Unsaturated flow in hydrating porous media: application to cemented paste backfill

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ABSTRACT
The dissipation of pore-water pressures is important to barricade design and strength development in cemented paste backfill (CPB) systems. One factor contributing to dissipation of pore-water pressure is self-desiccation, which occurs through the consumption of water by cement hydration. For certain stope geometries and rates of paste deposition, it is known that pore-pressures can become negative and the CPB may partially desaturate. This paper presents an analysis of pore-water pressures using an unsaturated flow framework. Such analysis is complicated by the fact that the flow properties of the CPB, such as hydraulic conductivity and the water-retention curve (WRC), evolve with hydration. The authours' approach is therefore to find bounding solutions, solving the unsaturated flow equation using either flow properties of the CPB before or after hydration. This approach is evaluated using a 1 m tall column test in the laboratory, and appears to give reasonable results.

RÉSUMÉ

La dissipation de la pression d'eau interstitielle d est important pour la conception des barricades et le développement de la puissance du remblai en pâte cimenté (CPB). Un facteur contribuant à la dissipation de la pression d'eau interstitielle est auto-dessiccation, qui se produit à travers la consommation d'eau par hydratation du ciment. Pour des géométries et des taux de certains chantiers de dépôt pâte, il est connu que les pores pressions peut devenir négative et l'OPC peut partiellement désaturer. Ce document présente une analyse des pressions d'eau interstitielle à l'aide d'un cadre de flux insaturés. Une telle analyse est compliquée par le fait que les propriétés d'écoulement de la CPB, telles que la conductivité hydraulique et la courbe de rétention d'eau (WRC), évoluent avec l'hydratation. La démarche des auteurs est donc de trouver des solutions de délimitation, basée sur les propriétés d'écoulement du CPB, avant et après l'hydratation. Cette approche est comparée à un test de 1 m de haut de colonne dans le laboratoire. Les resultats sont raisssonables.

1 INTRODUCTION

Cemented paste backfill (CPB) comprises a mixture of wet tailings (70-85% wt solids), binding agent (3-7% wt) and process water, that is often employed to fill mined out voids (stopes) in underground mining. CPB technology is widely used in underground mining operations, as it increases ore recovery and the percentage of tailings stored underground, when compared to other kinds of backfilling. However, the state of practice is highly conservative, as CPB is a complex material and little data is available on field performance.

CPB technology is often applied to stopes that are over 50 meters tall. At the bottom of an open stope, a structural barricade is placed to contain the fill. It is not uncommon that mining operations employing CPB using vertical rise rates in excess of 10m per day (Le Roux et al. 2004,, 2005). As CPB uses total tailings (coarse and fine fractions), it drains relatively slowly (saturated hydraulic conductivity less than 1 x 10^{-6} m/s), compared to more traditional fills that use only the coarse fraction of the tailings. Very little water, if any, is visually observed to drain out the bottom of CPB stopes (Le Roux et al. 2004, 2005).

The combination of poor drainage and high fill rates would suggest that consolidation occurs relatively slowly. However, consolidation in CPB may be accelerated by the phenomenon of self-desiccation. The rate of consolidation influences strength gain, which in turn is critical for sequencing removal of adjacent pillars of ore (Belem et al., 2001; Li et al., 2005; and Grabinsky and Bawden, 2007). In practice, the strength of CPB is evaluated through unconfined compressive strength (UCS) tests performed on laboratory-cured specimens (e.g. Belem et al., 2004; Belem and Benzaazoua, 2008; and among others). Such tests provide a very useful index as to the evolution of strength due to hydration or other processes such as sulphate attack. UCS tests, however, do not provide information on the influence of consolidation, drainage and hydration on the stress and strength distributions throughout the stope. It is generally expected that design based on UCS alone is very conservative.

Self-desiccation is a well-known phenomenon in cement hydration in concrete (Hua et al., 1995; Kim and Lee, 1999; and Acker, 2004), whereby the total volume of unhydrated constituents is less than the total hydrated volume, which induces negative pore-water pressure (PWP) and / or desaturation. In hydrating CPB, significant dissipation of pore-water pressure can occur even though the quantity of water removed by hydration is relatively small. This holds true if the pore-pressure is positive, or at least lies above the air-entry value (Simms and Granbinsky 2009). Evidence of self-desiccation has been observed in CPB; for example, Grabinsky and Simms (2006) observed significant generation of matric suctions (i.e. 100 kPa during the 6th day of curing) in sealed laboratory specimens contain 5% binder material. Helinski et al. (2007) conducted laboratory experiments on saturated CPB samples and found that self-desiccation significantly reduced excess pore-water pressures. Helinski et al. (2010).have developed an analysis of CPB stopes using an elasto-plastic large–strain consolidation framework .

This paper examines the role of self-desiccation in CPB using the framework of unsaturated flow. This will have application to early age consolidation in stopes with relatively low filling rates and/ or high binder content, as well as to predicting the long-term drainage behaviour of CPB stopes. The proposed framework also has application to uhe use of CPB layers in surface deposits of thickened tailings, such as proposed by Deschamps et al (2008).

2 THEORY OF UNSATURATED FLOW IN HYDRATING POROUS MEDIA

The 1-D unsaturated flow equation may be stated as:

$$m_v \frac{\partial \psi}{\partial t} = S_k - \frac{\partial}{\partial z}\left[K(\psi) \frac{\partial h_z}{\partial z} \right] \tag{1}$$

where m_v *(1/kPa)* is the specific storage (the slope of the water-retention curve in the negative pore-pressure range, or the compressibility in the positive pore-pressure range), K(ψ) (m/s) is the unsaturated hydraulic conductivity as a function of matric suction, h_z is the total head(m), and S_k is the sink term due to hydration (1/day).

In CPB, the use of Equation 1 is complicated by the evolution in the material properties due to hydration. We can, however, measure the WRC without binder, and with binder but after hydration has almost stopped. This will give us upper and lower bounds on the water retention behaviour of CPB. The following experiments were designed to generate the WRC and saturated hydraulic conductivity before and after hydration, as well as the necessary data to describe the sink term.

3 MATERIALS AND METHODS

3.1 Materials

Tests on tailings from two different mines are presented. One tailings were from the Williams Gold Mine in Northern Ontario. The CPB mixture for these tailings contained 3% binder by dry mass of tailings, consisting of 1.5% Portland cement and 1.5 % fly ash. The water content (mass of liquid/mass of solid) of the CPB was 38.9 % and its slump was 8 inches. The tailings themselves were predominantly silt sized and non-plastic (PL 20%, PI 2%).

The Kidd creek tailings were comprised of 55% gold tailings and 45% alluvial sand. The gold tailings were very similar to the tailings from Williams mine. The binder used in these tests was 2.2% by dry mass of tailings and sand, of which 90% was blast furnace slag and 10% was Portland cement.

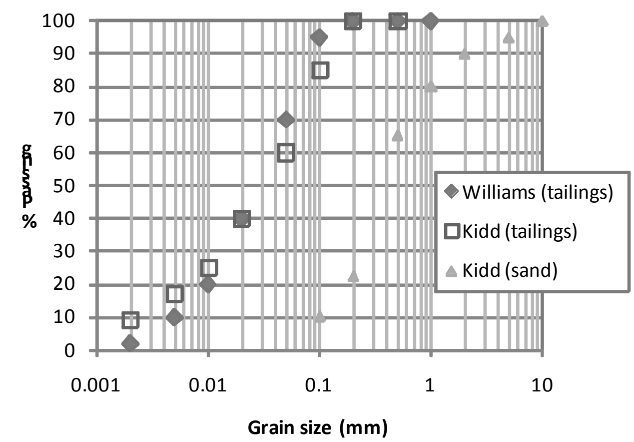

Figure 1 Grain-size distributions for tailings and aggregates in Williams and Kidd CPB mixtures

3.2 Experiments

3.2.1 Self-desiccation tests

CPB specimens for a range of binder contents (0 to 7%) were prepared and poured into cut PVC cylinders. Tensiometers (Model T5 from UMS) were inserted in the paste material through holes in the cylinders. The cut edges of the PVC cylinders were covered with plastic wrap to prevent water loss from evaporation. Matric suction measurements were recorded every 5 minutes for the first 48 hours and at every 10 minutes thereafter for 28 days. Some release of bleed water typically occurred within the first hour of setting for all three binder specimens, while the control (uncemented paste) settled for over 24 hours. Water that pooled onto the surface from settling was removed with a syringe.

Replicate samples were prepared without tensiometers, in order to sample for gravimetric water content over time to track hydration by a change in the solids to water ratio. These samples were weighed to ensure no loss of water by evaporation. The change in gravimetric water content (GWC) was then used to calculate the sink term for Equation (1).

3.2.2 Water-retention curves

The axis-translation tests follow standard methods; except that volume change is estimated at each stage by removing the cell's top after equilibration and taking vertical displacement measurements using a non-contact displacement sensor.

To determine a "post-curing" WRC, the sample was poured into the cell, sealed from any moisture loss and cured with zero gauge air pressure (i.e. without applied air pressure). During this time, weight and volume changes were recorded and measured during the 28 days of curing. On Day 29, the axis-translation test was initiated. For suctions in excess of 500 kPa, the specimen was removed from the axis-translation cell, and allowed to dry. Small samples were periodically cut from the larger sample. Each of these samples was then inserted into a WP4 Wenglor Dewpoint hygrometer to determine total suction. The same sample was then placed in an oven to determine GWC.

The WRC of the uncemented sample was determined using the same procedure, but without the curing phase.

3.2.3 Column tests

The column test was conducted in a 0.20 by 0.20 m square Plexiglas column. A column had a drainage port at the bottom with a geotextile filter. Water flowing out the drainage port was collected in a beaker resting on a scale. A cover was placed on top of the column to minimize evaporation. The column had a number of ports for tensiometers (5), volumetric water content sensors (8), and for sampling pore-water. The tensiometers were the same model used in the self-desiccation tests. Two kinds of volumetric water content sensors were used: EC2H0-5 model and 10-S models from Decagon. Both of these infer water contents from electrical permittivity measurements of a local domain.

The CPB was placed in 4 subsequent layers. The first layer was left to cure for twenty days before placing the next layer, each subsequent layer was cured for about 30 days. The CPB mixture used was for Williams tailings with 3% binder. The first layer was 0.15 m deep, subsequent layers were 0.20 m deep. Tensiometers and VWC sensors were placed roughly in the middle of each layer.

3.3 Numerical modelling

Equation 1 is solved used a commercially available unsaturated-saturated flow finite element code. The code includes automatic time-step and mesh refinement controls to minimize numerical errors due to discretization problems.

3.3.1 Material parameters

Alternate sets of parameters (WRC, saturated hydraulic conductivity, stiffness) are employed, one set for tailings with no binder, the other set for tailings cured for 28 days. The first set is used to model each fresh layer; the second set is used to model all other layers. The sink term measured during the self-desiccation tests are employed in both alternate sets of data. Unsaturated hydraulic conductivity function are estimated using the Fredlund et al. (1997) method built into the code, which extrapolates the relative hydraulic conductivity function from the measured WRC. As discussed elsewhere (e.g. Fisseha et al. 2010.), the appropriate type of WRC for estimation of the relative hydraulic conductivity function is the degree of saturation versus matric suction curve based on measured volume change, due to the sensitivity of unsaturated flow analyses to the location of the air-entry value.

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3.3.2 Boundary and initial conditions

The flow measured out the bottom of the column was directly imposed as a boundary condition, while the top was set to no-flow. The initial pore-pressure distribution was hydrostatic, with the PWP is zero at the base of the simulated experiment.

4 RESULTS

4.1 Water- retention curves

The WRC for the Williams and Kidd Creek tailings are presented in Figures 2 and 3 in terms of gravimetric water content. The degree of saturation curves for the post-curing samples have moiré or less the same shape as the gravimetric water content curves, as very little volume change occurs during these tests. The degree of saturation curves looks quite different for the un-amended tailings, as a significant amount of volume change occurs at low suctions. The AEV for the amended Williams and the Kidd tailings are 50 and 40 kPa, respectively. By comparison, the AEV of the post-curing specimens are 200 and 160 kPa for Williams and Kidd, respectively.

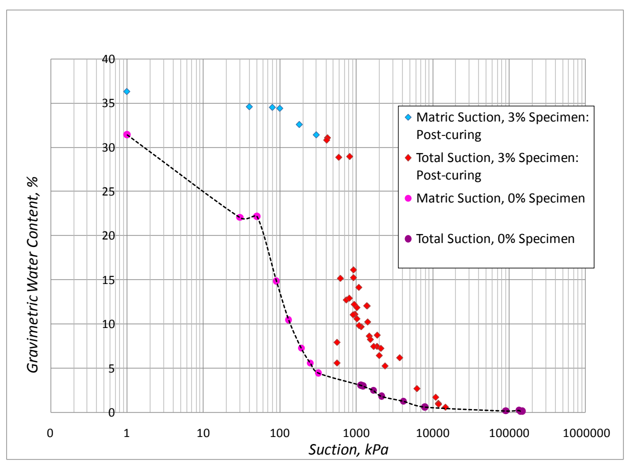

Figure 2 Water-retention curves for Williams tailings., with no binder, and after curing for 28 days

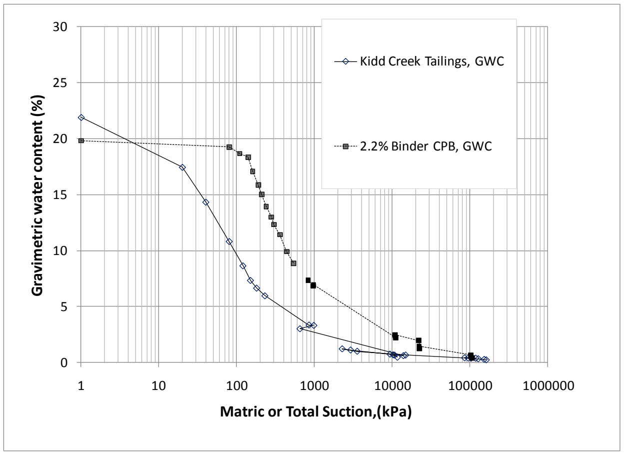

Figure 3 Water retention curves for Kidd Creek Mine, with no binder, and after curing for 28 days

4.2 Self-desiccation tests

The self-desiccation tests produce matric suction versus time curves (Figures 4 and 5) as well as the rate of water content depletion data (Figure 6). The latter data is used to define the sink term in Equation 1.

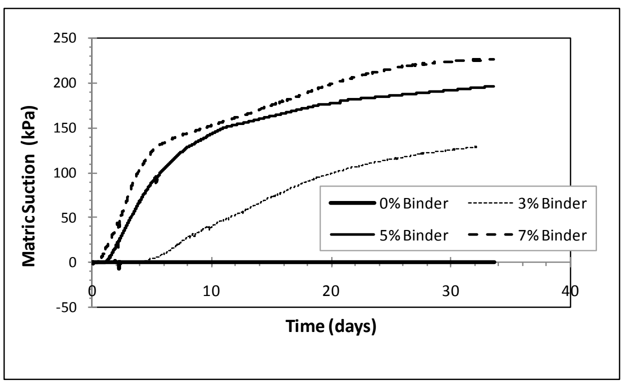

Figure 4 Self-desiccation tests for Williams tailings

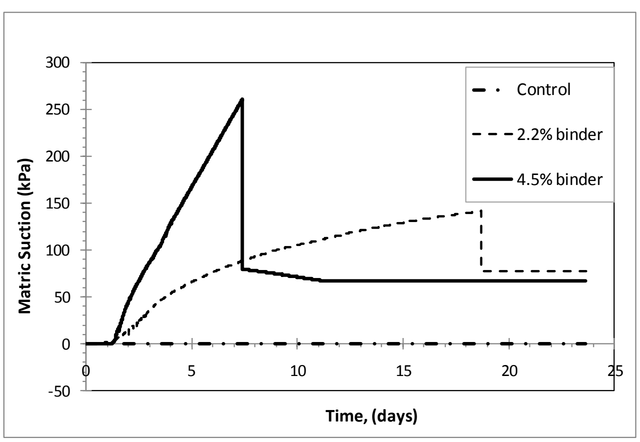

Figure 5 Self-desiccation tests for Kidd tailings

As observed in Simms and Grabinsky (2009), the generation of matric suction follows in proportion to the binder content for each tailings. The relatively rapid increase in matric suction in the Kidd Creek tailings compared with the Williams tailings, is due to the lower water / cement ratio (Initial gravimetric water content of 18-20%) in the former. The very rapid decrease in matric suction observed towards the end of these tests is caused by cavitation in the water reservoirs of the matric suction sensors.

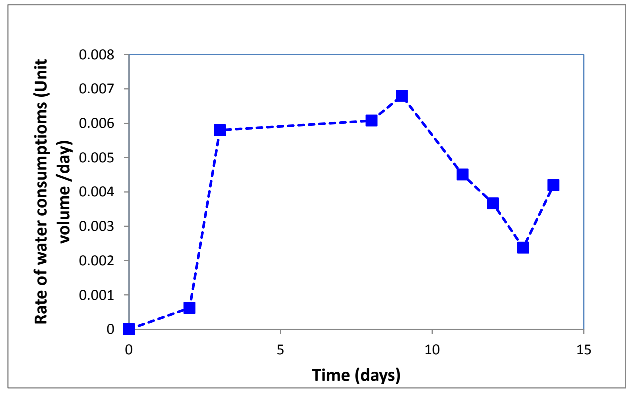

Figure 6 Rate of water consumption by hydration alone in Williams CPB with 3% binder

This data in Figure 6 is obtained from replicate sealed samples, where the overall change in mass is negligible, and hence the change in water content represents the change in proportion of the mass of water and the mass of solids. As with the matric suction measurements for Williams tailings with 3 % binder (Figure 4), there is an initial setting period in which no hydration takes place.

4.3 Column tests

Matric suction and volumetric water content values from the column test are presented in Figures 7 and 8 respectively. While there are visible trends of decreasing water content, the magnitudes of the changes are relatively small (Figure 8). This is not surprising, due to the high AEV of the fully hydrated tailings (Figure 2). Matric suction values do not rise about 70 kPa, well below the AEV of the hydrated tailings (Figure 7). The difference in matric suctions between layers is small.

With the addition of each layer, the rate of matric suction generation decreases. This is also not surprising, as the demand of water by hydration in the fresh layer can be satisfied by water from the entire column, not just the fresh layer.

Both the relatively small difference in matric suctions between layers, and the decrease in matric suction generation with the addition of each layer, is well-simulated by the modelling approach (Figure 7 and 9). The numerical predictions initially fall below the rate of matric suction generation in the first layer. This is also expected, as the WRC for tailings with no binder is used to model each fresh layer. Indeed, it is surprising that the matric suction values are as close as they are. The numerical predictions for the different layers also report closer matric suction values than was measured. Possibly the saturated hydraulic conductivity function value used for the old layers in the model was too high. This value of saturated hydraulic conductivity (2 x 10^{-8} m/s), was measured in a falling head test on a sample after 28 days of hydration. It is possible that the hydraulic conductivity representative of the scale of the column test is larger than the hydraulic conductivity representative of the falling head test.

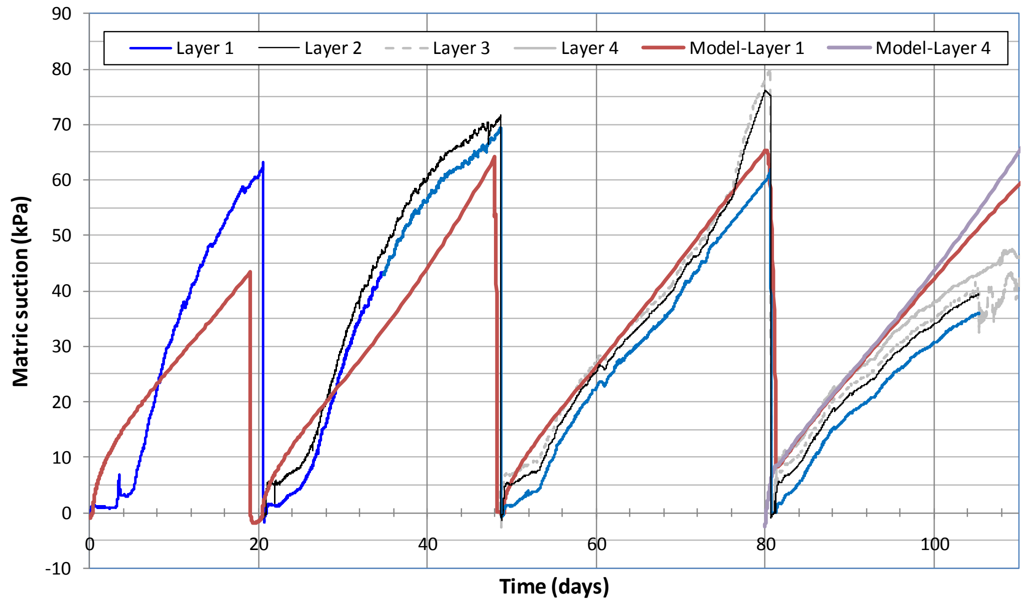

Figure 7 Measured matric suction values and select modelling results in column test on Williams tailings

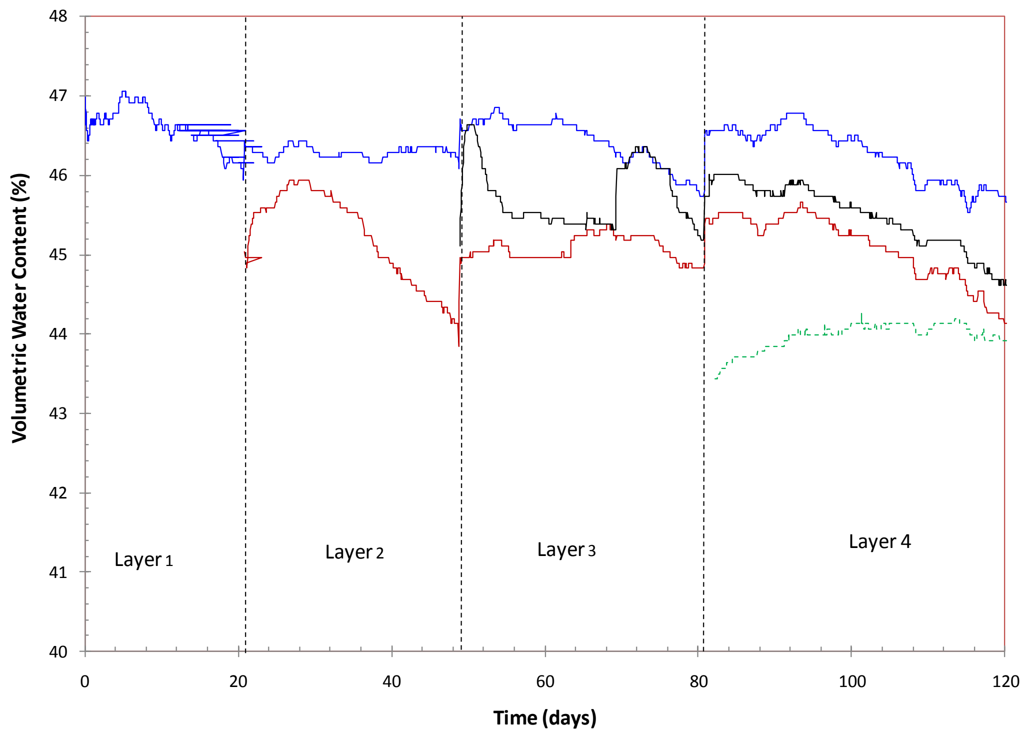

Figure 8 Volumetric water contents measured in column test

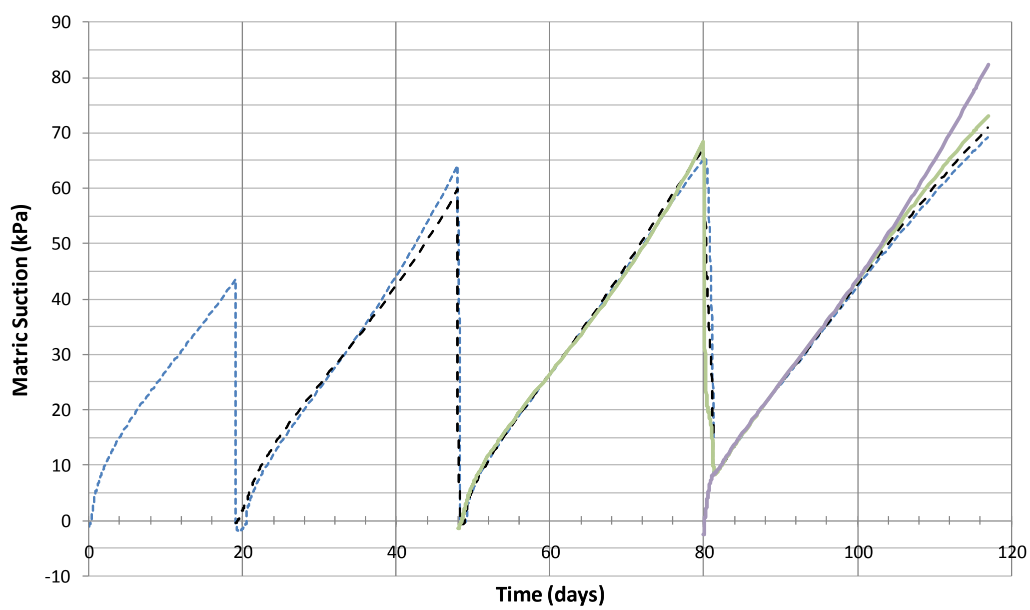

Figure 9 Simulated matric suction values in column test, each line corresponds to a mid-layer prediction (4 layers)

5 APPLICATION TO REALISTIC RATE OF DEPOSITION DURING STOPE FILLING

As presented in Witteman and Simms (2010), using unsaturated flow to model PWP in stopes,in a plug layer at the Williams mine, with reasonable agreement. However, the application of the method to the dissipation of pore-pressures in a filling stope would require more modelling effort, specifically increasing the domain of the problem with time as the CPB mass increases in height. A simpler technique is therefore proposed, based on the experimental findings and a simplification of the proposed theory.

Even for the multilayer deposition column test (very slow deposition rate in the context of CPB), matric suction developed relatively slowly, and we can assume that for many stopes the AEV of the evolving CPB will not be exceeded. Therefore, for this case, we assume the hydraulic conductivity will remain at the saturated value. If the fill rate is expressed in terms of total stress increase over time, and incorporating the influence of the stress field, Equation 1 becomes:

$$m_v\left(\frac{\partial\psi}{\partial t}+\frac{\partial\sigma_{sk}}{\partial t}\right)=S_k-\frac{\partial}{\partial z}\left[K_{sat}\frac{\partial h_z}{\partial z}\right] \quad (2)$$

Where σ_{sk} is the incremental contribution of the total stress field to pore-water pressure following Skempton (1954). Evaluation of $\partial\sigma_{sk}/\partial t$ is not straightforward, as arching will draw some of the weight of CPB to the stope walls. However, if we ignore arching, and ignore drainage (though the contribution of drainage may not be negligible), we can modify Eqn 2 to give a conservative prediction of pore-water pressure dissipation:

$$\left(\frac{\partial\psi}{\partial t}+\frac{\partial\sigma_{sk}}{\partial t}\right)=S_k/m_v \quad (3)$$

One way to determine m_v is from the self-desiccation tests. In this case, the tests are no flow and the drainage term disappears. Equation 3 can then be arranged as:

$$m_v=S_k/\left(\frac{\partial\psi}{\partial t}\right) \quad (4)$$

Applying this analysis to the self-desiccation test for the Williams tailings with 3% binder, we find a relatively steady m_v value of 0.0004 1/kPa once significant matric suctions are generated.

Employing Equation 3 and the stiffness and sink terms measured in this paper for the Williams tailings, we can estimate the development of PWP reported by Thompson et al. (2011) at the Williams mine. Thompson et al. (2011) reports the measurement of vertical and horizontal total stresses as well as PWP measured in a stope at a height of 1.4 m above its base. The stope was roughly 5 m wide, 55 m tall, with a 70 degree dip. The measurement of horizontal and vertical total stress allows us to avoid the issue of arching. Calculating the contribution of total stress to pore pressure using Skempton's coefficient for an elastic medium (1/3), and using an average value for an overconsolidated soil (0), the predicted and measured pore-water pressures are shown in Figure 10. The measured S_k/m_v ratio was 10 per day. The better prediction is the one employing a Skempton A value of 0.

The assumptions that were used in this analysis were:

i) No change in S_k or m_v. Both these terms in fact evolve with hydration.
ii) B value of 1. CPB is usually quasi-saturated (Degree of saturation between 0.85 and 0.95).
iii) The contribution of drainage to PWP dissipation is ignored.

The proposed method is therefore useful only for preliminary, conservative, estimates of PWP pressure dissipation. This simple method is presented as an alternative to the more rigorous but time-consuming analysis using unsaturated flow theory.

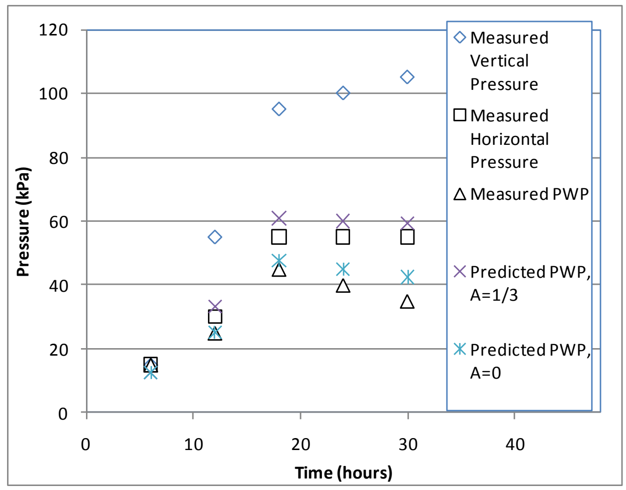

Figure 10 Predictions of pore-water pressure at the bottom of stope, along with measured total stresses and pore-water pressures (Data from Thompson et al. 2011)

6 SUMMARY AND CONCLUSIONS

A framework using unsaturated flow theory for modelling pore-water pressure dissipation and matric suction generation in CPB stopes is presented. The framework includes the use of a sink term to account for the self-desiccation phenomenon. As the water-retention curve, the hydraulic conductivity, and the stiffness of CPB all evolve with hydration, the framework proposes bounding analyses employing either the properties of the tailings with no binder, or the properties of the CPB after 28 days of hydration. The framework is applied to analysis of a column experiment, and found to reasonably reproduce measured matric suctions.

A simple method is proposed to analyze the dissipation of PWP during filling. The parameters for the method can be determined from the self-desiccation experiments described in the paper.

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