Rheology and Hydrogeological Behavior of Thickened Tailings Disposal using Field Experimental Cell

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ABSTRACT

Due to the current global context of the mining industry, many open pit mine projects are being developed. In the cases where the dimensions of the open pits are very important (order of km), the mining industry faces many challenges, particularly the management of mine tailings produced during mineral extractions. For that, different surface disposal technologies can be used such as dry, paste and thickened tailings disposals. These methods allow reducing the deposition area covered by the tailings and limit the environmental footprint. The rheological behavior of the tailings influences their flow distance, which in turn can affect the segregation behavior. The hydrogeological behavior of these types of deposition is mainly related to soil-atmosphere exchange.

To evaluate the geotechnical properties of thickened tailings and their hydrogeological behavior during their deposition, an experimental cell was constructed with three instrumented monitoring stations. The tailings thickness was included between 28 and 40 cm. These monitoring stations allowed to measure changes in volumetric water contents, suctions and pore pressures. Also, before tailings deposition in cell, grain-size distribution and % solids were analyzed. The % solids, rheological yield stress used as the initial design criterion correspond to 68 % and 16 Pa, respectively. During deposition, tailings samplings were performed and these samples were used to evaluate the grain size distribution and rheological properties.

The grain size distributions are typical for hard rock and did not present any segregation during tailings deposition. Rheology properties analysis show that the yield stress values obtained with the Bingham and Herschel-Bulkley models are very close to 8 Pa. The Sicko and Cross models provide similar values for the dynamic viscosity η_{∞} (= 0.46 Pa.s) at high shear stress or rate ranges. Volumetric water content (VWC) measurements performed show that after tailings deposition and during drainage, the VWC are higher in the bottom and in middle than in the top tailings layer. These values remain higher in the bottom, whereas in the middle and top layer there is a rapid decrease indicating that the tailings materials drain relatively well. Finally pore pressure measurements showed that the pressure dissipation takes about 10 days to reach the initial state. These results allow concluding that these materials can be used as thickened tailings and allow to manage properly the wastes tailings and to limit the environment impact.

Keywords: Mine tailings, Experimental cell, Rheological properties, Hydrogeological

INTRODUCTION

The extraction of mineral resources plays an important role in the Canadian economy. However, ore extraction generates large amount of wastes. In Canada, about 650 Mt of solid wastes are generated each year by mining operations (*in* Winfield et al. 2002). These wastes include overburden, fine-grained mill tailings produced by the ore processing plant and waste rock extracted to reach the orebody.

Due to the current global context of the mining industry, many open pit mine projects are being developed. In the cases where the dimensions of the open pits are very important (order of km), the mining industry faces many challenges, particularly the management of mine tailings generated during mineral extractions (Oxenford & Lord 2006; Fourie 2009). Over the last few years, new and modified approaches have been proposed to increase the geotechnical and geochemical stability of mine tailings to better insure environmental protection (Bussière 2007). For the surface disposal, different technologies can be used such as 1) thickened (Robinsky 1999, Oxenford and lord 2006), 2) slurry, 3) paste (Hassani and Archibald, 1998; Benzaazoua et al. 2004), and 4) dry tailings disposals (Devies and Rice 2001, Kemp 2005). These technologies allow reducing the deposition area covered by the tailings and limit the environmental footprint.

The thickened paste technology offers significant economic incentives and environmental benefits (Meggys and Jefferies, 2012) because particle segregation cannot occurs during process, the paste material exhibits much greater stability than conventional tailings; there is no need for a pond on top of the deposit; which itself forms a gently sloping surface promoting runoff of rain water; and the overall costs are lower than for conventional slurry technologies

To evaluate the hydrogeological behavior of thickened tailings during and after deposition, an experimental cell was constructed and instrumented using monitoring stations. The main objectives of this paper are to evaluate in first the possible segregation of tailings during deposition and their rheological properties and in second the drainage behavior of the thickened tailings after deposition.

This article starts by field experimental cell description and its instrumentation followed by material characterization and rheological properties. Then hydrogeological behavior using volumetric water content and water pressure are presented. Finally this paper ends by a conclusion

FIELD EXPERIMENTAL CELL AND MATERIALS CHARACTERISATION

Experimental cell and monitoring stations

The field experimental cell was constructed using three dykes in the north, east and west side (see Fig. 1). Then three monitoring stations were installed in the thickened tailings flow direction, station 1 being closest to the discharge point. Each station is equipped with 1) 5TM sensors for volumetric water content and temperature measurements; 2) MPS sensors for the suction measurement (see Figure 1). Volumetric water content and suction sensors are connected to data logger for continuous measurements (see Maqsoud et al. 2007). The location of different sensors from the bottom, corresponding to the initial surface before deposition of tailings cell, is shown in Table 1 where one can observe that the average spacing between sensors is about 10 cm.

At each monitoring station, a well point was installed prior to the tailing depositions and it is equipped with a mini-Diver logger for continuous measurement of water pressure (see Figure 1).

Table 1 Sensor locations from the bottom surface installed at different monitoring stations

	Bottom sensors	Middle sensors	Top sensors
Station 1	10 cm	20 cm	35 cm
Station 2	7 cm	21 cm	32 cm
Station 3	9 cm	18 cm	28 cm

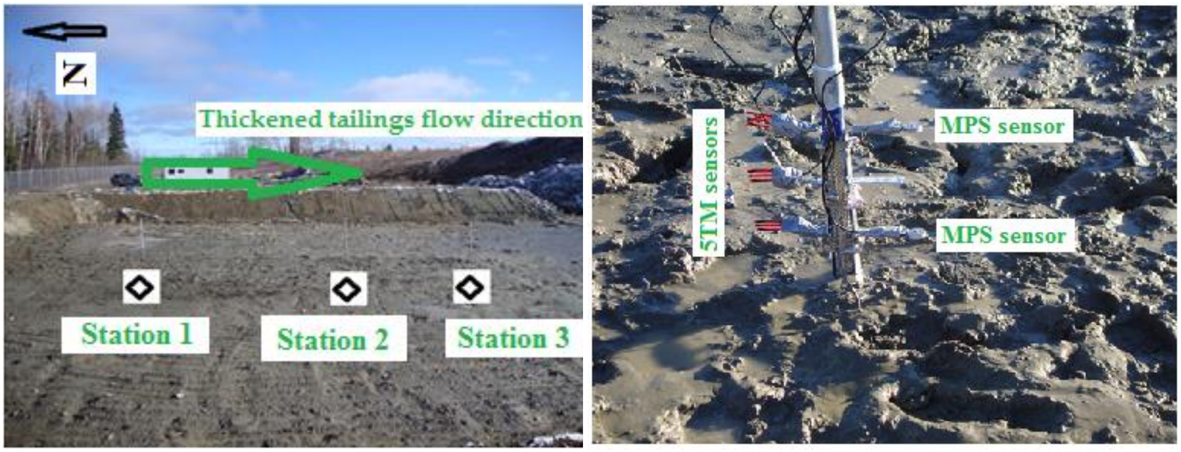


Figure 1 Experimental cell: a) Location of the different monitoring stations; b) details of instrumentation

After installation of monitoring stations, solid percent were verified using different methods then tailings deposition occurred in the experimental cell. Two layers were deposited in the experimental cell and during deposition 5 tailings samples were collected for each layer (see Fig. 2 for sampling locations).

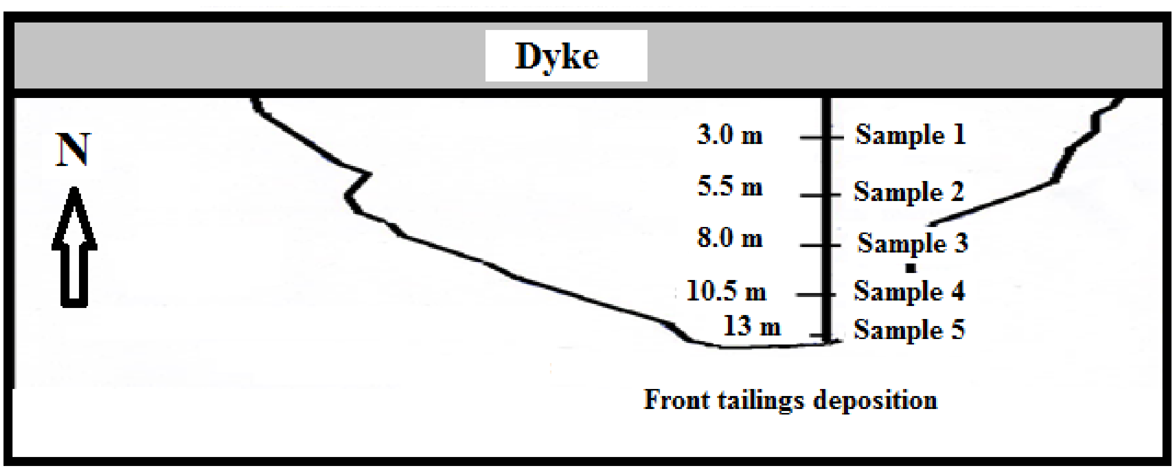


Figure 2 Samples location during tailings depositions

Grain size distribution and rheological properties

The grain-size distribution of the tailings was measured with a particle size analyzer based on laser diffraction. The apparatus used is a Mastersizer Standard Type S from Malvern Instrument (Merkus

2008; ASTM D 6913-04, 2009). The grain size measured with this equipment is included between 0.01 and 1000 μm.

The rheological properties of tailings were studied using an AR 2000 apparatus from TA Instruments. The tests were performed following the protocol:

- Preparation of a small pastefill batch (50 ml) at a given solid content;
- Pastefill mixing for 2 minutes;
- Rheological testing on a specimen of 28 mL at times t = 10 min (t =0 corresponds to the beginning of pastefill mixing);
- Each tests series was triplicated to ensure reproducibility of the results.

The rheological tests were performed at 20°C using a 14 -diameter by 42 mm-high vane geometry. The gap between the rotating vane and the wall of the stationary cylinder was 1 mm. This geometry gap must be at least 10 times higher than the largest grain size of the tested mixture. The following shear protocol was used:

- Conditioning step: a pre-shear stage of 30 s at a shear rate of 800 s^{-1} is performed;
- Flow procedures: the specimen was sheared from 800 to 0 s^{-1} using a continuous shear ramp test, stepped flow step and a steady state flow step.

The down flow and viscosity curves obtained were fitted using 4 models available in *TA instruments* data analysis software to obtain some rheological parameters such as the yield stress, etc.:

- Bingham and Herschel-Buckley models for flow curves;
- Cross and Cisko models for viscosity curves.

The Herschell–Bulkley and Bingham models are described with equations (1) and (2), respectively.

$$\tau = \tau_{0HB} + K_{HB}\dot{\gamma}^{n_{HB}} \quad [1]$$

$$\tau = \tau_{0B} + \eta_B\dot{\gamma} \quad [2]$$

The Sisko and Cross equations are defined with equations (3) and (4), respectively.

$$\eta = \eta_\infty + K_S\dot{\gamma}^{n_S-1} \quad [3]$$

$$\eta = \eta_\infty + \frac{(\eta_0-\eta_\infty)}{1+K_C\dot{\gamma}^{n_C}} \quad [4]$$

In equations (1) to (4), τ is the shear stress, $(\dot{\gamma})$ is the shear rate, and η is the dynamic viscosity. $(=\tau/\dot{\gamma})$. In eq. (1), τ_{oHB}, K_{HB} and n_{HB} represent the Herschell–Bulkley yield stress, viscosity (or consistency) and flow rate index, respectively. The following behavior applies: $n_{HB} < 1$ for shear-thinning, $n_{HB} > 1$ for shear-thickening and $n_{HB} = 1$ for Binghamn behavior (see eq. 2). In eq.(2), τ_{oB}, η_B correspond the Bingham yield stress and viscosity. In eqs. (3) and (4), η_0 and η_∞ are dynamic zero-rate ($\dot{\gamma}$ =0) and infinity-rate ($\dot{\gamma} \rightarrow \infty$) viscosities, respectively. K_s and K_c are consistency parameters and n_s and n_c are viscosity rate indexes. The performance of the different models can be compared using the standard error (SE) defined with equation (5). SE is deemed acceptable when it is less than 20 ‰ (TA Instrument manual).

$$SE = \left[\frac{\left(\sum\frac{(x_m-x_c)^2}{(N-2)}\right)^{1/2}}{\text{Range}} \times 1000\right] \quad [5]$$

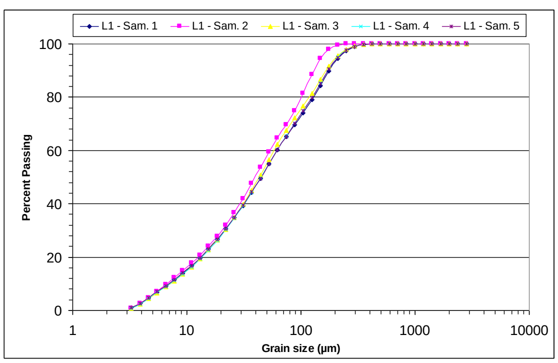
where Range = difference between the maximum and minimum value measured, N is the number of points, x_m and x_c represent measured and calculated (with the fitting model) values, respectively.

MAIN RESULTS

In this paragraph, one can find results of the grain-size characterization, rheological properties and hydrogeological behavior of tailings during and after deposition.

Grain size distribution

The grain size distributions of different sampled materials are presented in figure 3 where one can observe that grain size range included between 2 and 74 µm (corresponding to silt fraction) corresponds to percent included between 65 and 69. The other percent corresponds to sand fraction. These different curves were used for determination of the geotechnical parameters D_{10}, D_{60} *and coefficient of uniformity* ($C_U = D_{60} / D_{10}$). These values are presented in Table 2, where one can observe that D_{10} is included between 6.47 and 7.16 (mean = 6.84) µm; D_{60} is included between 53.47 and 61.94 (mean = 59.84) µm and C_U, is included between 7.97 and 9.13 (mean = 8.75). These values are typical for hard rock tailings (see Aubertin et al. 2002).



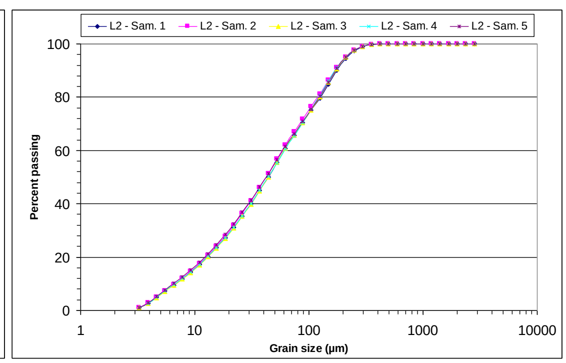


Figure 3 Grain-size distribution of tailings sampled during deposition (L1: layer 1, L2: layer 2, Sam: sample)

Tableau 2 Geotechnical parameters of tailings (Sam: sample)

	Layer 1					Layer 2				
	Sam 1	**Sam 2**	**Sam 3**	**Sam4**	**Sam 5**	**Sam 1**	**Sam 2**	**Sam 3**	**Sam 4**	**Sam 5**
D_{10} (µm)	6.96	6.71	7.16	7.11	6.93	6.77	6.66	6.93	6.74	6.47
D_{60} (µm)	61.8	53.47	58.23	61.55	61.93	60.81	58.28	61.94	61.33	59.06
C_U	8.89	7.97	8.13	8.66	8.94	8.99	8.76	8.94	910	9.13

Rheological properties

Figures 4 shows typical flow and viscosity curves obtained from the tests made following the three flow procedures. These figures show that all obtained results using different procedures are very close. These triplicated results were merged using built-in rheological data analysis software to obtain one representative flow curve and viscosity curve. The merged flow and viscosity curves were fitted with the rheological models described above by applying the best fitting option available in the software (See Figure 5).

a) **b)**

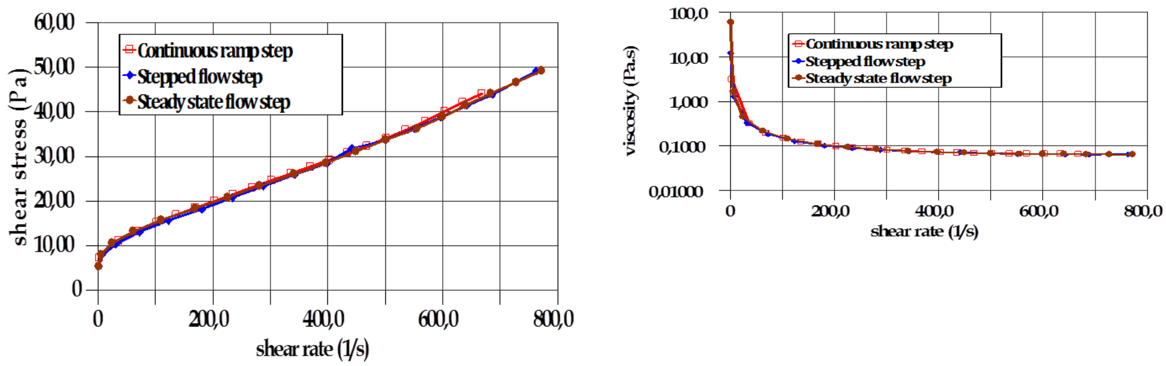


Figure 4 Flow (a) and viscosity (b) curves obtained for different flow procedures

a) **b)**

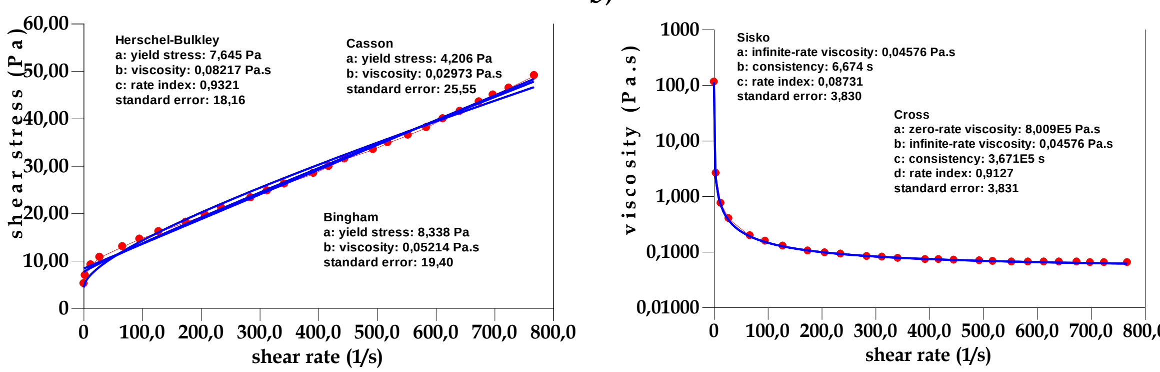


Figure 5 Merged flow (a) and viscosity (b) curves fitted with differents models

Table 3 summarizes the model parameters obtained. The yield stress values obtained with the Bingham and Herschel-Bulkley models are very close about 8 Pa.

Table 3 Rheological parameters obtained by fitting the merged flow and viscosity curves with different rheological models

Parameters	Models			
	Bingham	Herschel-Buckley	Cross	Sisko
Yield stress τ_{0B} or τ_{0HB} (Pa)	8.3	7.6	/	/
Viscosity η_B (Pa.s)	0.052	/	/	/
Consistency K_{HB} (Pa.s)	/	0.082		6.7
Rate index		0.93	0.91	0.87
Zero-rate viscosity η_0 (Pa.s)	/	/	$8\text{x}10^5$	
Infinite-rate viscosity η_∞ (Pa.s)	/	/	0.046	0.046
Consistency K_c	/	/	3.7×10^5	/
Standard error SE (‰)	19.4	18.2	3.8	3.8

The Sicko and Cross models provide similar values for the dynamic viscosity η_∞ (= 0.46 Pa.s) at high shear stress or rate ranges.

Hydrogeological behavior of tailings

Volumetric water content measurement

Volumetric water content (VWC) measurements performed at stations 1, 2 and 3 (see Fig. 1 for location) are presented in Figures 6 a, b and c. Due to the experimental cell configuration (tilt from north to south) and the limited volume of deposited tailings, sensors placed at the top (see table 1 for location) were not completely covered at stations 2 and 3. For these raisons, measurements results from these sensors are not presented.

Figures 6a, b and c show that VWC at saturation is about 0.44. Also, one can observe that after tailings deposition and during drainage, the VWC are higher in the bottom and in middle than in the top tailings layer. These values remain higher in the bottom, whereas in the middle and top layer there is a rapid decrease indicating that the tailings materials drain relatively well.

It is important to recall that after tailings deposition, different fluctuations were observed in the VWC. Some of these changes are related to precipitations, such as those that took place during November 23, that induce an increase in the volumetric water content. Other fluctuations are induced by temperatures decrease (below the freezing point) causing the water freezing and therefore reducing the amount of liquid water that can be measured by the equipment (figure 6d). This effect is illustrated by the lower VWC (close to residual volumetric water content) observed at the top of the layer at stations 1 (figure 6d)

Suction measurements

Suction measurements were performed in the top and bottom at the station 1 and 3. However, for the station 2, suction measurements were performed in the bottom and middle of the layer. Due to the limited volume of tailings deposition, sensor installed in the top of station 3 was not completely covered by tailings; consequently measurements results at this level will not be presented.

Suctions measurements results (not shown here due to space limitations) indicate that there is a good agreement between volumetric water contents and suctions measurements at different tailings layers: when volumetric water contents increase, there is a drop in the suction values while when volumetric water contents fall, suction value increase. Also, in the bottom layer suction remain constant at about 10 kPa, and this until November 24. After November 24, the measured suctions value show different fluctuations (exception for station 1). It is important to recall that the observed fluctuations and particularly the suction increases are related to freeze effect. Also, in the top and in middle the tailings layer, the measured suctions show many variations that are related to drying effect during water distribution and to wetting effect of tailings by precipitations.

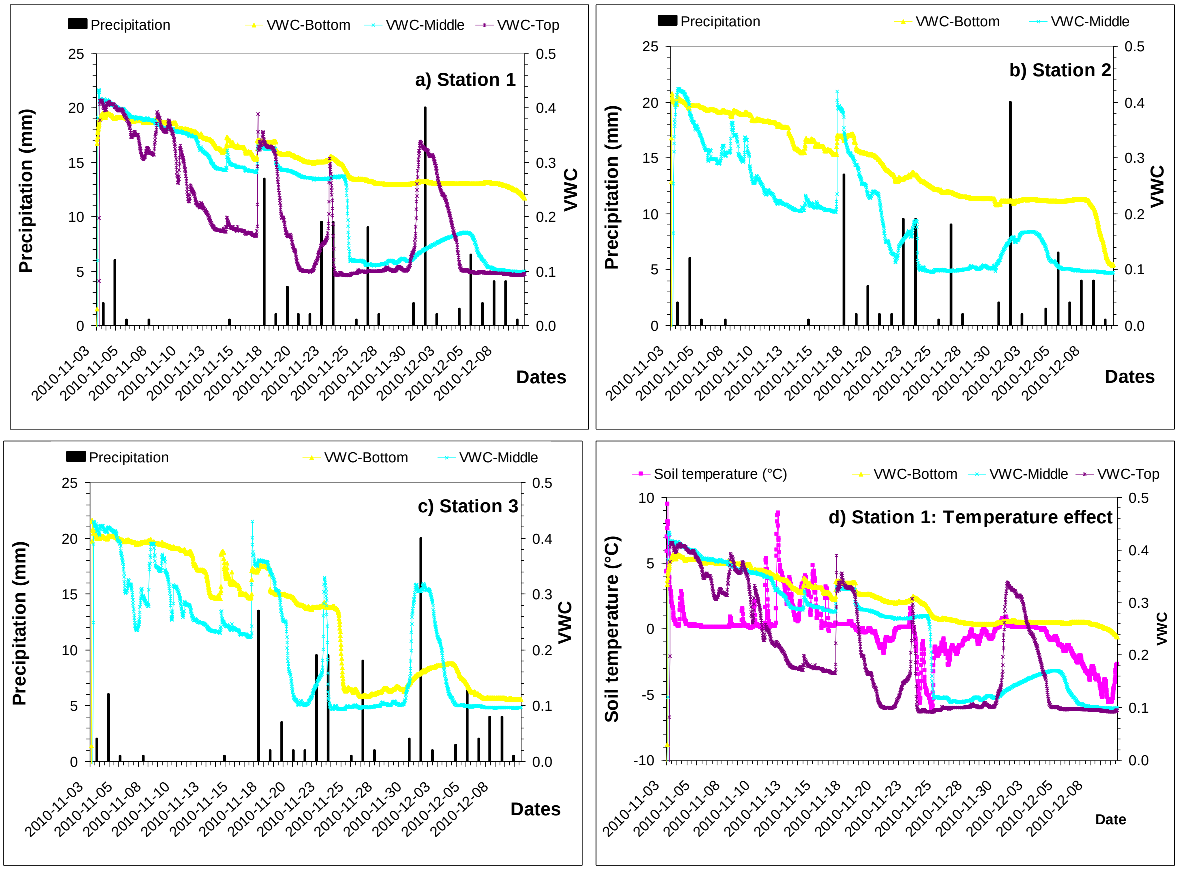


Figure 6 Volumetric water content measurements: a) station 1, b) station 2, c) station 3 and d) temperature effect

Well point pressure

Water pressures measured in the three well points are presented in Figure 7. Thus, in the three well points, one can observe in first an increase in water pressure during tailings depositions (2 and 3 November). Then there is a drop in the water pressure to reach the initial level after about 10 days (see Figure 7). Then one can observe that water pressure increases, especially during the 14, 17 and 23 November; these increases in water pressure are related to the precipitation that occurred in the region. As final remark, it is important to note that the water pressure decreases from the well point P1 (near the deposition area) to the well point P3 (at the bottom of the cell). The tailings thickness being greater near P1, it is fitting that the pore pressure is greater than that P2 and P3.

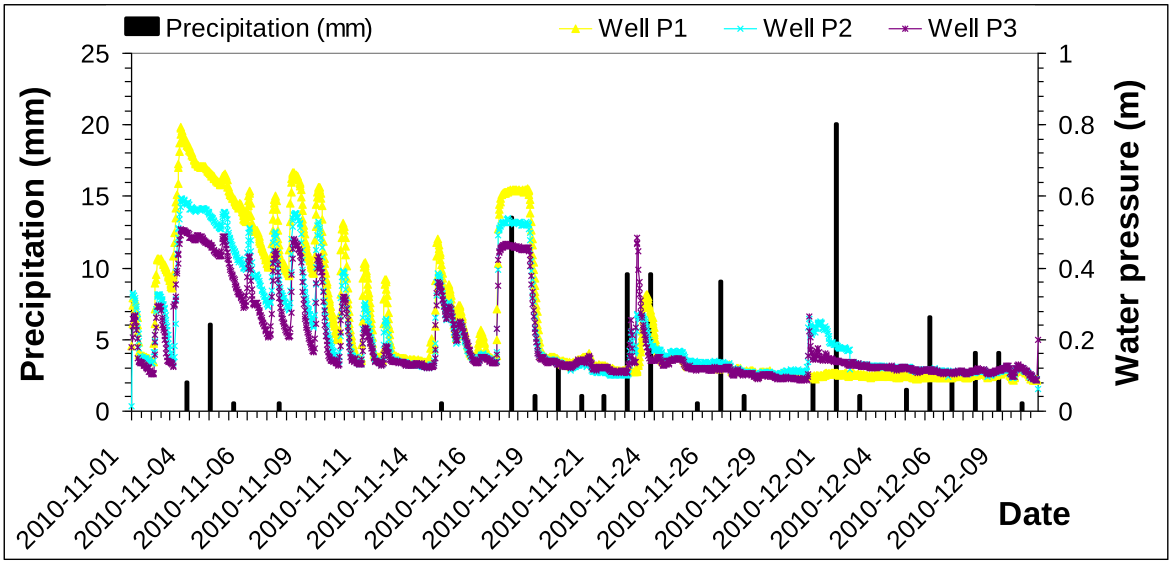


Figure 7 Water pressures measured in the three well points: P1, P2 et P3

CONCLUSION

An experimental field cell was constructed to evaluate the drainage behavior of the thickened tailings during and after deposition. Three monitoring stations were installed for volumetric water content, suction and water pressure measurements. During deposition, 10 thickened tailings samples were collected for analysis of grain size distributions and rheological properties.

Analysis results show that the grain size distributions are typical for hard rock where silt fraction corresponds to percent included between 65 and 69. Also, grain size analyzes show that there is no particle segregation during thickened tailings deposition. Rheology properties analyses show that the yield stress values, obtained with the Bingham and Herschel-Bulkley models, are very close about 8 Pa. The Sicko and Cross models provide similar values for the dynamic viscosity η_∞ (= 0.46 Pa.s) at high shear stress or rate ranges. Measurements show that after tailings deposition and during drainage, the VWC decrease from the bottom to the top layer. These VWC values remain higher at the bottom, whereas in the middle and top layer there is a rapid decrease indicating that the tailings materials drain relatively well. After tailings deposition, different fluctuations were observed in the VWC. Some of these changes are related to precipitations but others are related to freezing effect. Finally pore pressure measurements showed that the pressure dissipation takes about 10 days to reach the initial state. These results allow concluding that these materials can be used as thickened tailings and all to manage properly the wastes tailings and limit the environment impact.

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