force, which is found to be reversible. The presence of bitumen also can cause such transient behavior but to a lesser degree. For appropriate measurement of hydraulic conductivity in the laboratory, the flow velocity should be measured with time and the steady state velocity must be used.

Deformation of bitumen from seepage forces makes the hydraulic conductivity of fine tails dependent on the hydraulic gradient. The hydraulic conductivity of fine tails, therefore does not conform to Darcy's law. Measuring hydraulic conductivity at field hydraulic gradients of less than 0.2 will lead to reliable use in predictions. It was determined that the hydraulic conductivity of the fine tails can be expressed in a power law form in terms of void ratio.

In fine tails - sand mixes, the fines content controls the hydraulic conductivity. The effect of sand content results in reduced fines content and, hence, alters the void ratio - hydraulic conductivity relationship. The addition of chemicals to fine tails - sand mixes may have a significant effect on the hydraulic conductivity. The pH of the nonsegregating tailings may play an important role in coagulation or aggregation mechanisms and, hence, have an influence on the hydraulic conductivity.

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Table 1. Properties of fine tails-sand slurries used in hydraulic conductivity tests

Test no.	Chemical Additives		Initial Solids Content	Fines Content	Initial Void Ratio	Initial Fines Void Ratio
	Type	Concentration				
		g/m3	(%)	(%)	-	-
Syncrude Fine Tails - Sand mixes*						
1	none	-	48	54	2.72	5.27
2	calcium chlorite	375	52	27	2.39	9.42
3	none	-	70	20	1.22	6.63
Syncrude NST						
1	quick lime	1250	55	12	2.12	16.00
2	"	1500	56	12	2.04	15.40
3	"	1200	54	17	2.21	11.77
4	"	1250	52	19	2.40	11.44
5	"	1250	52	26	2.40	8.36
Suncor NST						
1	sulfuric acid/quick lime	750/450	56	29	2.08	6.50
2	"	1200/400	60	26	1.75	6.10
3	"	1150/350	61	20	1.58	7.15
4	"	1200/400	64	17	1.48	7.88
5	"	700/450	65	14	1.40	9.06
6	sulfuric acid/fly ash	600/2000	40	38	4.40	10.49
7	"	600/2000	40	33	4.71	12.93
8	"	600/2000	59	22	1.81	7.45
9	"	700/2000	61	20	1.62	7.34
10	"	750/2500	64	17	1.47	7.83
11	"	750/2500	65	15	1.42	8.57
12	gypsum	1500	59	18	1.82	9.16
13	"	1500	57	22	2.00	8.23
14	"	900	56	21	2.05	8.84

*- from Pollock (1988)

Table 2. Viscosity of the bitumen at different temperatures (Peacock 1988)

Temperature	Viscosity (mPa.s)
11	5500000
17	1800000
20	1100000
25	500000
30	200000
40	45000
60	5000

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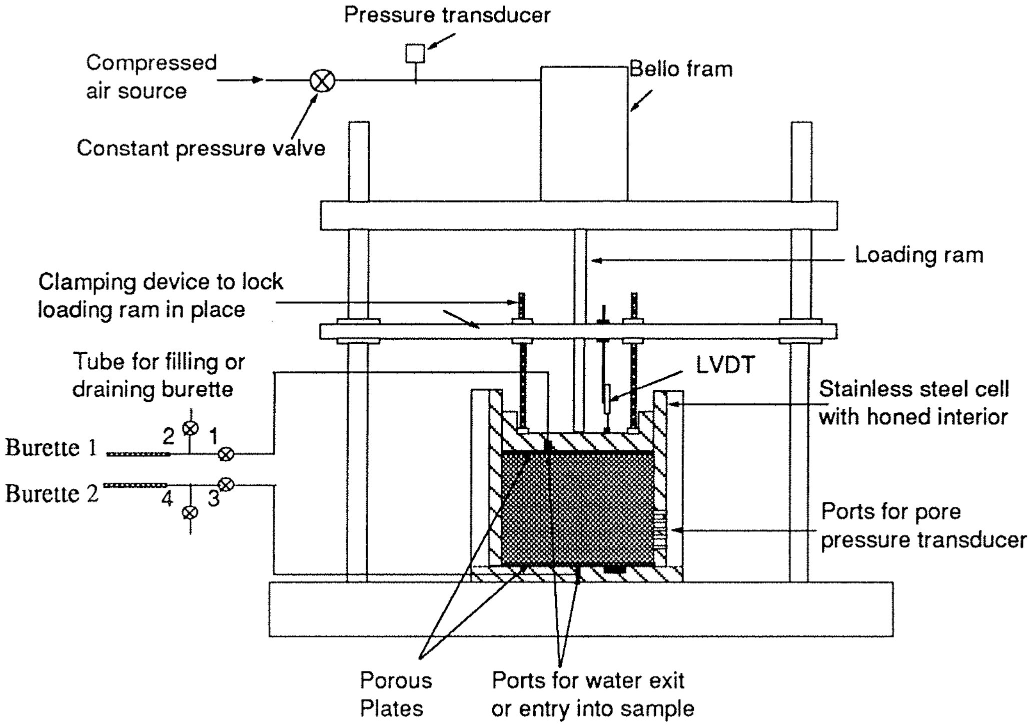


Figure 1 Slurry Consolidometer

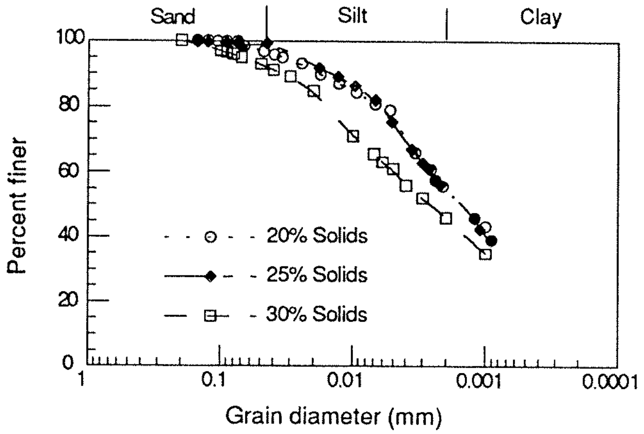


Figure 2. Grain size distribution of fine tails

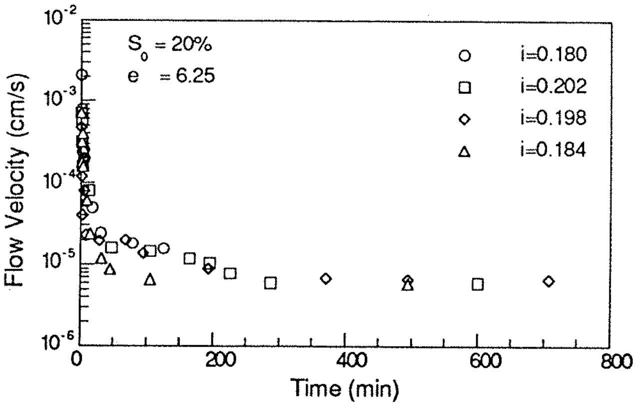


Figure 3. Variation of flow velocity with time at a high void ratio

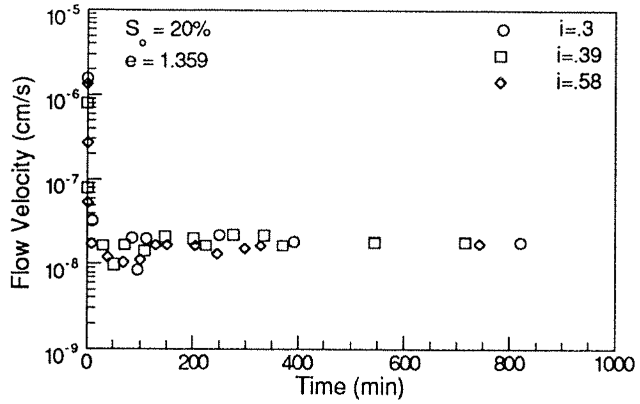
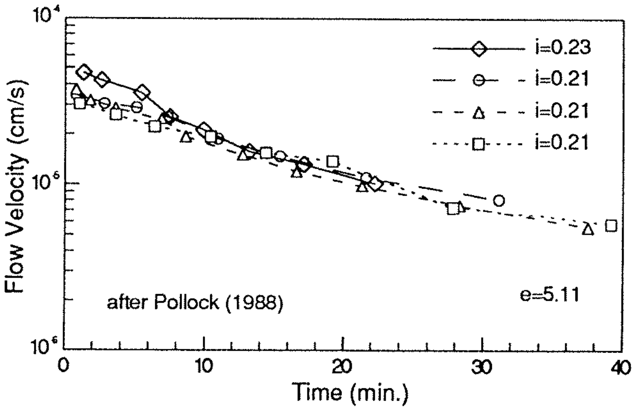


Figure 4. Variation of flow velocity with time at a low void ratio



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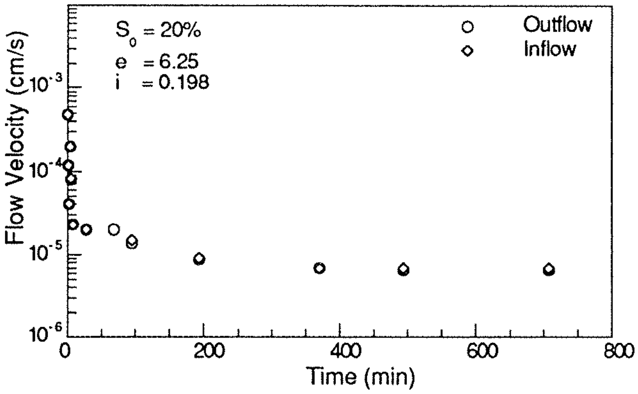

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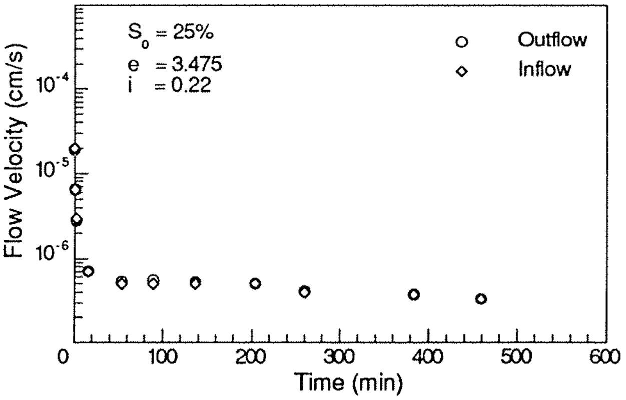


Figure 7. Variation of inflow and out flow with time at a low void ratio

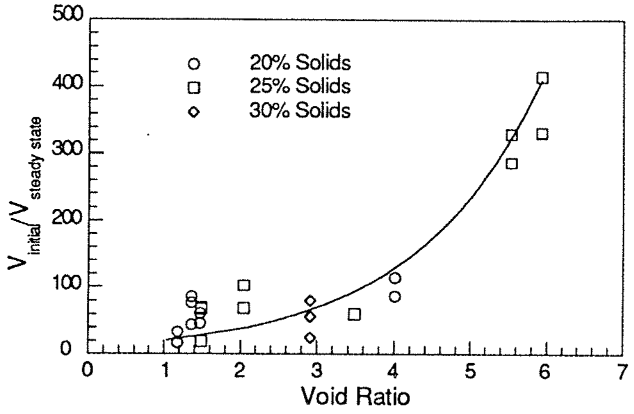


Figure 8. Ratio of initial flow velocity to steady state flow velocity

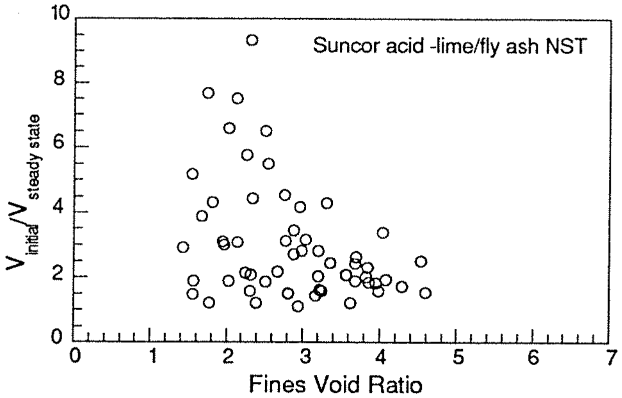
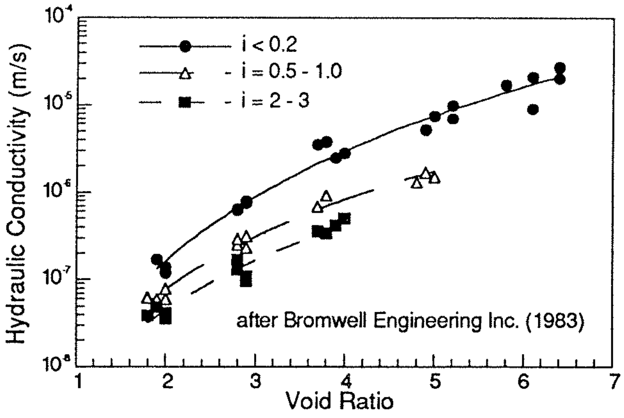


Figure 9. Ratio of initial flow velocity to steady state flow velocity for nonsegregating tailings



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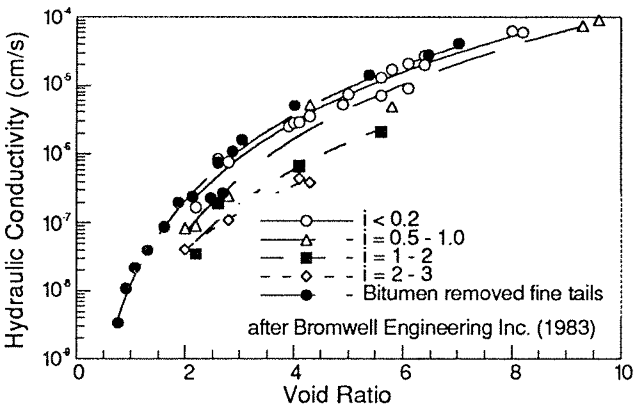

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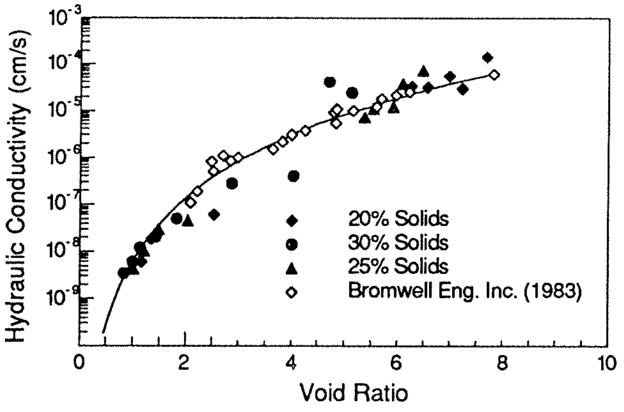

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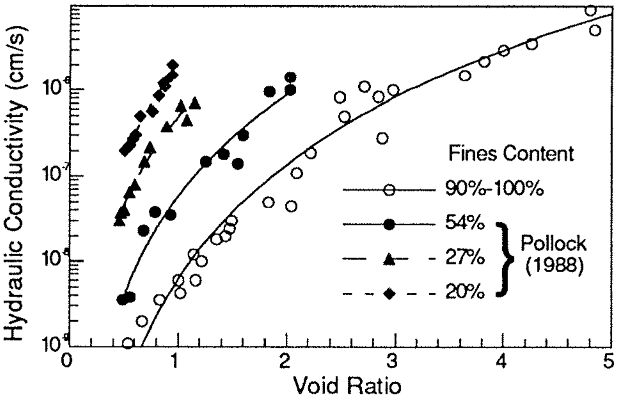

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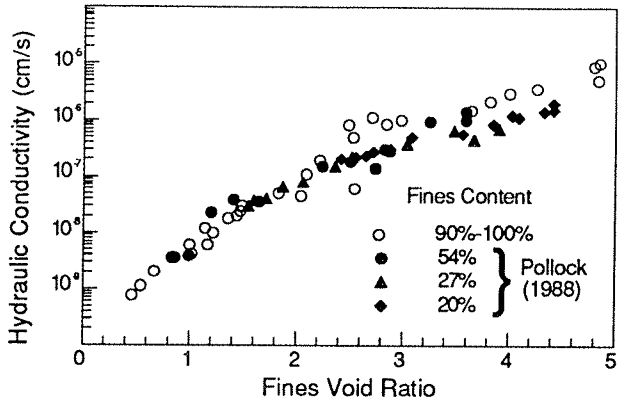

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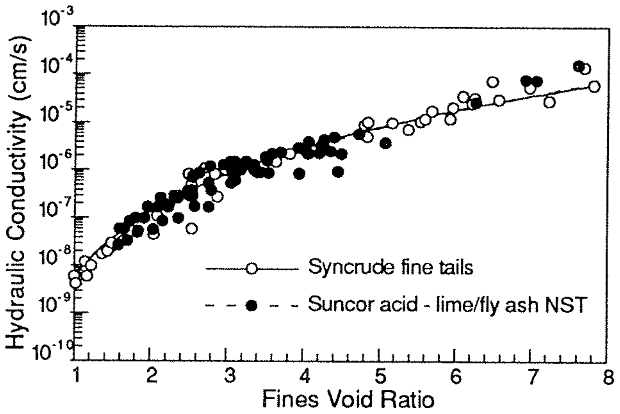

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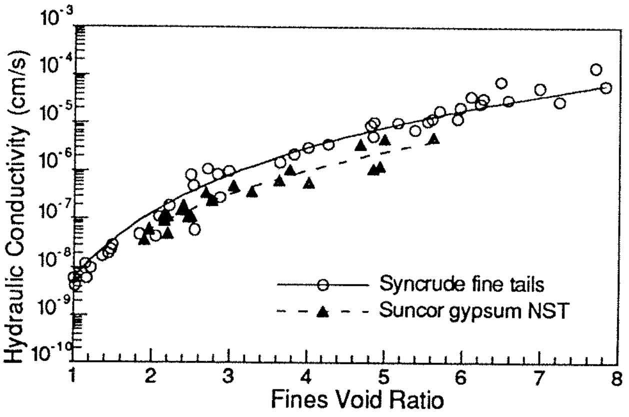

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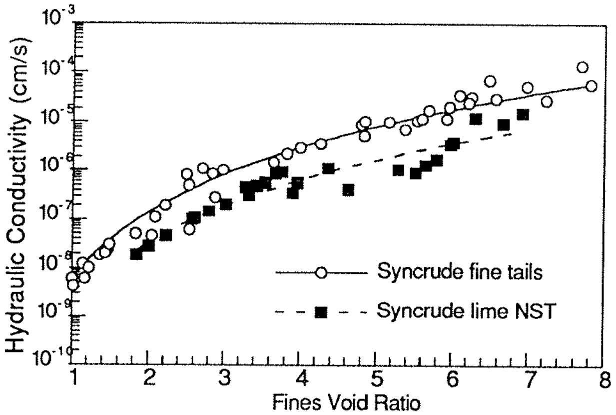

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