PROPERTIES OF TREATMENT SLUDGE DURING SEDIMENTATION AND CONSOLIDATION TESTS[1]

Lincar Pedroni[2], Jean-Baptiste Dromer, Michel Aubertin, Greg Kennedy

Abstract. Sedimentation and consolidation tests have been conducted on sludge produced from an acid mine drainage (AMD) treatment plant. The testing program involved the development of a new laboratory system, designed and constructed to assess the specific properties of low density slurry. During the instrumented large size column tests, the evolution of sedimentation and hydrodynamic consolidation was monitored with optical observation of the solid-liquid interface, evaluation of density ρ with gamma ray sensors, and measurement of pore pressure u using transducers. At the end of each test, physical and geotechnical properties of the resulting sludge were measured. In this paper, the authors will present a brief overview of the set up, followed by a presentation of new test results with the analysis using sedimentation-consolidation theories. The results presented here will be used in future analyses to evaluate the volume changes of AMD treatment sludge in storage basins.

Additional Key Words: AMD, large strain, mechanical properties.

[1] Paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

[2] Lincar Pedroni is PhD candidate of Mineral Engineering, Ecole Polytechnique, Montreal, QC, H3C 3A7, Canada. Jean-Baptiste Dromer is a MScA in Mineral Engineering, Now, Process Engineer, Mines Seleine, Grosse-Île, QC, G4T 6A6, Canada. Michel Aubertin is a Professor in the CGM Engineering Department, Ecole Polytechnique de Montreal. Greg Kennedy is a Research Scientist in the Department of Engineering Physics, Ecole Polytechnique de Montreal.

Introduction

Mining operations which produce acid mine drainage (AMD) have to treat their effluent before discharge. These acid waters typically contain high amounts of solubilized elements such as sulphates and heavy metals which are then precipitated with lime and recovered in the treatment sludge (e.g. Walton-Day, 2003; Aubé, 2005). Lined ponds are often used to store the large volume of sludge produced. The design of these ponds remains largely empirical as little is known about the hydro-geotechnical behaviour of treatment sludge, which typically contains only 10 to 25% of solids by weight. There was thus a need to develop measurement techniques to assess the behaviour of sludge after their discharge.

In this paper, the authors present the theoretical background and a brief description of the testing system. The main results of two tests performed on sludge are shown with the interpretation based on the sedimentation-consolidation theory. The evaluation of changing volumes in storage basins of AMD treatment sludge is discussed. A previous paper (Dromer et al., 2004) contains more details on the testing system.

Basic Concepts for Sludge Behaviour

Treatment sludge is a mining by-product which is usually transported hydraulically to the disposal area. The deposited pulp (or hydraulic mixture) then shows 3 broad stages of behaviour as shown in Fig. 1. During the first stage, the solid particles are suspended in the fluid. In this stage each particle behaves more or less independently from the others. In the second stage, there is a progressive deposition of the solids, producing an interface with clear water above the sedimentation zone. At the base, there is a zone of accumulated particles whose thickness progressively increases with time.

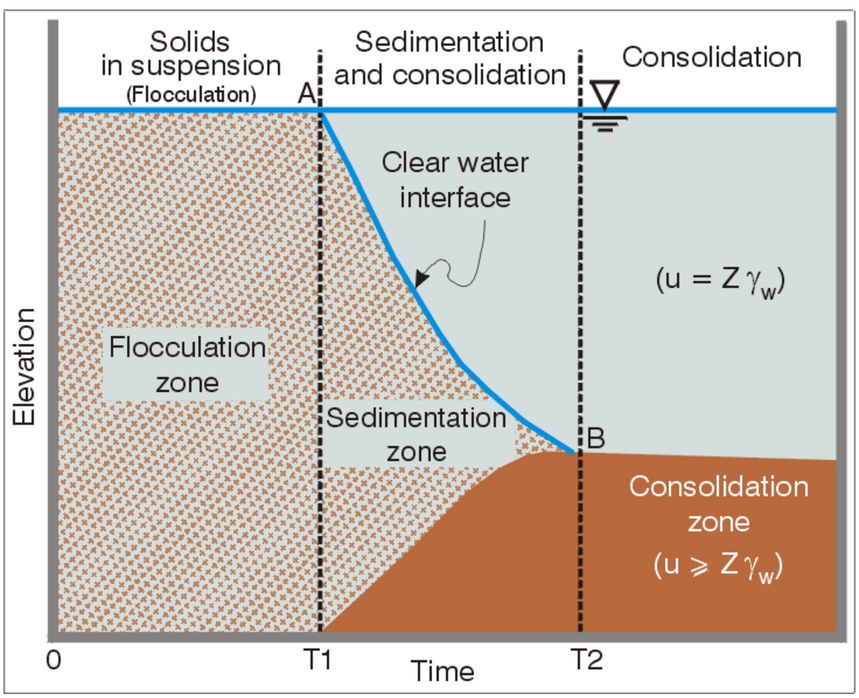

Figure 1. Schematic representation of sludge sedimentation and consolidation in a vertical column (adapted from Schiffman et al. 1988, see also Dromer et al. 2004)

The sludge behaviour progresses from a sedimentation process, where particles are interacting through fluid motion, to a consolidation stage where the grains form a solid skeleton behaving as a porous medium. During the consolidation stage, settlement takes place as water is expelled by the pressure exerted by the self-weight of the solids. Above the consolidating sludge, the water pressure u is that of the water column at a given position z ($u = z\gamma_w$), while it tends to be higher than its equilibrium (hydrostatic) value in the consolidation zone. Hydrodynamic primary consolidation ends when all the excess pore pressure (i.e. $u > z\gamma_w$) is dissipated. The solid settlement can nevertheless continue under its own weight due to secondary compression.

<u>Sedimentation</u>

Early in the process, in the flocculation zone, the particles behave according to Stokes' law. There is a drag force on each particle that depends linearly on its size, on fluid viscosity, and downward velocity. This velocity is limited by the maximum velocity, which is given by:

$$v = \frac{D^2 \gamma_s^{'}}{9\eta} \tag{1}$$

where D is the particle diameter (L), γ_s' (F/L^3) is the submerged (effective) unit weight of the solid grains, and η (M/T.L) is the fluid viscosity.

Later, in the sedimentation phase, the solid concentration becomes high enough so particles can interact with each other through their influence on the fluid motion. The sludge behaviour can then be defined with the Kynch (1952) equation which is expressed as (Alexis et al. 1992; Gallois 1995):

$$\frac{\partial \gamma_d}{\partial t} + \frac{d(\gamma_d v_s)}{d\gamma_s} \frac{\partial \gamma_d}{\partial x} = 0 \tag{2}$$

where γ_d is the dry unit weight of the pulp, and v_s is the absolute velocity of the grains, which then depends on the local solid concentration (see also Pedroni, 2003; Dromer, 2004).

<u>Consolidation</u>

During the consolidation stage, the sludge behaviour can be described with equations initially proposed by Terzaghi (1942) in soil mechanics. The main equation can be formulated as (e.g. Holts and Kovacs, 1981):

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \tag{3}$$

where u (F/L^2) is the pore pressure, c_v (L^2/T) is the coefficient of consolidation, and z (L) is the vertical position. This equation indicates that the variation of the pore pressure u over time t and position is related to the coefficient of consolidation c_v, which is itself expressed as:

$$c_v = \frac{k}{\rho_w g} \frac{1 + e_0}{a_v} \tag{4}$$

where k (L/T) is the hydraulic conductivity, ρ_w (M/L^3) is the water density, g (L/T^2) is the gravitational acceleration, e_0 (–) is the initial void ratio, and a_v (L^2/F) is the coefficient of compressibility. The latter coefficient is the slope of the effective stress – void ratio ($\sigma' - e$) relationship:

$$a_v = -\frac{de}{d\sigma'} \tag{5}$$

The primary consolidation settlement due to a change in the void ratio is typically expressed from the compression index C_c:

$$C_c = \frac{-de}{d\log\sigma'} \tag{6}$$

The settlement of the sludge deposit is then calculated as:

$$S_{pc} = \frac{H}{(1+e_0)} C_c \left[\log\left({\sigma'_{vf}}/{\sigma'_{v0}} \right) \right] \tag{7}$$

where H is the thickness of the sludge layer, e_0 is the initial void ratio, C_c is the compression index, σ'_{v0} is the initial vertical effective stress and σ'_{vf} the final vertical effective stress.

The parameters that describe sedimentation and consolidation of sludge can be defined by measuring the evolution of the interface position, density, pore pressure, and effective stress state. However, the above equations were developed for small displacements. In the case of sludge, the basic conditions for their application may not be satisfied. For such highly compressible materials, a large strain theory formulation is more suitable; such theories have been proposed by Gibson et al. (1967; 1981; see also Been and Sills, 1981; Cargill, 1984), but these will not be presented or used in this paper.

Unified formulation

Sedimentation and consolidation processes often occur simultaneously in a column. For that reason Pane and Schiffman (1985) developed a unifying theory, based on the following equation:

$$\sigma = \beta[e]\sigma' + u \tag{8}$$

In this equation, the parameter β depends on the void ratio e. It is related to the magnitude of the effective stress σ' between the solid grains. In the sedimentation stage, β is nil so $\sigma = \sigma'$; in the consolidation stage, β is equal to one so $\sigma = \sigma' + u$. The transition between the two conditions occurs progressively (in practice the transition can be difficult to evaluate). When the value of β is unknown, it is introduced in the following unified equation (Pane and Schiffman, 1985):

$$\frac{\partial}{\partial e}\left[\gamma_r k_{rz}\right]\frac{\partial}{\partial z} + \frac{\partial}{\partial z}\left[\frac{k_{rz}}{\gamma_r}\frac{\partial \sigma'}{\partial e}\beta\frac{\partial e}{\partial z}\right] + \left[\frac{k_{rz}}{\gamma_r}\sigma'\frac{\partial \beta}{\partial e}\frac{\partial e}{\partial z}\right] + \frac{\partial e}{\partial t} = 0 \tag{9}$$

where z indicates the position along the column, $k_{rz} = k_z/(1+e)$ (L/T) is the reduced hydraulic conductivity along the z axis, $\gamma_r = \gamma_s/\gamma_w - 1$ (–) is the relative density, γ_s (F/L^3) is the solid unit weight and γ_w (F/L^3) is the water unit weight. This function is similar to the Kynch (1952) sedimentation equation (when β = 0). The large strain consolidation theory of Gibson et al. (1981) is retrieved when β = 1 (see also Azevedo et al., 1994).

The information required to apply the equations presented above can be obtained from tests conducted in the system described below.

It is worth mentioning here that another unifying approach has also been formulated by Toorman (1996, 1999). It is based in a combination of Kynch's equation and the diffusion equation. Toorman's formulation will not be presented or used in this paper. However, in order to better follow (and represent) the evolution of sludge properties during sedimentation and consolidation, Toorman's formulation is being concurrently analysed (Pedroni and Aubertin, 2005).

Testing System

The system described here was based on an early experimental version put together by Bédard et al. (1997). Figure 2 shows the main components of the testing system that was installed in the laboratory facilities of the NSERC Polytechnique-UQAT Industrial Chair, in Montreal. It includes the column and its support (1), pressure transducers (2), a digital camera for the position of the interface, a signal treatment system (3), and a density measurement device (4). These components have been described in detail by Dromer (2004); a very brief summary is presented here.

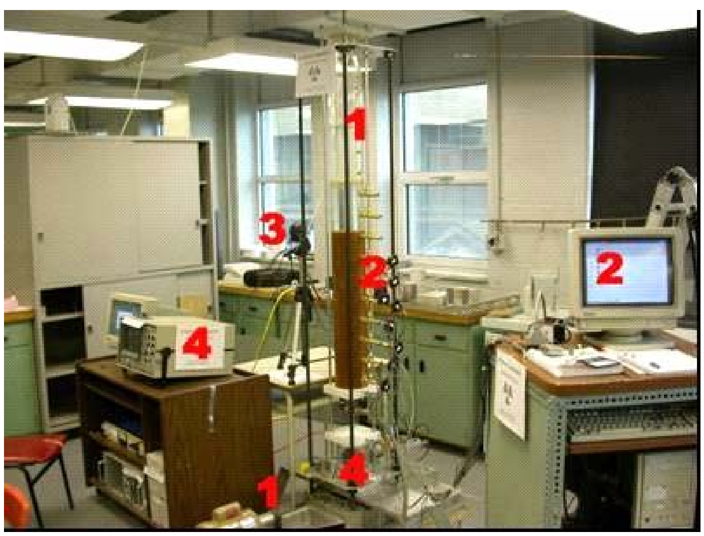

Figure 2. Picture of the experimental testing system showing the main components; see text for details (taken from Dromer, 2004; see also Dromer et al., 2004)

The column is made of Plexiglas. It has a height of 180 cm, with an internal diameter of about 15 cm. A small calibration column filled with water is installed below the main column, for calibrating the density measuring device. Four threaded bolts run along the column to keep the components together. The threaded bolts also serve to raise and lower a plate on which the density measuring device is installed using an electric motor. The support plate moves at a rate of about 40 cm/min.

Pore pressure is measured with transducers installed every 10 cm, starting at 4 cm from the base plate. These are connected to porous cups inserted along the column. The transducer range for pore pressure measurement is ±103 kPa. The transducers are linked to a data acquisition system.

A digital camera follows the position of the free water interface. The imaging frequency is adapted to the test requirements, and relies on a measuring tape placed along the column. Images are used to determine the displacement rate of the interface.

Much effort was required to develop the density measurement system. This system was designed with researchers from the neutron activation laboratory (Dept. of Engineering Physics, École Polytechnique de Montréal), using their equipment. It uses gamma ray emission, transmission and detection, a technique often used in others industrial processes (Moens 1981). Gamma rays are used instead of x-ray devices (e.g. Been, 1981; Been and Sills, 1981; De Campos et al. 1994), because their penetrating power is higher, allowing more precise determination of the actual density of relatively thick media. The gamma ray source (103keV) is placed in a casing on the side of the column. Depending on the density of the sludge, a certain fraction of the emitted rays are transmitted through the column along its diameter and are captured by a detector placed on the other side at the same elevation (on the moving plate). The validity and precision of the system were evaluated under well-controlled conditions. More details on the verifications of the experimental system are presented by Dromer (2004).

Testing Procedure

For the actual tests, the samples are first prepared by mixing the sludge to obtain a homogeneous material. The sludge is then put into the column from the top with a tubing system. The pressure transducers and digital camera are started when the sludge is placed in the column. Readings are stored in a computer. The data can be retrieved and transferred for analysis.

The radioactive sources (Sm-153, half-life 48 hours) are activated two times a week during the measurements. Readings are made at regular intervals by moving the γ source-detector system along the column, to obtain the density profile at different times during the experiment.

A pseudo-steady state is reached (i.e. no change in the interface position, density, and pore pressure) after 3 to 15 days, depending on the material. Then external loads are added on top of the column using a perforated plate placed on the sludge. Loads are added periodically, like in a consolidation test. The addition of a load increases the pore pressure u suddenly (see below); this pressure decreases as the water is expelled upward (drainage occurs only from the top). Monitoring of the pore pressure, position of the surface, and density of the material along the column are used to analyse the behaviour of the sludge.

At the end of a test, which may last up to 3 months, the column is dismantled and the sludge is retrieved in an "intact" state (Fig. 3). Tests are run on the sludge samples to measure density, to analyse the chemical composition of the solids and pore water, and to assess other mechanical characteristics using vane and fall cone apparatus.

Figure 3. Sampling of the sludge.

Experimental Results

Column tests

The testing system described above has been used to conduct tests on a kaolin mixture and on a sludge sampled from a treatment plant located in Abitibi, Québec. A previous paper by Dromer et al. (2004) presented some preliminary results obtained from this sludge. New results obtained from other tests on the same sludge are presented here.

The solid grain relative density for this sludge is about 3.14. Its D10 is of about 1 μm and has a D60 of about 20 μm. During a typical test, the pulp density P changed from about 8.6 % to 13.2% ; the water content *w* was reduced from 809% to 503%, while the void ratio *e* decreased from 25.4 to 15.8 (for a maximum applied stress of 14.56 kPa).

The position of the sludge surface over the duration of the first phase is shown in Fig. 4. In this figure the first level corresponds to the sedimentation stage (no applied load), which is followed by consolidation due to the added pressure applied on top of the sludge. In these tests, the pressure applied on top of the column represents the effect of additional layers of sludge being discharged on the pond surface (although the boundary drainage conditions are somewhat different in the latter case). The experimental approach retained here is also used to conduct laboratory tests on other soft saturated media (such as sediments and clayey soils).

The evolution of the density profiles measured with the gamma ray system during a test is shown in Fig. 6. It shows two stages: one for the self-weight sedimentation-consolidation, and the other after the external loads were applied. During the test, density tends to increase particularly near the top of the column (as water is expelled upward during consolidation). In the field, the sludge vertical response (i.e. pore pressure and density distribution) may be somewhat different, depending on the drainage conditions at the base of the pond. In many situations, the maximum density is expected to occur at an intermediate elevation between the impervious base and sludge surface (in the absence of significant evaporation and desiccation). Nevertheless, the consolidation parameters determined here also apply for these other boundary conditions, so they can be used for the specific analysis at hand.

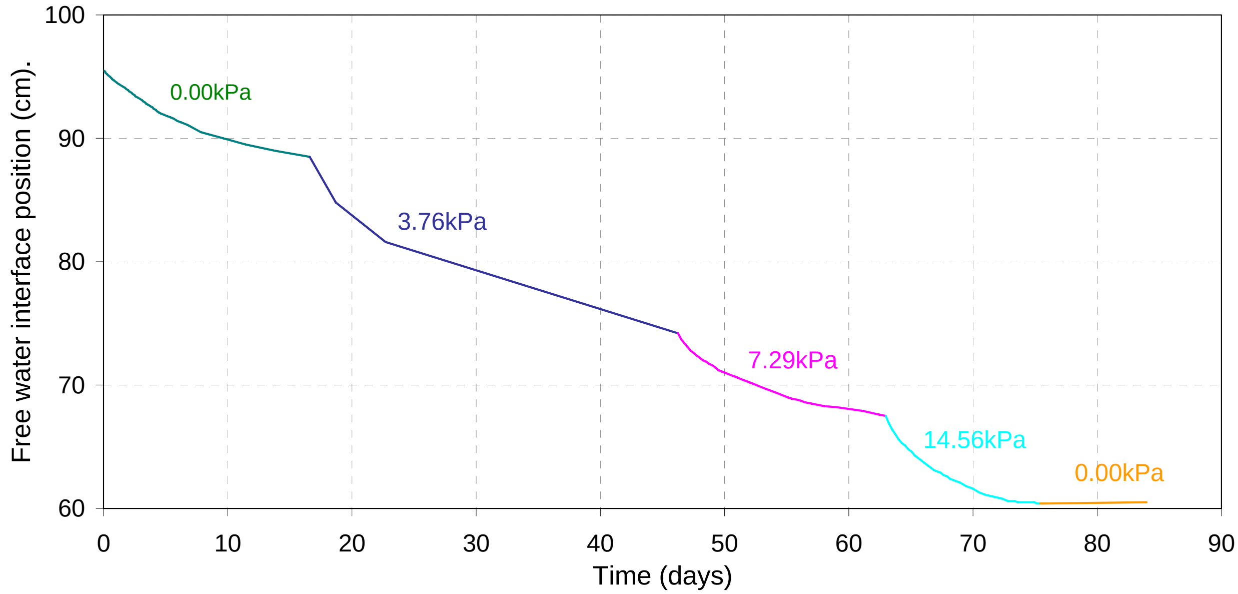

Figure 4. Position of the interface for a test conducted on the treatment sludge.

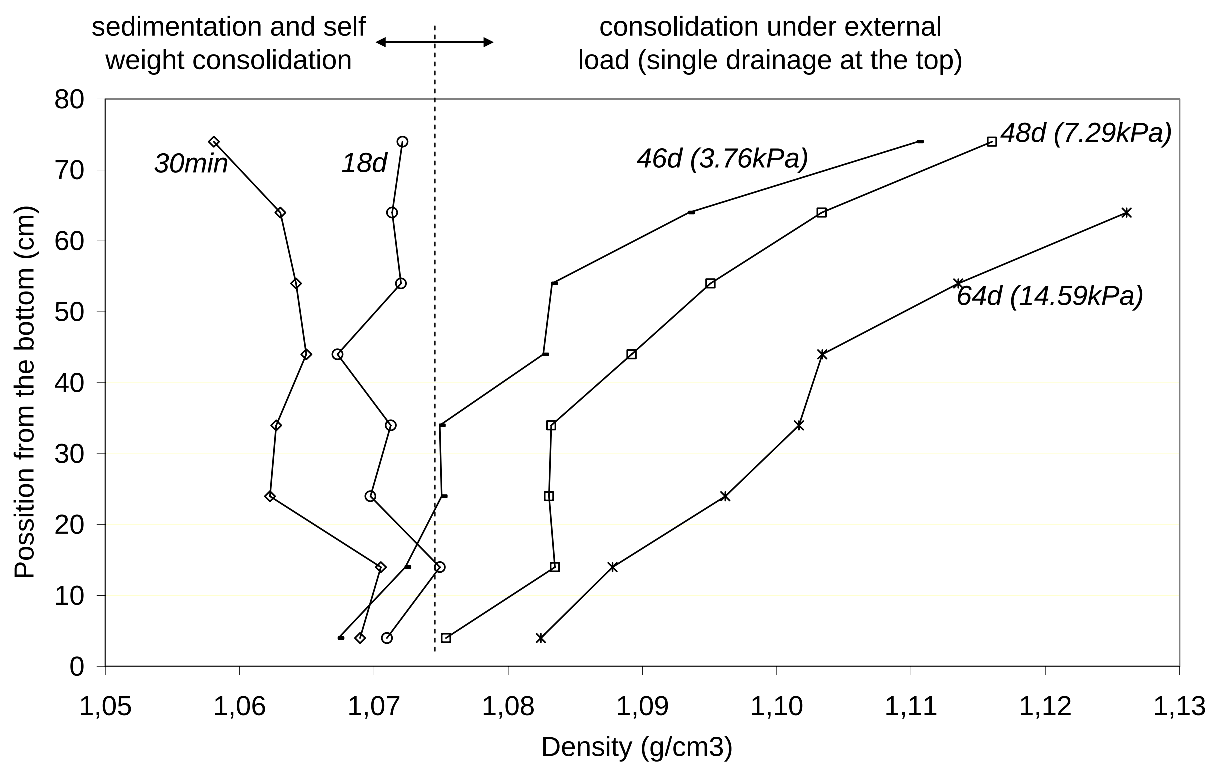

Figure 6. Evolution of the density profiles measured with the gamma ray system during a test conducted on the AMD treatment sludge.

Pore pressure evolution in the test presented in Fig. 4 and 5 is shown in Fig. 6. This shows the effect of adding the loads, with a sudden increase of pore pressure followed by a slow decrease (as expected from the consolidation theory).

During a test, the effective stress along the column can be calculated as the difference between the total stress and the measured pore pressure.

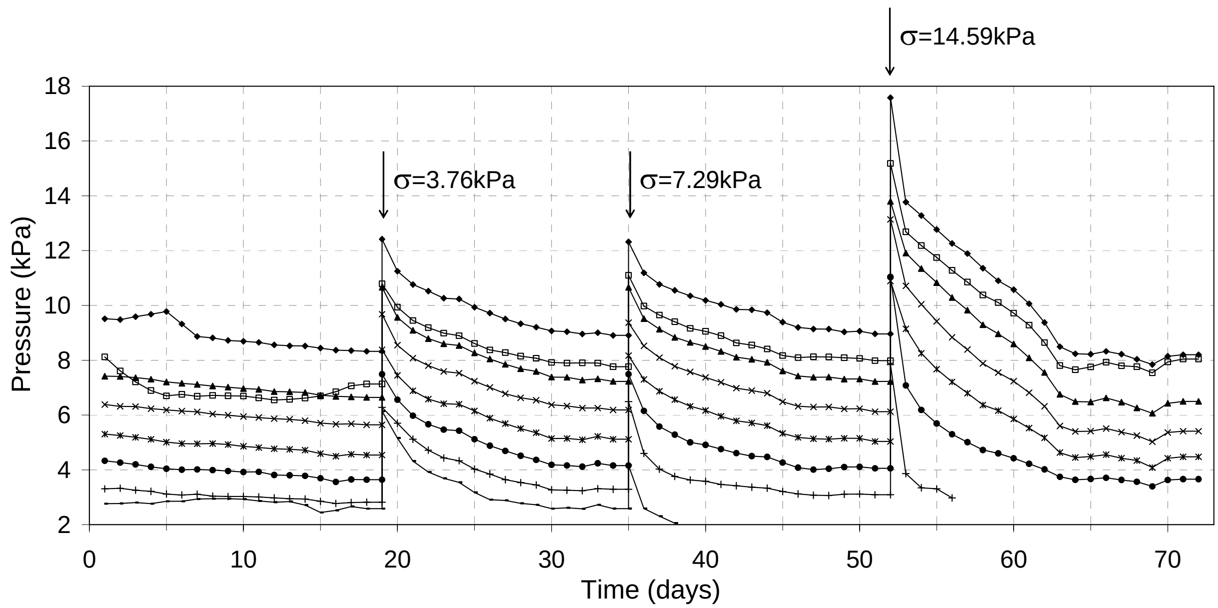

Figure 6. Pore pressure measured during a sedimentation and consolidation test on the AMD treatment sludge.

The experimental results are used to obtain key parameters required to analyse sedimentation and consolidation. Some preliminary values were presented by Dromer et al. (2004), following an early analysis of the results obtained from a test that lasted almost 50 days. Another test of longer duration was conducted later. The estimated values for some geotechnical parameters for the two tests conducted on the sludge are presented in Table 1.

Table 1. Geotechnical parameters for two tests conducted on the AMD treatment sludge.

	Dromer et al. (2004)	This study (Figures 5, 6 and 7)
Cv range (m2/s)	5×10^{-8} to 2×10^{-4}	6×10^{-9} to 2×10^{-5}
Cv average (m2/s)	4×10^{-7}	3×10^{-7}
a_v (kPa^{-1})	–0.3 to –1.5	–1.0 to –2.1
k (cm/s)	3×10^{-5} to 3×10^{-6} *	2×10^{-5} to 8×10^{-6} *
Cc range	3 to 10	4 to 12
Cc average	7	7

* depending on *e*.

The results presented in Table 1 indicate a good consistency between the two long-term test results. They indicate that the value of the consolidation coefficient *Cv* is comparable to that of some soft clays, while the range of *k* values (hydraulic conductivity) would be typical of silty soils. The value of *Cc* is also similar to that of clays. It has also been observed that *Cc* is almost linearly related to e_o, as is the case with many normally consolidated clays (e.g. McCarthy 2002).

Tests on sludge samples

There are different methods available to determine the undrained shear strength of a soft saturated media (such as clay), including the vane shear test, penetration test, unconfined compression test, and direct shear test. The vane shear test is relatively simple and convenient for many applications (Silvestri and Aubertin 1993). It is well suited for measuring low shear strengths of very soft soils and sediments. Vane shear tests were performed at the end of the column test on undisturbed sludge samples.

The testing apparatus included vanes with a height of 50mm and diameter 25mm. The vane was gently introduced into the consolidated sludge sampled at the base of the column. The torque was applied until the specimen failed.

Additional tests were done on the sludge samples using the fall cone apparatus (ASTM D3441-98).

Figure 7 presents the undrained shear strength measured with the vane test and the fall cone test. Results are given as a function of the water content (and void ratio) of the sludge. The beaviour shows similarities with others sludges, such as those presented by Sridharan and Prakash (1999) for bentonite and kaolin sludges.

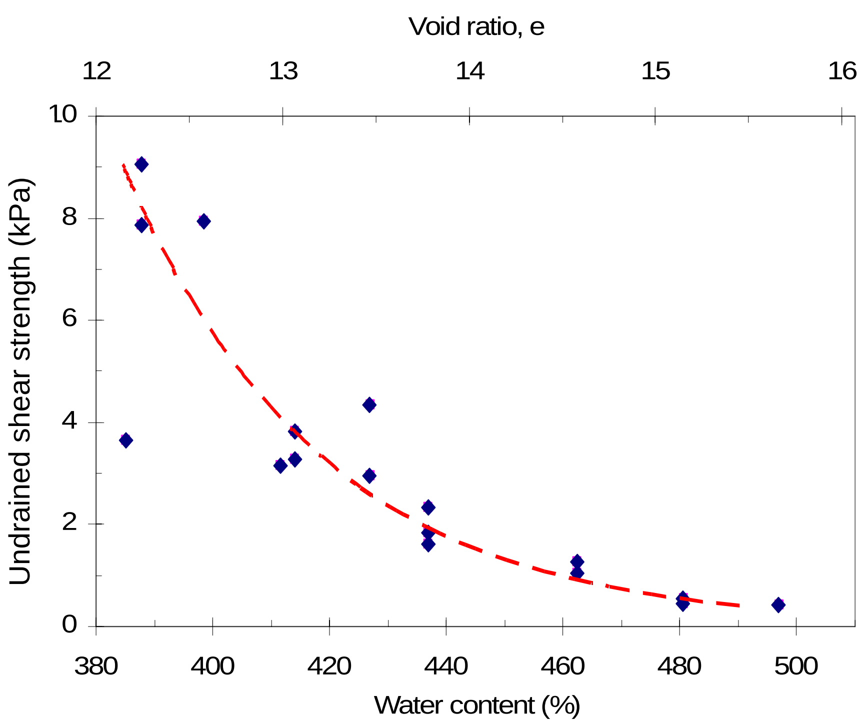

Figure 7. Undrained shear strength measured with the vane test and the fall cone test. Results are shown as a function of the water content and the void ratio of the sludge.

Also, a one-dimensional consolidation test was conducted on a sample taken from the top of the sludge column. The results are presented in Fig. 8 (details are given in Pedroni, 2006, PhD thesis under preparation).

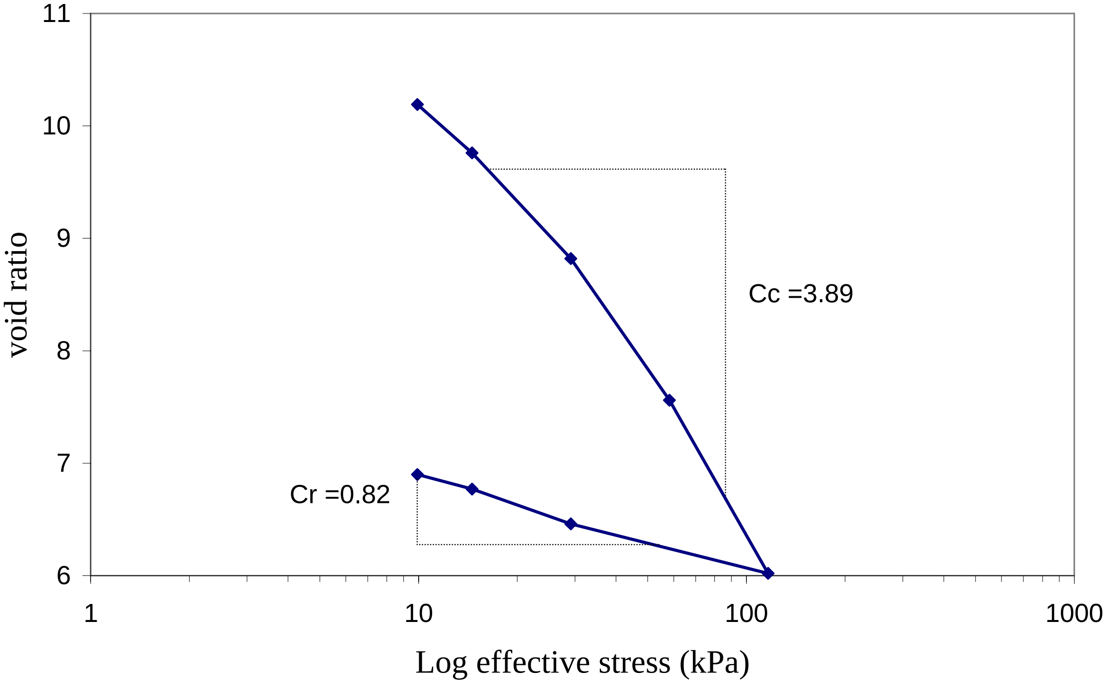

Figure 8. The result of a consolidation test on a sludge sample taken at the top of the column.

As seen in Figure 8, the consolidation of the sludge with respect to the log of the effective stress is relatively linear. This consolidation behaviour of the sludge beyond the stress level attained in the column is consistent with the latter test. The measured value of *Cc* is approximately 4 for a range of void ratios from 11 to 6. Upon unloading, the sludge exhibited considerable rebound; the rebound index *Cr* of the sludge is approximately 0.8.

Other tests are underway to further study the sedimentation and consolidation of the sludge. These new tests involve modifications to the system and new interpretation techniques (Pedroni and Aubertin, 2005).

Conclusions

The properties of treatment sludge have been measured under controlled laboratory conditions using a specially designed system. The system was used to monitor changes during the sedimentation and consolidation phases. The measurements during the tests included the position of the solid-liquid interface as well as the pore pressure and density profiles. Upon dismantling of the column at the end of a test, which can last for months, other properties (such as shear strength) were also measured. The description of the testing and measuring system is summarized in the paper. The results of two tests conducted on sludge are presented.

More tests will be run on AMD treatment sludge and other types of slurry, so constitutive laws can be validated or developed.

Future Work

Another test on sludge is currently in progress. The theoretical formulations will be tested with the data obtained from these most recent tests. Numerical modeling will be critical for this stage. New tests on other materials such as fine tailings and sludge mixtures (sludge and tailings) will also be completed and new γ sources (e.g. Au-198, with energy 412keV) are currently being tested in order to adapt the testing system (i.e. gamma ray system) to tests on higher density materials (e.g. mine tailings).

The work presented by Dromer (2004) and Pedroni and Aubertin (2005) will be updated with the analysis of the new test results on different materials and using the new theoretical formulations.

Also, the volume change in storage basins of AMD treatment sludge will be assessed with the above mentioned equations (and with more elaborate models), using the parameters determined from the column tests (such as Cv, a_v, k, and Cc). For actual field conditions, the analysis is best performed using a numerical model that can take into account the conditions that apply to field situations. This work, together with further investigation of sludge behaviour under large deformation, is the focus of the ongoing program.

Acknowledgement

Part of this work has been financed through founds from NSERC and from the Industrial NSERC Polytechnique-UQAT Chair on Environment and Mine Wastes Management (http://www.polymtl.ca/enviro-geremi/).

Literature Cited

Alexis, A., Bassoulet, P., Le hir, P. and Teisson, C. 1992. Consolidation of soft marine soils: unifying theories, numerical modelling and in situ experiments. p. 2949-2961. *In:* Proc. of the 23rd International Conference on Coastal Engineering ICCE'92 ASCE. Venice, Italy. Ed Edge.

Aubertin, M., Bussière, B. and Bernier, L. 2002. Environnement et gestion des rejets miniers. Ville Mont-Royal. Québec : Presses internationales Polytechnique. 1 CD.

Aubé, Bernard. 2005. Une étude en usine pilote de la production de boues à haute densité durant le traitement des eaux de drainage minier acide. *In:* Proceedings of the Symposium 2005 Mines and the Environment. Rouyn-Noranda. Canada. (To be published.)

Azevedo, R.-F., Alves, M.-C.-M. and De campos, T.-M.-P. 1994. Numerical analysis of the sedimentation and consolidation of a neutralized red. p. 433-439. *In:* First International Congress on Environmental Geotechnics. Edmonton. Canada.

Bédard, C., Aubertin, M. and Kennedy, G. 1997. Une nouvelle technique pour caractériser les propriétés de sédimentation et de consolidation des boues de traitement. rejets industriels et prévention de la pollution. p. 323-335. *In:* C.R. 20e Symposium sur les eaux usées, AQTE/AESEQ. Collection Environnement de l'Université de Montréal.

Been, K. 1981. Non-destructive soil bulk density measurements by X-ray attenuation. p169-176. Geotechnical Testing Journal. Vol. 4, n 4.

Been, K. and Sills, G.-C. 1981. Self-weight consolidation of soft soils: an experimental and theoretical study. p. 519-535. Geotechnique. Vol. 31, n 4.

Cargill, K.-W. 1984. Predictions of consolidation of very soft soil. p. 775-795. ASCE Journal of Geotechnical Engineering. Vol. 110, n 6.

De campos, T.-M.-P., Alves, M.-C.-M., and Azevedo, R.- F. 1993. Laboratory settling and consolidation behavior of a neutralized red mud. p. 461-466. *In:* First International Congress on Environmental Geotechnics. Edmonton. Canada.

Dromer, J.-B. 2004. Mise au point d'un système de mesure pour caractériser le comportement hydromécanique des boues de traitement des eaux acides minières. Masters Thesis, École Polytechnique de Montréal. Canada.

Dromer, J.-B., Aubertin, M., Kennedy, G., Pedroni, L. and Bussière, B. 2004. A new testing system to investigate the sedimentation and consolidation of sludge and slurry. 1E, p. 16-23. Proceedings of the 57th Canadian Geotechnical Conference. Quebec, Canada.

Gallois, S. 1995. Modélisation de la sédimentation/ consolidation et expérimentations sur les vases estuariennes. PhD Thesis. Université de Nantes. France.

Gibson, R.-E., England, G.-L. and Hussey, M.-J.-L. 1967. The theory of one-dimensional consolidation of saturated clays. Part I: Finite non-linear consolidation of thin homogeneous layers. p. 261-273. Geotechnique. Vol. 17.

Gibson, R.-E., Schiffman, R.-L. and Cargill, K.-W. 1981. The theory of one-dimensional consolidation of saturated clays. Part II: Finite non-linear consolidation of thin homogeneous layers. p. 280-293. Canadian Geotechnical Journal. Vol. 18.

Holtz, R.-D. and Kovacs, W.-D. 1981. Introduction à la géotechnique. Éditions de l'école Polytechnique de Montréal. Traduit par Lafleur, J.

Kynch, G.-J. 1952. A theory of sedimentation. Transactions of the Faraday Society. 48p.

McCarthy, D.-F. 2002. Essentials of soil mechanics and foundations. Basic geotechnics, 6th edition. Prentice Hall.

Moens, L., De Donder, J., Xi-lei, Lin, De Corte, F., De Wispelaere, A., Simonits, A. and Hoste, J. 1981. Calculation of the absolute peak efficiency of gamma-ray detectors for different counting geometries. p. 451-472. Nuclear instruments & methods in physics research. Vol. 187, issues 2-3.

Pane, V. and Schiffman, R.-L. 1985. A note on sedimentation and consolidation. p 69-72. Geotechnique. Vol. 35, n 1.

Pedroni, L. 2003. Réalisation et interprétation d'essais de sédimentation en colonnes visant à évaluer les propriétés de divers sols et boues. Final Report, MSc in Civil Eng., École Nationale d'Hydraulique et de Mécanique de Grenoble, INPG, France, in collaboration with École Polytechnique de Montréal, Canada.

Pedroni, L. and Aubertin, M. 2005. Evaluation of sedimentation and consolidation of slurry: state of the art (in French). École Polytechnique de Montréal. Québec. Canada. (To be published.)

Schiffman, R.-L., Vick, S.-G. and Gibson, R.-E. 1988. Behavior and properties of hydraulic fills. p. 166-202. *In:* Hydraulic Fill Structures, Geotechnical Special Publication n 21.

Silvestri, V. and Aubertin, M. 1993. Study of undrained shear strength using various vanes. p. 228-237. Canadian Geotechnical Journal. V. 16, n 2.

Sridharan, A. and Prakash, K. 1999. Mechanisms controlling the undrained shear strength behaviour of clays. p. 1030-1038. Canadian Geotechnical Journal. Vol. 36, n 6.

Terzaghi, K. 1942. Theoretical soil mechanics. John Wiley and sons. Inc., New York.

Toorman, E. A. 1996. Sedimentation and self-weight consolidation: general unifying theory. p. 103-113 .Géotechnique. Vol. 46, n 1.

Toorman, E. A. 1999. Sedimentation and self-weight consolidation: constitutive equations and numerical modelling. p. 709-726. Géotechnique. Vol. 49, n 6.

Walton-Day, K. 2003. Passive and active treatment of mine drainage. Environmental aspects of mine wastes. p. 335-359. *In:* Jambor, J.-L., Blowes, D.-W. and Ritchie, A.-I.-M. Editors, Mineralogical Association of Canada, Short Course Series, Vol. 31.