CONSOLIDATION BEHAVIOR OF OIL SAND FINE TAILINGS [1]

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Abstract: In northern Alberta, oil sand deposits are mined and processed to recover heavy oil. Oil sand plants produce about 650,000 mt/d of tailings. Approximately one-half of the fines in the tailings streams flows into tailings ponds to form fine tails deposits which presently total 325 million m^3.

A slurry consolidometer has been developed to allow for large deformations during consolidation and to allow permeability tests to be performed on the fine tails. Development of a top cap clamping system has permitted permeability testing to be conducted on the high-void-ratio slurries without having seepage-induced consolidation. The equipment, the fine tails material, and the testing methods are described.

The permeability test results revealed a time-dependent flow with a constant hydraulic gradient. The flow velocity drops up to two orders of magnitude before reaching a steady-state value. Unlike normal soils, it was found that the amount of compressibility of the fine tails is influenced by the initial void ratio of the sample, which suggests that aging changes the microstructure of the fine tails. This suggests that there is a time-dependent parameter involved in the compressibility of fine tails. Therefore, a single void ratio-effective stress relationship is not sufficient to describe the consolidation behavior of fine tails. The permeability-void ratio relationship, however, is not influenced by the initial void ratio. These experimental results suggest that permeability and compressibility are controlled by different elements of pore structure.

Additional Key Words: tailings, compressibility, hydraulic conductivity, mine waste.

Introduction

In mining operations, the waste material from a mineral processing plant is generally in the form of a slurry. The slurry is deposited hydraulically and contained in some type of pond-dyke arrangement. Design problems associated with these ponds include storage capacity, embankment stability, seepage, and land reclamation. The physical properties of the waste material that affect the design of the waste storage facility are compressibility, permeability, and shear strength. Many waste mineral slurries contain significant amounts of silt and clay fraction. The presence of clay can result in a very high initial void ratio and subsequently very large volume changes during consolidation.

In northern Alberta, oil sand deposits are mined and processed to recover heavy oil from two oil sand plants, Syncrude Canada Ltd. and Suncor Inc. The tailings streams are composed of

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about 85% sand and 15% fines by weight plus a small amount of heavy oil that bypasses the extraction plant. Syncrude and Suncor produce, respectively, about 480,000 mt/d and 170,000 mt/d of tailings, which range in solids content from 40% to 60%. The tailings sand forms the pond dikes and beaches and accumulates at a rate of 225,000 m^3/d. Approximately one-half of the fines in the tailings streams flow into the pond to form a fine tails deposit. After sedimentation and approximately 2 yr of consolidation, the fine tails form a deposit at about 30% solids, which accumulates at a rate of 45,000 m^3/d. Approximately 325 million m^3 of this fine tails are presently held in the tailings ponds. The material, by economic necessity, must rely on self-weight consolidation for its densification. Self-weight consolidation is very slow in the tailings ponds. The result is a necessity to continually enlarge the containment ponds and dikes to hold the rapidly accumulating large volumes of material. Therefore, it is necessary to understand the consolidation rates and behavior of the fine tails before an assessment of the effectiveness and feasibility of long range disposal plans can be made.

The consolidation behavior of the fine tails is controlled by the compressibility, permeability, thixotropic strength, and creep properties of the material. Laboratory tests have been performed to measure these properties and their variations with porosity and time. The fine tails material is unique because of its properties and the vast volume that must be disposed in an acceptable environmental and economical manner. The consolidation and permeability equipment, the fine tails material, and the testing methods are described in the following sections.

Consolidation Testing

The standard oedometer test is developed for small-strain consolidation problems and generally adopts small-strain theory. In the oedometer test, constant loads are applied to the sample, and the settlement with time is observed for each load. This allows a relationship between stress and void ratio, coefficient of compressibility, and, by using theory, a coefficient of consolidation and then the hydraulic conductivity to be obtained.

There are two significant experimental difficulties in using the standard oedometer test for the fine tails. The main problem is the large strain that takes place. The other problem is the determination of hydraulic conductivity. Permeability testing may cause seepage-induced consolidation. There are several methods of determining the coefficient of consolidation and calculating the hydraulic conductivity from the laboratory data. All incorporate the assumption that the compressibility and the coefficient of consolidation are constant during each load increment. This assumption presents the major restriction to the applicability of the analytical procedures. The accuracy of the determination of the coefficient of consolidation is inversely proportional to the size of the load increment (Znidarcic et al. 1984).

Modified Consolidation Testing

Advanced testing techniques have been developed to overcome the problem of the test duration of large-strain oedometer tests. Such tests include the constant rate of deformation (CRD) test (Lee 1981), the constant hydraulic gradient (CHG) test (Lowe et al. 1969), and the constant rate of loading (CRL) test, all of which are faster than the step-loading oedometer test. These test procedures employ an inversion of the Terzaghi infinitesimal consolidation theory to yield usable results. Therefore, their applicability is restricted by this theory's assumptions (Znidarcic et al. 1984).

The CRD test has to be done at the field deformation rates since the test results are dependent on the rate of deformation. The assumptions required for the reduction of data include infinitesimal strain, constant coefficient of consolidation, and the assumptions regarding the relationships between either the void ratio and time or the void ratio distribution in the sample. Neither assumption can be validated (Znidarcic et al. 1984).

In the CHG test, the loading rate is continually adjusted through a feedback mechanism, such that the pore pressure at the undrained boundary remains constant; hence the hydraulic gradient is constant within the sample throughout the test. The assumptions include infinitesimal strains, constant permeability, a linear compressibility, and a constant void ratio throughout the sample (Znidarcic et al. 1984).

The CRL tests (Aboshi et al. 1979) and constant loading tests (Janbu et al. 1981) have similar assumptions and restrictions (Znidarcic et al. 1984). The seepage test (Imai 1979) does not rely on Terzaghi's theory for consolidation parameters. However, sample rebound at the completion of this test may lead to erroneous results.

The above-mentioned tests, except for the seepage test, with their analyses have been set up for soils that obey the assumptions involved in Terzaghi's infinitesimal consolidation theory. These tests are not applicable to highly compressible soils such as dredged materials and mine waste slurries, which undergo large deformations during consolidation. To overcome such setbacks, slurry consolidation tests have been developed for these very soft materials.

Slurry Consolidation Testing

Slurry consolidometers have been developed to allow large deformations during consolidation and to allow permeability tests to be performed on the samples. The test is conducted similar to the oedometer test in which a step-loading procedure is applied, allowing for the direct determination of the effective stress-void ratio relationship. The permeability-void ratio relationship can be determined by conducting permeability tests on the sample after each load increment. Seepage-induced consolidation can be prevented using a load-fixing device. Therefore the major difficulty remaining with the procedure is the test duration.

Though several procedures have been developed to decrease the time involved in consolidation testing of clayey soils, they involve inverting the complex finite-strain consolidation theory, and therefore their usefulness depends on the assumptions used in the inversion process. Therefore in this research, a long test duration was accepted and a slurry consolidometer with step loading procedure was used.

Imai (1981) noted that for highly active soil slurries that undergo hindered settling during the sedimentation phase, the initial void ratio at the start of consolidation is strongly dependent on the initial void ratio of the slurry. In Imai's study, several compression curves were found in the low-pressure range (less than 0.1 kPa). Above this effective stress value, there was a unique compression curve. To investigate the effect of the initial void ratio on the consolidation of oil sand fine tails, three different initial solids contents were employed in this research.

Permeability Testing

To understand the consolidation properties of a soil, laboratory testing is necessary to determine its hydraulic conductivity. For soils undergoing large changes of void ratio, it is necessary to determine the hydraulic conductivity as a function of the void ratio.

Indirect Methods of Determining Hydraulic Conductivity

Indirect methods of determining the hydraulic conductivity are carried out by inverting a consolidation theory and applying it to the rate of compressibility data obtained from a consolidation test. The most common method of indirectly determining the hydraulic conductivity in the standard oedometer test is either from the logarithmic time plot or square root time plot of the consolidation of a soil under a constant stress. These methods of determining hydraulic conductivity have been found to be unacceptable for slurry consolidation because of experimental (e.g., high strain rates) and analytical reasons (Terzaghi's assumptions).

Tavenas et al. (1983) indicated that the back-calculated values of permeability underestimated the measured values by up to six times for soft clays. The reason for the difference is the assumptions in Terzaghi's consolidation theory. The assumptions that are mostly violated are constant permeability, constant compressibility, and hence a constant coefficient of consolidation. Tavenas et al. concluded that indirect methods are unacceptable in determining the permeability characteristics of soft clays.

Direct Methods of Measuring Permeability

The direct method involves forcing a fluid through the soil and monitoring either the rate of flow through the soil or the hydraulic head changes induced by it. The two most widely used methods of directly determining the hydraulic conductivity of a soil are the constant-head and the falling-head permeability tests.

The advantages of these two tests are their simplicity in testing procedure, apparatus, and evaluation of the test data. The disadvantage of the conventional methods is the length of time required when performing low-gradient permeability tests. When direct methods are used for highly compressible slurries, low gradients must be used since large gradients induce consolidation due to seepage. The falling-head test is unfeasible with low gradients.

A constant-head technique was chosen for this research because it allows for extremely small head drops during the test and because of its ability to monitor time effects on flow rate. A variable-head test is not feasible for both of these reasons.

Experimental Program

To determine the compressibility and permeability data for the oil sand fine tails, a large-strain slurry consolidometer was used (fig. 1). This apparatus allows a void ratio-effective stress relationship and a permeability-void ratio relationship to be obtained.

A step-loading procedure, similar to a standard oedometer test, was employed owing to its simplicity and the ability to perform permeability testing after the completion of consolidation under each load increment. A constant-head technique was employed for the permeability portion of the test. Since a change in pore fluid chemistry may affect the permeability, tailings pond water was used as permeant to achieve consistent results with the field conditions.

Common to all slurry consolidation test methods is the danger of consolidating the slurry during the permeability test. Consolidation occurs when the stresses introduced by the seepage force of the permeant are greater than the stress under which the sample was previously consolidated. To overcome this problem, a clamping system was used to fix the loading ram, which sits on the soil, to prevent its movement. This system then allows an upward hydraulic gradient to be applied to the sample, up to a gradient where the induced seepage stress is equivalent to the previously applied consolidation pressure.

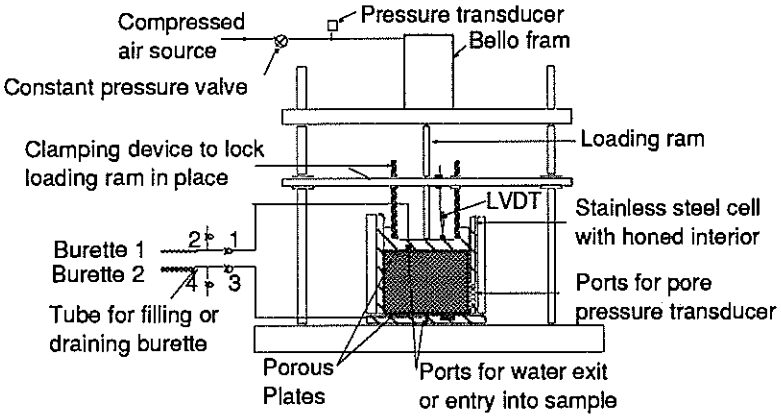

Figure 1. Slurry consolidometer.

Oil sand fine tails with three different initial solids contents (20%, 25% and 30%) were tested in the slurry consolidometers. Liquid and plastic limits of fine tails are approximately 59% and 23%, respectively. Bitumen content by mass of the fine tails is 3% of the mineral solids. The applied stress increments were equal to the previously applied stress. The consolidation tests and permeability tests lasted for up to 2 yr. This elapsed time is from the start of the self-weight consolidation stage to the end of the last permeability test of the final load increment.

Results and Discussion

Figure 2 shows a typical change of void ratio with elapsed time. For some of the smaller applied increments, it was necessary to stop the consolidation before the displacement had leveled out on a logarithm time plot. Although on the log time plot the material appears to be rapidly consolidating, the material has entered the 10^4-min log cycle, and any additional change in void ratio would be very small.

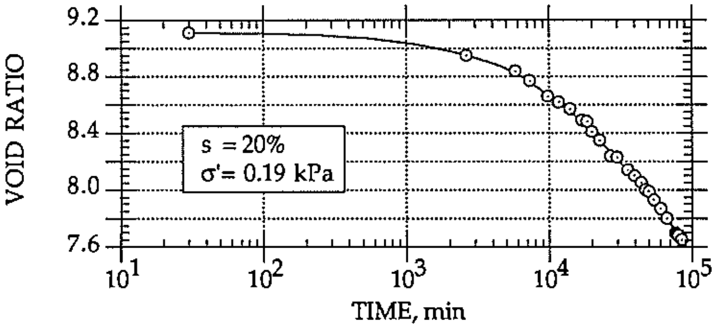

Figure 2. Void ratio variation with time.

Excess pore pressures were measured at five ports using a pressure transducer. The ports are numbered from the top (fig. 1). Figure 3 shows a typical excess pore pressure variation with time.

Initially, the consolidation stress is the midheight self-weight in the sample. Subsequently, the stress is the midheight self-weight plus the stress applied by the loading ram.

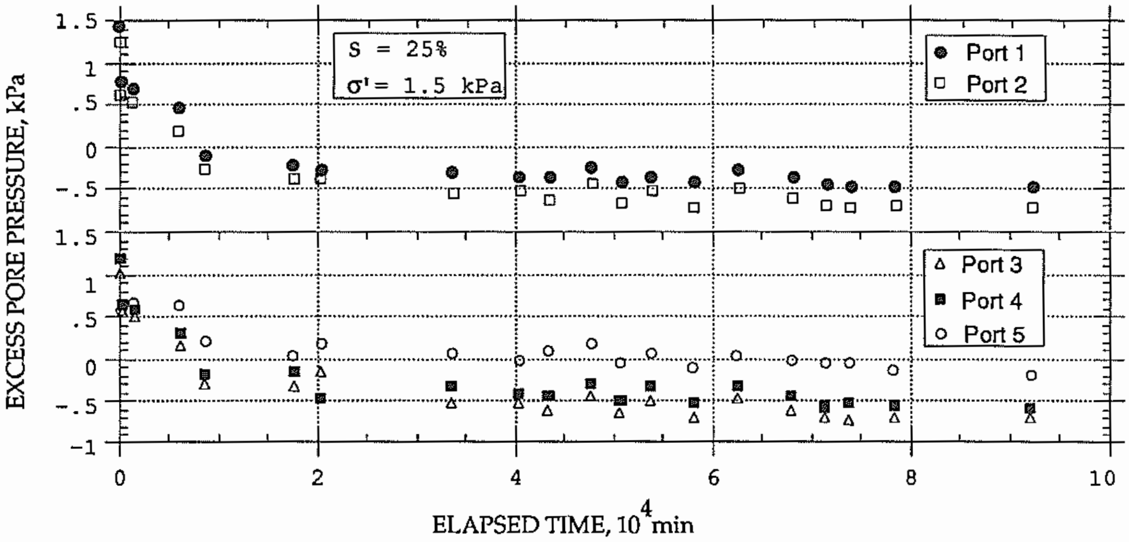

Figure 3. Excess pore pressure variation with time.

Figure 4 shows a typical relationship of flow velocity with elapsed time during a permeability test. The flow velocity decreased until it approached a steady-state value. The flow velocity at this steady state was used to determine the hydraulic conductivity. Several permeability tests were run at different gradients, and this phenomenon was found to occur repeatedly. This finding suggests that the decrease in flow velocity may have been triggered by seepage forces and is reversible. The bitumen in the fine tails might account for this phenomenon. Although considered as a solid in calculations, the bitumen is deformable under stress and not totally rigid. This deformable quality could allow bitumen to move to block pore throats while being subject to a seepage stress. Once the seepage has stopped, the bitumen would revert to its initial position or shape. A similar drop in flow velocity was also experienced at lower void ratios; however, the drop in flow velocity from initial to steady state became less as the void ratio decreased. It would be expected that the flow velocity drop would be less, because at very low void ratios very little movement of the bitumen can take place.

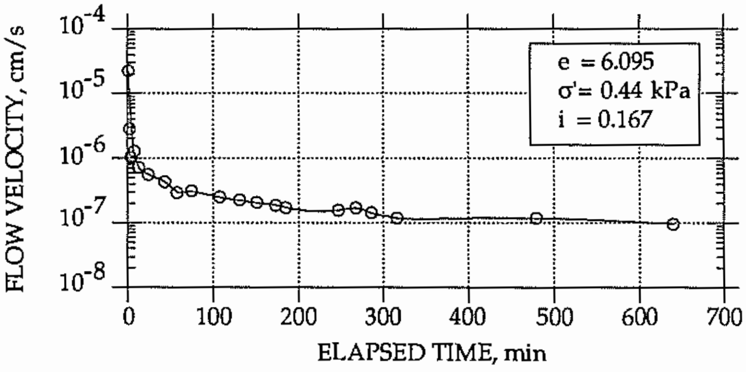

Figure 4. Variation of flow velocity with time.

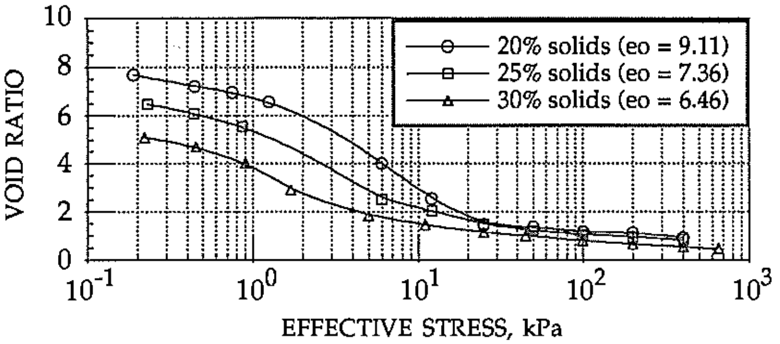

Figure 5. Compressibility of oilsand fine tails.

Figure 5 depicts the compressibility of the fine tails. The results for the 30% initial solids content test were obtained from Pollock (1988). It is clear from figure 5 that the effect of initial void ratio is substantial in the low effective stress range that exists in the tailings pond. When the effective stress reaches about 100 kPa, the effect of initial void ratio becomes small. The conclusion is that the compressibility of the fine tails is dependent on the initial void ratio of the sample. Usually, in soil mechanics, the recompression of overconsolidated soils follows a different void ratio-effective stress relationship until the virgin compression state is reached. However, fine tails are not overconsolidated soils; they are underconsolidated and therefore should follow the virgin compression line irrespective of the initial void ratio. The experimental results suggest that the process of aging develops different fine tails microstructures. Therefore a time-dependent factor has to be taken into account which connects the individual void ratio-effective stress relationships.

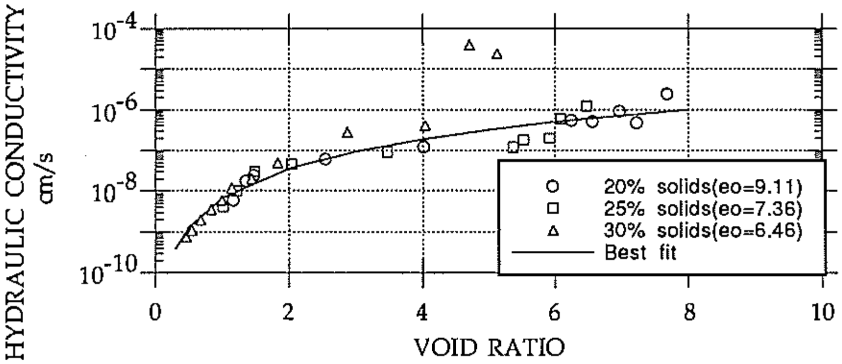

Figure 6. Permeability of fine tails.

Figure 6 shows all the hydraulic conductivity values for different void ratios. Unlike the void ratio-effective stress behavior, void ratio-permeability behavior does not appear to be influenced by the initial void ratio. It suggests that different micropore structures control the permeability and the compressibility.

Conclusions

A slurry consolidometer has been developed to allow large deformations during consolidation and to allow permeability tests to be performed on the fine tails. Development of a top cap clamping system has permitted permeability testing to be conducted on the high-void-ratio slurries without introducing seepage-induced consolidation. The permeability test results revealed a time-dependent flow discharge at a constant gradient. The flow velocity would drop up to two orders of magnitude before reaching a steady-state value. The steady-state values were used to calculate the hydraulic conductivity.

Unlike normal soils, the compressibility of the fine tails is controlled by the initial void ratio of the sample, which suggests that aging changes the microstructure of the fine tails and hence the compressibility. The above analysis suggests that there is a time-dependent parameter involved in the compressibility of fine tails. The older the fine tails, that is, the longer they have consolidated in the tailings pond, the smaller the void ratio they will reach under an applied effective stress. Therefore a single void ratio-effective stress relationship is not sufficient to describe the consolidation behavior. On the other hand, the permeability is not influenced by the initial void ratio, which suggests that permeability and compressibility are controlled by different elements of pore structure.

The above properties have been measured to allow the development of an analytical model for the long-term consolidation behavior of fine tails. The design of the eventual disposal and reclamation procedures and facilities for the oil sand fine tails requires such an analytical model.

Literature Cited

Aboshi, H., H. Yoshikuni, and S. Maruyama. 1979. Constant loading rate consolidation test. Soils and Foundations 10(1): 43-56.
http://dx.doi.org/10.3208/sandf1960.10.43

Imai, G. 1979. Development of a new consolidation test procedure using seepage force. Soils and Foundations 19(3): 45-60.
http://dx.doi.org/10.3208/sandf1972.19.3_45

Imai, G. 1981. Experimental studies on sedimentation mechanism and sediment formation of clay materials. Soils and Foundations 21(1): 7-20.
http://dx.doi.org/10.3208/sandf1972.21.7

Janbu, N., O. Tokheim, and K. Senneset. 1981. Consolidation tests with continuous loading. p. 645-654. In Proceedings of the Tenth International Conference on Soil Mechanics and Foundation Engineering, Vol.1.

Lee, K. 1981. Consolidation with constant rate of deformation. Geotechnique 31 (June): 295-329.
http://dx.doi.org/10.1680/geot.1981.31.2.215

Lowe, J., E. Jonas, and V. Obrician. 1969. Controlled gradient consolidation test. ASCE Soil Mech. and Foundation Div. 95(SM1): 77-97.

Pollock, G.W. 1988. Large strain consolidation of oil sand tailings sludge. M.Sc. Thesis, Department of Civil Engineering, Univ. AB, Edmonton, AB, Canada 276 p.

Tavenas, F., P. Leblond, P. Jean, and S. Leroueil. 1983. The permeability of natural soft clays: I, methods of laboratory measurement. Can. Geotech. J. 20(4): 629-644.
http://dx.doi.org/10.1139/t83-072

Znidarcic, D., P. Croce, V. Pane, H.W. Ko, H.W. Olsen, and R.L. Schiffman. 1984. The theory of one-dimensional consolidation of saturated clays, III, existing testing procedures and analyses. Geotech. Testing J. 7(3): 123-133.
http://dx.doi.org/10.1520/GTJ10488J