Use of a reduced scale physical model of a mine stope for assessing waste rock barricades potential instabilities due to early age pastefill pressure

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ABSTRACT

This paper presents a reduced scale physical model of a mine stope used to reproduce the underground stope backfilling practiced in some Canadian mines. The objective is to study the geomechanical behavior of the waste rock barricades in interaction with the mine backfill. The instrumentations along with visual observations and preliminary results are presented. The main results demonstrated that: i) the stability of barricade depends on the properties of the barricade (size, position, particles gradation and compaction) and the friction between the barricade and the drift walls; ii) for two backfills containing 76% and 70% of solid percentage (by weight), the volumetric strain after the self-weight consolidation inside the filling chamber varied from 2% to 10%, respectively. In addition, the results showed the importance of using shotcrete around the barricade especially at the top of the downstream side to close the gaps and bind the barricade particles, which improves the barricade stability.

RÉSUMÉ

Cet article présente un modèle physique à échelle réduite d'un chantier minier utilisé pour reproduire le remblayage de chantier souterrain pratiqué dans certaines mines canadiennes. L'objectif est d'étudier le comportement géomécanique des barricades de stériles en interaction avec le remblayage de la mine. Les instrumentations ainsi que les observations visuelles et les résultats préliminaires sont présentés. Les principaux résultats ont montré que: i) la stabilité de la barricade dépend des propriétés de la barricade (taille, position, gradation et compactage des particules) et du frottement entre la barricade et les murs de la galerie; ii) pour deux remblais contenant 76% et 70% de pourcentage de solides (en poids), la déformation volumétrique après la consolidation du poids propre à l'intérieur de la chambre de remplissage variait de 2% à 10%, respectivement. En outre, les résultats ont montré l’importance d’utiliser du béton projeté autour de la barricade, en particulier en haut de l’aval, pour combler les vides et lier les particules de la barricade, ce qui améliore la stabilité de la barricade.

1. INTRODUCTION

Massive quantities of waste rock and tailings are produced and stocked in piles and tailings storage facilities during the operations of the mining industries. Acid mine drainage or contaminated neutral drainage can be generated when these wastes are exposed to atmospheric conditions, resulting in environmental pollution. Underground backfilling offers significant economic and environmental advantages to mining operations (Thomas 1979, Hassani & Archibald 1998, Potvin et al. 2005, Belem & Benzaazoua 2008). Of the three types of backfill currently used in the mining industry (rock fill, hydraulic fill and paste fill), paste fill appears to be the most successful and popular. Underground backfilling requires the construction of a barricade placed in drift (draw point) to retain the backfill in filling chamber (termed stope). Serious consequences can occur if barricades fail, such as damage to mining equipment, injuries or even death of workers. The barricade are usually made of permeable brick, fibrecrete, concrete (hydraulic fill), timber frame (hydraulic & paste fill), shotcrete (hydraulic & paste fill) or waste rock (paste fill) depending on backfill type (Belem et al. 2013). Barricades in waste rock are profitable and widely used in many underground mines because they are available during underground development (Belem et al. 2013). These barricades are still poorly documented (e.g., Li & Aubertin 2011, Yang et al. 2016) and must be properly designed to avoid any failure that could slow down mining production. Barricade analysis stability requires a correct estimate of pore water and total pressures in backfilled stopes and on barricades during the backfilling and shortly thereafter. After backfilling, the total stresses on backfilled stopes and on barricades can decrease drastically due to several phenomena, such as the development of the arching phenomenon, pore water pressure dissipation and the cemented backfill hardening. Through the literature, numerous analytical solutions, numerical modeling and in situ measurements have been proposed, in which each investigation has its advantages and limitations, but further investigations are needed to assess the critical backfill pressure on the barricade and its design procedure. A number of mine stopes were implemented with in-situ instrumentation (e.g., Belem et al. 2004, le Roux et al. 2005, Thompson et al. 2009, Helinski et al. 2010, Thompson et al. 2012, Hasan et al. 2014) to evaluate the PWP and total/effective stresses in stopes. Also, several reduced physical models of mine stopes have been used to study the distribution of vertical stresses (Sivakugan & Widisinghe 2013, Widisinghe et al. 2013, Widisinghe et al.

2014, Widisinghe 2014) or to study the self-weight consolidation settlement of the paste backfill in different drainage conditions (see Belem et al. 2016). Numerical modeling is another approach commonly used to evaluate the state of stress in backfilled stopes and to study the influence of different parameters, such as backfill properties, characteristics of the fill wall interface, the rate filling and pores water pressures (e.g., Li et al. 2003, Li et al. 2007, Pirapakaran & Sivakugan 2007, Hassani et al. 2008, Li & Aubertin 2008, Fahey et al. 2009, Li & Aubertin 2009a, 2009b, Li et al. 2010, El Mkadmi 2012, Veenstra 2013, Emad et al. 2014, Falaknaz 2014, Yang 2016). However, waste rock barricade design remains a major challenge and more investigations are needed to evaluate the critical backfill pressure exerted on the barricade. In this work, a small-scale model is used to conduct qualitative experiments on the stability and failure mechanisms of waste rock barricades during paste backfill placement.

2. MODEL AND EQUIPMENT DESCRIPTION

The small-scale model was constructed for qualitatively reproducing underground longitudinal-type stope backfilling in conjunction with the construction of waste rock barricades. This model with a length scale factor of 1/50 ($L^* = L_{model}/L_{stope}$) will mimic a typical mine stope in the Abitibi region (Canada). Figure 1 shows the reduced model and associated measurement tools.

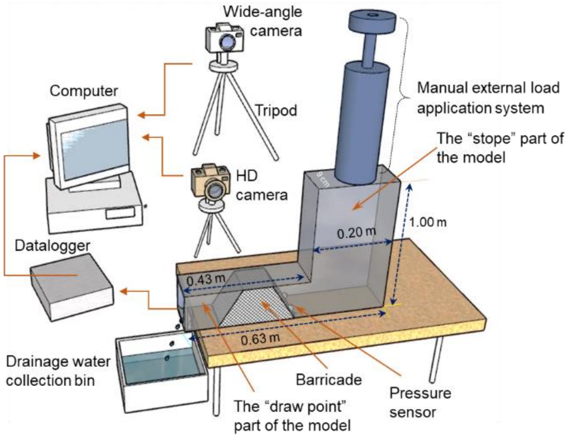

Figure 1. Small-scale model in transparent plates

The model was built from acrylic glass or Plexiglass (Poly(Methyl MethAcrylate) PMMA-type polymer). The main feature of this type of polymer is its transparency, which allows monitoring the barricade and its interaction with the backfill during and after placement. The filling chamber (stope) has a horizontal section of 90 × 200 mm and a height of 380 mm (can be increased up to 1000 mm). The stope is connected to a drift (called draw point), which has a vertical section of 90 × 90 mm and a length of 630 mm. The pressure induced by the backfill on the barricade is measured using mini-pressure sensors positioned at different locations on the upstream side of the barricade. The scale model is also equipped with a manual external loading system (a piston) to increase the pressure on the barricade until its failure. The scale model does not satisfy first-order similarity due to cost constraints and inability to achieve some similitude conditions. A high-resolution camera was used to help analyze the barricade displacement and its failure mechanism. A second camera was also used to capture the manipulations during backfill placement (Fig. 1). The barricade surveillance is only recorded in 2D through the transparent walls of thedrift, assuming that the particles at the core of the barricade can have same behavior. The pressure sensors (316L SS with PVC threads, 0.35 bar, ±1 % accuracy, "TE connectivity measurement specialties" brand) were calibrated by filling the model stope with water before each test. Figure 2a shows three sensors (#3, #4, #5) were calibrated by pouring water until 38 cm heigh and the results were satisfactory ($p_{water} = \gamma_w \times h_w = 9.81$ kN/m$^3 \times 0.38$ m = 3.73 kPa; see Fig. 2b).

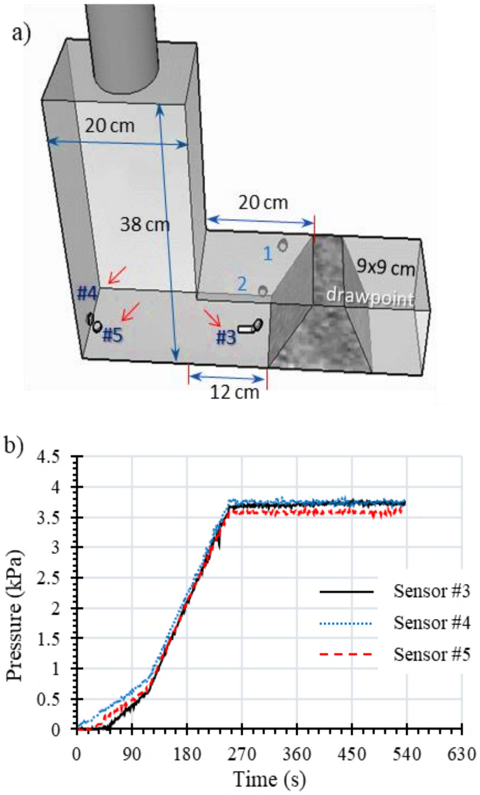

Figure 2. Pressure sensors calibration tests: a) location of the pressure sensors in the model, b) calibration pressure results

3. EXPERIMENTAL PROTOCOL

Five steps are required to perform the small-scale model testing: i) setting up the reduced-model, the instruments, and the materials; ii) calibrating the pressure sensors and verify the measurements; iii) starting the test according to the scenario, the material properties and backfill sequences, iv) measuring the induced pressures and displacements of the barricade during backfilling; and v) analyzing the results and varying the particles size of the barricade or the backfill properties for the next test.

3.1 Setting up the waste rock barricade

The materials used for the barricades construction are the development waste rocks that are also used for rock fill preparation underground. The strength of as-placed barricades are very difficult to evaluate. In practice, a layer of shotcrete is used to close the top gap after the barricade construction in order to avoid any risk of the backfill spill. Therefore, little information are available on their characteristics (e.g. grain size distribution, shear strength, angle of internal friction, etc.) for a proper design purpose. For this study, seven grain size distribution (GSD) curves will be tested (Fig. 3). These GSD were based on visual and experimental observation in the laboratory for suggesting different configurations in order to study the barricades behavior, stability and mechanisms of rupture. The barricade particles diameter varies from 0 to 8 mm on the reduced-scale model, assuming that this particles diameter varies between 0 and 400 mm in a the real stope size barricade. The first GSD curve represents a barricade made of fine materials (50% smaller than 1 mm), while the 7th GSD curve represents a barricade without fine particles (minimum diameter of 3.35 mm) and other GSDs are in between.

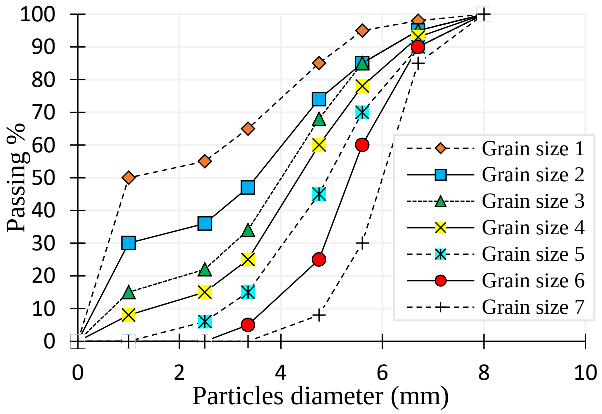

Figure 3. Particles size distribution curves of the waste rock barricade

Three steps were used for shaping the barricade in the draw point: (i) manufacturing various sizes of trapezoidal molds for use in building barricades made of crushed waste rock ; (ii) placing the mold in the access drift and then filling it with crushed waste rock (in two compacted layers) in accordance with a particle diameter scale factor of 1/50 ($d^{*}=d_{model}/d_{prototype}$); (iv) removal of the mold after shaping the barricade (Fig. 4).

For the tests presented in this work, the volume of the trapezoidal barricade used is 1304 cm^3 (25 cm base length, 7.2 cm top length, height = width = 9 cm). The waste rock apparent density ranges from 1.5 g/cm^3 to 1.9 g/cm^3 (increases with the increase of fine materials). For some scenario of testing, a number of PMMA shims are fixed at the base of the access drift in order to increase the frictional resistance between the barricade and the drift walls, and to avoid the barricade sliding.

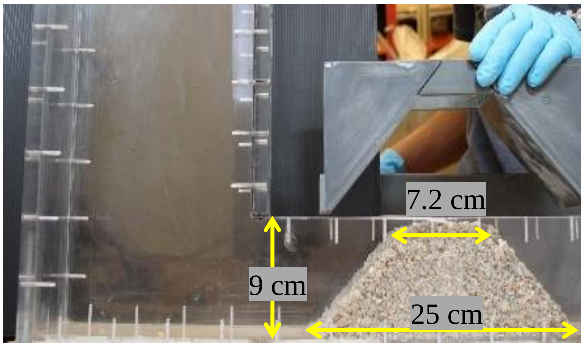

Figure 4. Setting up the barricade in the model access gallery

3.2 Cemented paste backfill mix design and preparation

The amount of cemented paste backfill ingredients (water, binder, and residues) can be calculated after knowing the expected backfill volume (V_f) for filling the reduced scale model, the required binder ratio (B_w) and the targeted final solid mass content of the CPB (C_{w-f}). The first step is to determine the specific density (ρ_{s-t}) of the tailings and their water content (w_t) on arrival at the lab. Next, the backfill mix design and proportioning can be done using the following equations 1, 7 and 9 as follows (see Belem et al. 2013):

The required total mass of dry tailings (M_t) in the backfill mixture is given by:

$$M_t = \frac{M_f}{1+w_f}\left[\frac{1}{1+B_w}\right] \qquad [1]$$

where M_f = the fill mass (g or kg), w_f = the fill water content (decimal; $w_f = [1/C_{w-f} - 1]$), B_w= ($M_{binder}/M_t = M_b/M_t$) = the binder rate used (in decimal).

The final solid mass concentration C_{w-f} of backfill is given as follows:

$$C_{w-f} = \frac{M_t+M_b}{M_f} \qquad [2]$$

The fill mass to be placed in the model is given as follows:

$$M_f = V_f \times \rho_{h-f} \qquad [3]$$

where ρ_{h-f} = bulk or wet density of the fill that is given by the following relationship:

$$\rho_{h-f} = \left[\frac{C_{w-f}}{\rho_{s-f}} + \frac{1-C_{w-f}}{\rho_w}\right]^{-1} \qquad [4]$$

where C_{w-f} is in decimal, $\rho_w =$ density of water (1g/cm^3), and $\rho_{s-f} =$ the specific density of the backfill which is given as follows:

$$\rho_{s-f} = (1 + B_w)\left[\frac{1}{\rho_{s-t}} + \frac{B_w}{\rho_{s-b}}\right]^{-1} \qquad [5]$$

where ρ_{s-t} is the density of the tailings solid grains (in g/cm^{3}or kg/m^3) and ρ_{s-b} is the density of the binder.

In mine backfill practice, several types of binding agents are used, but the most common is general use Portland cement (GU), which is usually fractionally replaced by mineral additives with pozzolanic effect, such as fly ash (FA) and smelter ground granulated blast furnace slags (GGBFS) (Belem & Benzaazoua 2008). In this case the binder solid grains density (ρ_{s-b}) is given as follows:

$$\rho_{s-b} = \left[\frac{p1}{\rho_{s-GU}} + \frac{p2}{\rho_{s-FA}} + \frac{p3}{\rho_{s-GGBFS}} + \cdots\right]^{-1} \qquad [6]$$

where $p =$ the proportion of each binder component (1, 2, 3, …).

The mass of binder (M_b) is given as follows:

$$M_b = B_w \times M_t \qquad [7]$$

In order to achieve a final target value of $C_{w\text{-}f}$, the total amount of water in the backfill mixture (M_w) is given as follows:

$$M_w = \left(\frac{1}{C_{w-f}} - 1\right)(M_t + M_b) = M_f - (M_t + M_b) \qquad [8]$$

Taking into account the amount of water already present in the tailings before the backfill preparation, the amount of water that should be added to the mixture (M_{w-add}) is given in the following relationship:

$$M_{w-add} = M_w - M_t \times w_t \qquad [9]$$

At the beginning of the backfill preparation, the water and the binder are first mixed to obtain a slurry before progressively adding the wet tailings ($M_{t\text{-wet}} = M_t(1 + w_t)$).

Backfill ingredients are mixed using the Hobart mixer (Fig. 5a) at low speed for about 15 minutes. At the end of mixing the backfill consistency is determined through the slump test (Fig. 5b) by using the standard Abrams' cone (Fig. 5b). The backfill was prepared with 70% solids percentage (except for the final test, $C_{w-f} = 76\%$) and 5% binder (Portland cement (GU)) to allow good control and easy filling by hand. The backfill resembled a heavy liquid and the measured slump was approximately 275 mm.

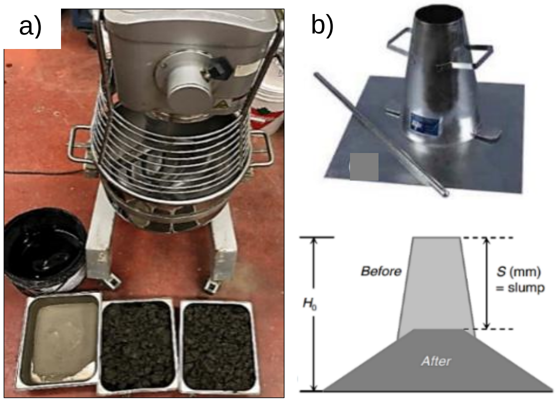

Figure 5. CPB mixture preparation : a) Hobart mixer and backfill ingredients (water or binder slurry, tailings, binder); b) standard Abrams' slump cone and slump height measurement

After backfill preparation, the model is filled with the backfill mixture (8136 cm^3 volume) over a short period (approximately 5 minutes maximum). When the model is well filled, the external loading system (piston) is installed to allow an increase of the pressure on the barricade until its collapse (failure or sliding). During the model stope filling, the behavior of the barricade is monitored using the high definition camera (see Fig. 1).

4. TESTING PROGRAM

A series of seven tests has been carried out to study the waste rock barricade behavior (the instability and/or failure mechanisms) for all the seven GSDs of the waste rock (Fig. 3) during placement of the backfill ($C_{w\text{-}f}$ =70%). In addition, two tests were performed to estimate the volumetric strain of the backfill due to the self-weight consolidation (settlement). Two solid mass concentrations of backfill were tested, 70 and 76%, respectively.

5. RESULTS

For the first group, the pressure measured when the barricade is sliding varied from 13 to 50 kPa. Intuitively it is possible to suggest that the barricade with higher apparent density (ρ_h) would fail/slide under a total pressure higher than that for barricade with lesser density. In fact, the barricade seems to develop higher frictional resistance generated by its particles in contact with the drift walls. It appeared that the barricade containing about 30% of fine material (diameter < 1 mm) exhibits higher frictional resistance (or sliding resistance) than the other barricade configurations, even if the total density is higher, as can be seen in Figure 6.

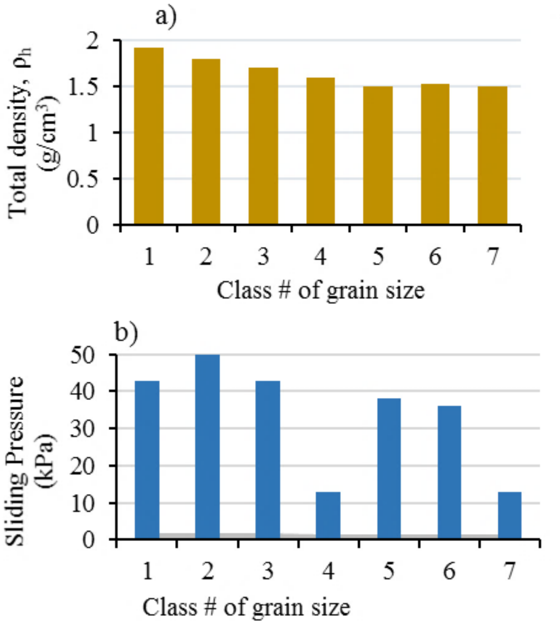

Figure 6. Barricade instability mechanisms testing: a) barricade total density as a function of particle size distribution; b) barricade sliding pressure for all particle size distributions

Although the tests were carried out under the same conditions (barricade placed in two compacted layers), it is still difficult to reproduce a single contact friction between the barricade and the drift. Therefore, the measured sliding pressure of the barricade can vary within a certain range. It should be noted that the drainage of water through the barricade during backfilling plays an important role in modifying contact friction. In addition, the amount of pressure exerted on the barricade depends strongly on the consistency of the paste backfill in place (from very soft to very stiff). This can be explained by the combined effects of backfill consolidation and the hardening process that reduces horizontal pressure on the barricade. The repeatability of future experiments will provide additional information on the parameters involved in barricade resistance.

The test results also show that the barricade partial failure susceptibility increases with the decrease of the fine materials (*d* < 1 mm) content of the barricade. The images in Figure 7 shows the interaction between the backfill and the barricade for the first (GSD #1) and last (GSD #7) particle size distribution, respectively.

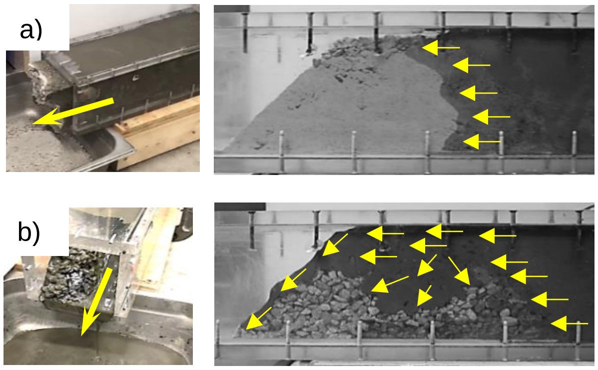

Figure 7. The barricade behavior during the backfill ($C_{w\text{-}f}$ = 70%) placement and at barricade collapse for: a) particle size distribution #1 (d_{50} = 1 mm); b) particle size distribution #7 (d_{50} = 6 mm)

Decreasing the fine particles of the barricade leads to a deep ingress of backfill into the barricade voids. The model filling without a stoppage can sweep the barricade particles at its top (Fig. 8), confirming the need for the application of a shotcrete layer to support the downstream side of the barricade.

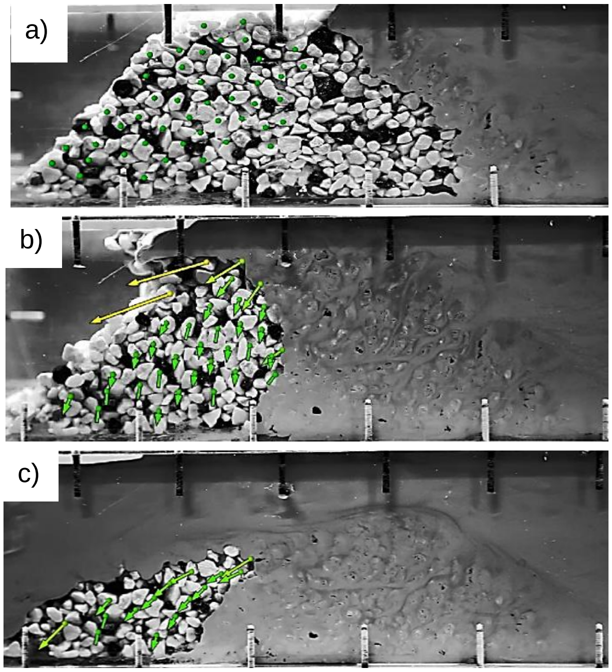

Figure 8. Analysis of the movement of a barricade (4/8 mm) contains shims at the base of the gallery: a) penetrating of backfill into the voids of the barricade; b) sweeping the barricade particles on top; c) barricade collapse

The second series of tests was done for estimating the volumetric strain ($\varepsilon_v = \Delta V / V_0$) of backfills having two different consistencies, namely two solid contents (70 and 76%). This volumetric strain is calculated based on the measurement of either backfill volume change (ΔV) or its measured settlement (ΔH). Settlement can occur only if self-weight consolidation take place after the dissipation of the excess pore water pressure. Immediately after the end of filling the measured vertical pressure initially equal to that of the overburden ($\rho_h \times g \times H$), and then gradually decreased with drainage. The full self-weight consolidation was reached after 24 h ($C_{w\text{-}f}$ = 70%) and 5 h ($C_{w\text{-}f}$ = 76%) with ε_v of 10% and 2%, respectively. On Figure 9, the curvature of the backfill top surface was more pronounced for the 70% solid backfill mixture, which may be related to the arching effect.

These experiments demonstrated the need to use pore water and total earth pressure sensors to measure and to calculate effective stresses during the drainage. In this paper, several parameters are not presented, such as effective stresses, friction angles, porosities and cohesions, but these will be presented in the future with complementary experiments.

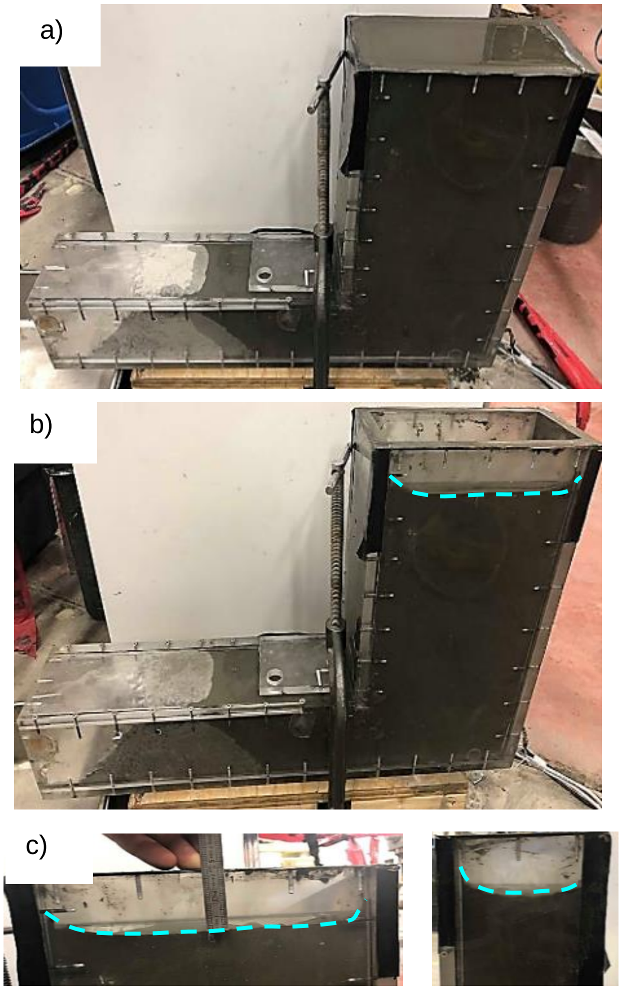

Figure 9. The filling chamber (stope) with backfill ($C_{w\text{-}f}$ = 70%) in backfill volumetric strain test: a) after backfill placement; b) during self-weight consolidation; c) volumetric strain measurement

6. CONCLUSION

The results obtained on the small-scale model demonstrated that: i) the stability of a waste rock barricade depends upon numerous factors, such as the waste rock particles gradation and degree of compaction, as well as the frictional resistance between the barricade and the draw point sidewalls; ii) for two backfills having 70% and 76% of solid, the volumetric strain due to self-weight consolidation of the backfill measured two days after the filling was 10% and 2%, respectively. The consequence of these observations is that a progressive backfilling of the stopes is preferable in order to dissipate the pore water pressure and to ensure the stability of the barricade.

The future tests will be carried out with pressure cells (total earth pressure and pore water pressure) allowing to deduce the effective stresses during filling and after pore pressure dissipation. These tests will study the influence of the barricade location in the draw point (offset distance), the type and percentage of binder. The digital image correlation method will be used to study the barricade failure mechanism and particles motion analysis.The anticipated results will be compared to numerical simulations and in situ measurement data.

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