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Hydraulic response in cemented paste backfill during and after hydration

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Abstract

The distribution of pore-pressures in mine stopes may have important implications to the design of cemented paste backfill (CPB) systems. Self-weight consolidation after filling stopes is inherently problematic when pore-water pressures begin to develop. However, during cement hydration, self-desiccation begins to occur and consequently, pore-water pressures gradually dissipate. In some cases, during self-desiccation, matric suctions can develop within stopes, depending upon adopted mining strategies such as, fill rate and percent water to binder content. Tracking the evolution and quantifying the hydraulic behaviour in cemented paste is rather difficult because of the complexity of the hydrating material. The current study investigates and attempts to capture CPB's transient responses during and after cement hydration through a series of self-desiccation tests and axis translation tests. Self-desiccation tests are conducted on cemented paste specimens containing 0, 3, 5 and 7% wt binder material. The water-retention properties of the material are measured without binder, and after 28 days of hydration. This data is then used to approximately model the dissipation of pore-water pressures measured at the bottom of stope during a plug pour. The approach shows promise. Significance and future improvement to the proposed methodology are discussed.

1 Introduction and background

CPB is a relatively recent form of backfilling — a material made up of a mixture of wet tailings (70–85% wt solids), binding agent (3–7% wt) and process water. CPB technology has gained popularity around the world, as it increases ore recovery while providing a disposal option for a significant fraction of the tailings. However, the state of practice is highly conservative, as CPB is a complex material and little data is available on field performance.

CPB technology involves filling underground voids (stopes) with cemented paste material. Depending upon mining procedures, underground voids may vary in height — up to 100 m tall. At the bottom of an open stope, a structural barricade is placed to contain the fill. It is not uncommon that mining operations employ CPB mixtures containing fine particle size distributions with rates that often result in more than 10 m vertical rise per day (le Roux, 2004). The combination of particle size distribution and fill rates have important ramifications upon adopted mining strategies. While mining operations tend to vary from site to site, a rapid rate of rise will increase the total stresses that are subjected onto a stope fill and hence, increase the level of risk of a barricade failure. The rate of consolidation and strength gain in CPB is critical for sequencing removal of adjacent pillars of ore (Belem et al., 2001; Li et al., 2005; Grabinsky and Bawden, 2007). Furthermore, ample strength must be maintain in filled stopes to allow for subsequent pillar removal while avoiding liquefaction of premature CPB from free standing exposure to nearby blasting of surrounding rock mass. Currently, 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; among others). However, UCS tests provide limited information on its properties as it does not account for consolidation, drainage and hydration affects on the stress and strength distributions throughout the stope (Simms and Grabinsky, 2009). Therefore, it is necessary to assess how CPB's mechanical and hydraulic properties evolve over time as it hydrates.

Self-weight consolidation occurs immediately upon deposition of fill, generating excess pore-water pressure. However, self-desiccation due to cement hydration can significantly reduce excess pore pressures. Self-desiccation is a known phenomenon in cement hydration (Hua et al., 1995; Kim and Lee, 1999; Acker, 2004), where the total volume of unhydrated constituents is less than the total hydrated volume. This change in volume or shrinkage per se, occurs when water in pore-air desaturates, producing a capillary depression between the liquid-vapour water phase, causing the solid matrix to contract or go under compression to balance capillary tension at the liquid-vapour boundary (Acker, 2004). Thus, the process of hydration has the combined effect of reducing the total volume of the water phase; increasing the water retention properties; and increasing strength and stiffness of the solid phase.

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 sixth day of curing) in sealed laboratory specimens contain 5% binder material. Furthermore, they examined in situ samples that were representative of highest binder to lowest fill rate, and found that under such conditions, the rate of hydration effectively suppressed excess pore-water pressure development due to self-weight consolidation. Helinski et al. (2007) and Fourie et al. (2006) conducted laboratory experiments on saturated CPB samples to assess the effects of hydration on consolidated sample and found that its contribution significantly reduced excess pore-water pressures. They also identified the rapid stiffening of CPB with hydration as being very important to dissipation of excess pore-water pressure (PWP) by self-weight desiccation. One aspect that has not been studied as of yet, is tracking the evolution of CPB's hydraulic behaviour under negative pore-water pressures (matric suction), where CPB stopes are potentially unsaturated due to self-desiccation and drainage, which is the focus of this work.

The remainder of the paper presents (i) a numerical methodology to track and predict the evolution of pore-pressure distribution during and after cement hydration; (ii) some initial test results to demonstrate the affects self-desiccation and drainage; and (iii) field measurements of pore-water pressure dissipation, which are compared with generic numerical modelling that incorporates the above data.

2 Methodology for predicting pore-water pressure due to drainage and self-desiccation as unsaturated

As with any unsaturated porous material, the relevant properties governing flow are the water-retention curve (WRC), also referred to as the soil-water characteristic curve (SWCC), the saturated hydraulic conductivity, the unsaturated hydraulic conductivity function, and its compressibility when the pore-water pressure is positive. These properties can be used in the one dimensional (1D) unsaturated flow equation to predict the dissipation of pore-pressure or generation of matric suction, with the addition of a sink term to account for removal of water due to inequality between the loss of water volume and the volume of generated hydration products. The 1D unsaturated flow equation may be stated as:

$$S \frac{\partial(\psi)}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\right]\frac{\partial h_z}{\partial z} - \textit{sink term} \quad (1)$$

where S is the specific storage (the slope of the water-retention curve in the negative pore-pressure range, or the compressibility (m_v) in the positive pore-pressure range), $K(\psi)$ is the unsaturated hydraulic conductivity as a function of matric suction, and h_z is the total head.

In CPB, the use of Equation (1) is complicated by the evolution in the material properties due to hydration. There are presently no published techniques to measure the complete evolving water retention characteristics of hydrating materials, in part because most techniques rely on achieving a steady state condition, which is not possible when the material's properties are constantly evolving. We can, however, measure the WRC without binder, and with binder once hydration has almost ceased. This will give us upper and lower bounds on the water retention behaviour of CPB. The following experiments were designed to generate the WRC data as well as the necessary information to formulate a sink term.

3 Materials and methods

The experimental tests included 1) self-desiccation tests: Monitoring of matric suction generation in sealed samples of CPB samples containing 3, 5, and 7% binder, with replicate sealed samples destructively tested at different times for gravimetric water content (GWC) to evaluate water consumption by hydration; and 2) axis translation tests to measure (i) the WRC of a CPB sample containing 3% binder material after

28 days, and (ii) a WRC of a sample without binder. These results were then used as inputs for a 1-D transient, unsaturated flow model to evaluate pore-pressure distributions within a generic stope. Further discussion on the numerical modelling simulation is presented in section 4 of this paper.

3.1 Materials and devices

Tailings from the Williams gold mine (Ontario, Canada) were used. The binder content for typical William mine CPB is 3% by mass of solid tailings particles. The binder material is made up of equal parts by mass of Portland cement (PC) and fly ash (FA). Filter cake, process water, and binder shipped in separate containers were received from the mine. The gravimetric water content of each sample was brought to 39 ± 0.5% of tailings solid particles before addition of the binder. A household electric mixer was used to mix the tailings, water and binder materials for one minute.

Matric suction and total suction were directly and indirectly measured, respectively. The T5x pressure transducers/tensiometers from Umwelt-Monitoring-Systeme (UMS), Germany were used to measure the matric suction during hydration. The T5x is capable of measuring pore-water pressures up to 100 kPa and suctions up to 250 kPa and in some instances, up to 400 kPa (UMS, 2009). A volumetric pressure plate extractor, the SWC – 150, Fredlund SWCC Device, from GCTS Testing Systems, USA, was used for WRC determination by axis translation. The volumetric pressure plate extractor cell was equipped with a high AEV ceramic disc of 15 bar (1,500 kPa). The cell was connected to a pressurised air supply, in which nitrogen gas was used. Total suctions were indirectly measured using the WP4 – DewPoint PotentiaMeter, (psychrometer) from Decagon Devices, USA. This device can measure suctions from 0 to -300 MPa with an accuracy of ±0.1 MPa from 0 to -10 MPa, and ±1% from -10 to -300 MPa. The WP4 uses the chilled-mirror dew point technique to measure the total suction of a sample. In this type of instrument, a small sample (<50 g) is equilibrated with the headspace of a sealed chamber that contains a mirror and a means of detecting condensation on the mirror. At equilibrium, the relative humidity of the air in the chamber is the same as the relative humidity of the sample (Decagon Devices, 2007). Table 1, is brief summary of the measuring devices used in this study.

Table 1 Devices and performance specifications

Measuring Devices	Parameter	Range	Accuracy
Direct measurement			
T5x tensiometer	Matric suction	250 kPa to -100 kPa	+/-0.5 kPa
Axis translation cell	Matric suction	0 to 1,500 kPa	–
Indirect measurement			
WP4 psychrometer	Total suction	0 to 300 MPa	+/-1.0%

3.2 Methodology

3.2.1 Self-desiccation in CPB specimens

CPB specimens containing 0, 3, 5 and 7% binder material were prepared and poured into concrete curing containers. The T5xs were inserted in the paste material and covered with plastic wrap to prevent water loss from evaporation. Matric suction measurements were recorded every five 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. Water contents before and after release of bleed water are shown in Table 2.

Replicate samples were prepared without tensiometers, in order to sample for gravimetric water content over time to track hydration by change in the solids to water ratio.

Table 2 CPB recipe for 3, 5 and 7% binder specimens

Mass (RE of +/- 0.005g)	3% Binder Specimen	5% Binder Specimen	7% Binder Specimen
M_{paste}	1,068.16	1,025.19	1,034.76
M_{solids}	766.64	735.80	742.67
M_{water}	301.52	289.39	292.09
$M_{evaporable\ water\ (removed)}$	23.25	13.59	9.12
Initial water content* (%)	39/28%		
M_{PC}	11.50	18.39	25.99
M_{FA}	11.50	18.39	25.99
M'^{+}_{paste}	1,091.16	1,061.98	1,086.75
M'^{+}_{solids}	789.64	772.59	794.66
M'_{water}	278.27	275.80	282.97
$\%_{solids}$	72.37	72.75	73.12
$\%_{water}$	25.50	25.97	26.04
Final water content* (%)	35/25.5%	36/26%	35.6/26%

* Gravimetric water contents of CPB, based on geotechnical (M_W/M_S) and mining process (M_W/M_{Paste}) calculations, respectively.

$^{+}$ Includes the amount of PC and FA added.

3.2.2 Axis translation technique on fully hydrated CPB

The axis-translation tests follow standard methods (Hilf, 1956); 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 ensure that contact between the specimen and ceramic disc was maintained, 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. Measurements were not recorded after 300 kPa, because the sample exploded inside the pressurised cell at 400 kPa. Another approach was taken to measure the remaining portion of the SWCC. The specimen was allowed to dry and total suction and gravimetric water contents were obtained by sampling the larger specimen at various times.

The WRC of the uncemented sample was obtained using axis-translation for matric suctions less than 1,000 kPa, while simultaneous sampling for total suction and gravimetric water content analyses of a drying sample was used to obtain higher values.

3.3 Experimental results

3.3.1 Self-desiccation tests

The sample test results are presented in Figure 1. There is a strong correlation between the amount of binder and the rate of suction generation. All the data exhibit a transformation in rate of suction generation in the range of 110–120 kPa. One might suspect cavitation in the tensiometers as the cause, but these sensors generally show a very sharp drop in suction subsequent to cavitation. The transformation may be because the AEV of the hydrating material is exceeded, and so the rate of suction to water removal is changing; or possibly the pace of hydration is slowing.

Matric suctions were observed in the non-cemented (control) sample after Day 9. This indicates that some evaporation does occur within the sealed samples, though the 0% binder sample would be the most susceptible to evaporation as it had the largest air-space in its container, as it experienced the most settling.

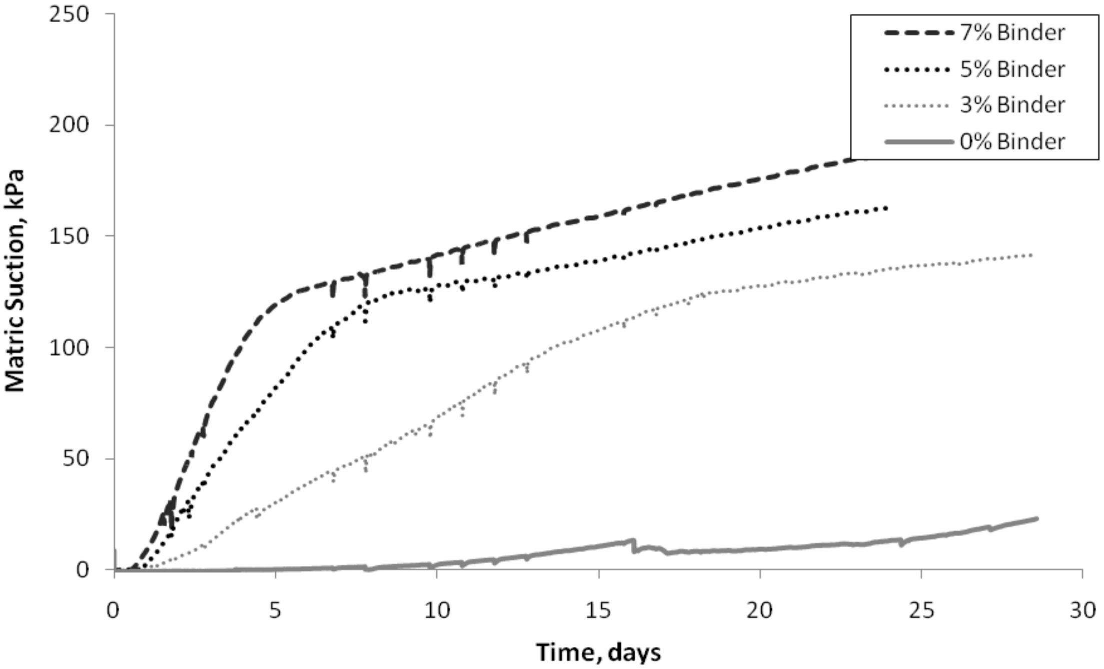

Figure 1 **Induced matric suction during paste hydration in sealed samples**

Figure 2 shows the decrease in gravimetric water content in eight (8) replicate sealed samples with 3% binder, each oven dried (at 98°C) at the times shown. As there is no significant water loss from these measurements, as checked by weighing, the change in gravimetric water content is due to the change in water to solids ratio due to hydration. The relatively linear shape of the plot will allow us to assume a constant rate of water removal (sink term) in our numerical simulations. However, the constant rate at which water is removed eventually decreases as the 'available water' becomes limited as the hydration progresses.

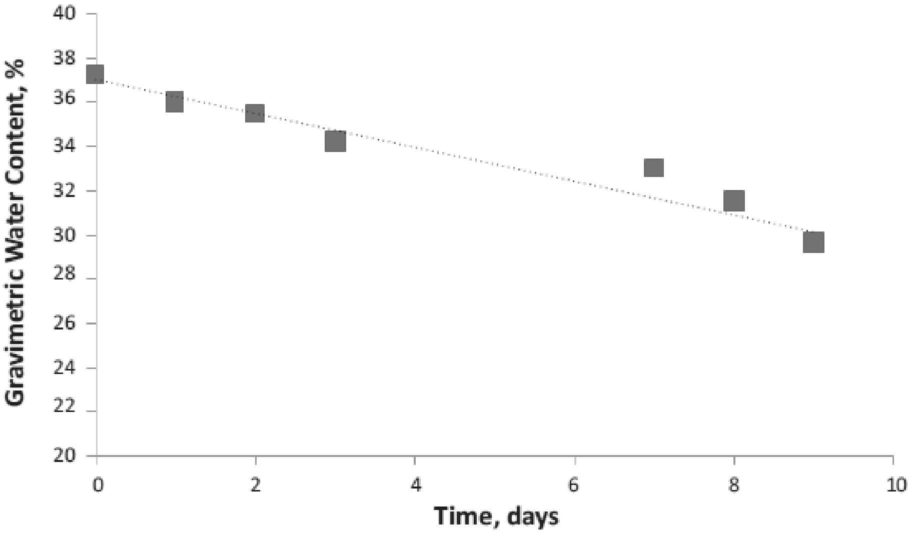

Figure 2 **Gravimetric water content of replicate sealed samples with 3% binder, showing increase in solids to water ratio due to formation of hydration products**

3.3.2 Water retention curves

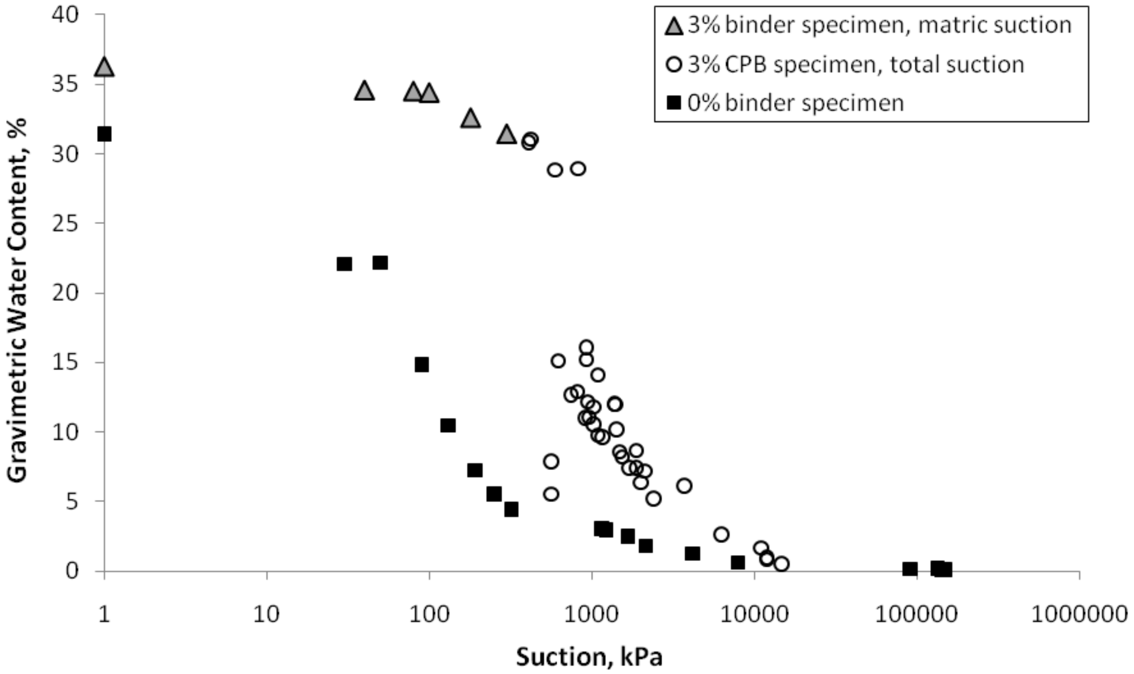

Figure 3 Pre and post-curing SWCC for 3% binder specimen

The WRC for the fully hydrated 3% CPB specimen and the uncemented specimen are compared in Figure 3. The prominent differences between the two curves are the slope before the air-entry value (AEV), and the AEV itself. The AEV for the CPB sample is ~150 kPa, and ~40 kPa for the uncemented tailings (the decrease in water content >23% GWC) is almost concurrent with shrinkage. In other words, the change in volume of water is roughly equal to the change in volume of voids for water contents >23%, as is expected in porous materials drying from a water content above their shrinkage limit. The slope of the fully hydrated specimen's WRC before the AEV is quite flat. As discussed in Simms and Grabinsky (2009), the flatness of the curve allows for significant generation of matric suctions by relatively small consumption of water due to hydration. The slope of the WRC before the AEV correlates to stiffness: the stiffer the material, the more resistant it is to dewatering by squeezing from matric suction. Figure 4 presents volumetric strain measurements made before the AEV for the CPB 3% binder specimen.

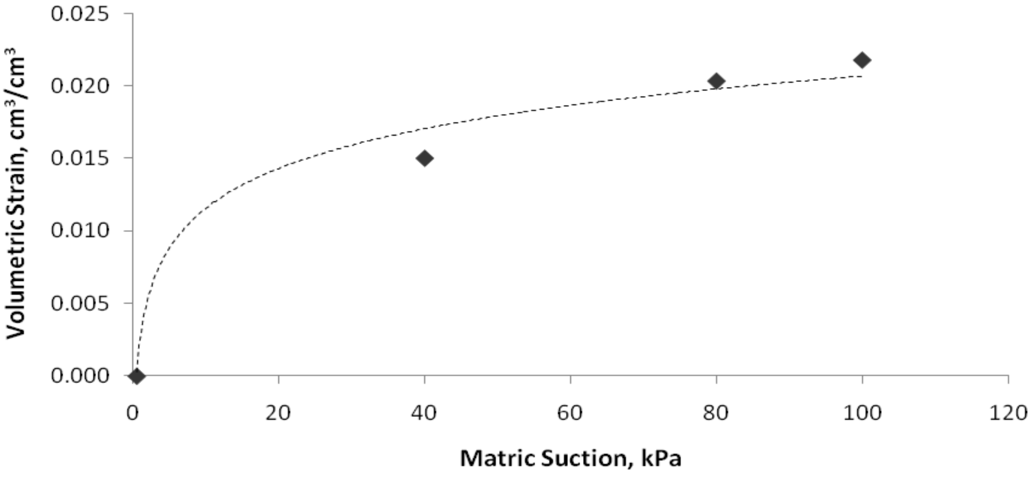

Figure 4 Volumetric strain and matric suction measured in axis-translation test of 3% binder CPB specimen after curing

4 Unsaturated flow modelling

4.1 Numerical simulation methodology

The authors attempted to simulate pore-pressure dissipation and matric suction generation measured at the Williams Gold mine in northern Ontario during and immediately after a plug pour, near the barricade at the bottom of the stope (Grabinsky and Bawden, 2007). The geometry of the stope and the location of the pore-water pressure sensors are shown in Figure 5. The 8 m height was filled with 24 hours and the paste submerged the barricade by 20 hours.

Equation (1) is solved using the finite element unsaturated flow software SVFlux, which automatically optimises time-stepping and mesh geometry. Since it is not know how the relevant properties evolve with time, several analyses have been performed, alternately using the WRC, compressibility (0.07 or 0.007) and hydraulic conductivity of the tailings (1 x 10^{-7} m/s or 1 x 10^{-8} m/s) of the either the tailings without binder or of the tailings with 3% binder after 28 days of curing. We have modelled an instantaneously placed 5 m thick layer of CPB for 20 hours. We assumed an initial hydrostatic PWP distribution, but assumed only half density, to account for the slow pour. The bottom boundary condition was set to a constant head of 0 — this is conservative and will underestimate drainage. The sink term in Equation (1) was determined by the rate of water removal observed during self-desiccation for the 3% binder specimen during the first two days, using the data shown in Figure 2.

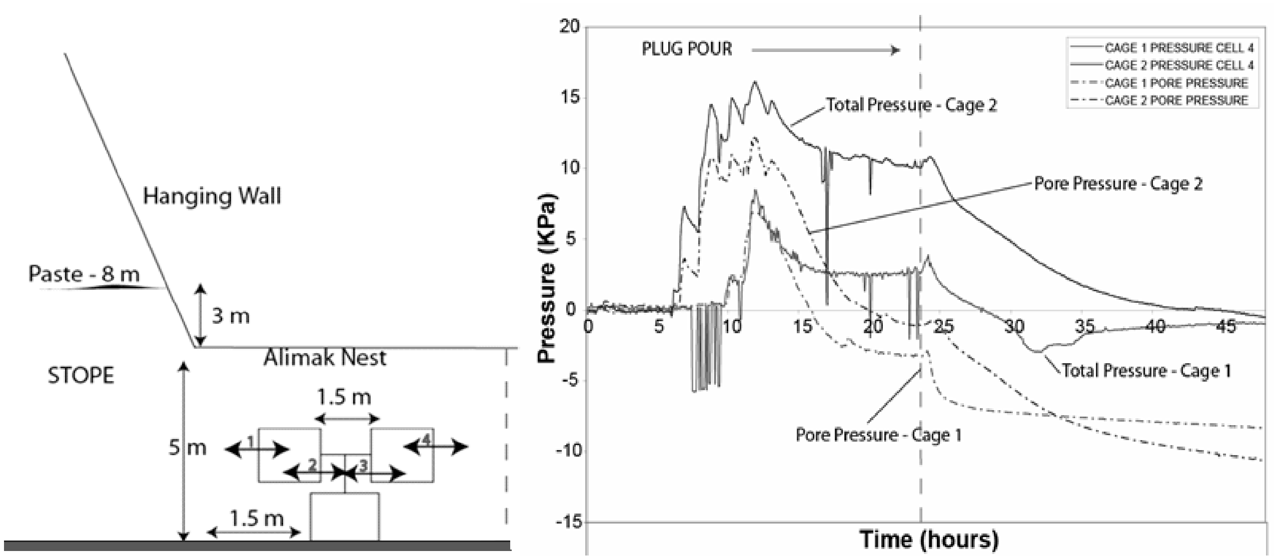

Figure 5 Geometry of simulated stope, field measurements of stress, and PWP during the plug pour

4.2 Generic modelling results

The results are presented in Figures 6 and 7, which explore the sensitivity of numerical simulations to the different parameters: WRC of the non-cemented or post-curing tailings, compressibility, and the sink term. Certainly the magnitude of the drawdown reported in the field can be simulated. As the compressibility decreases, and if the WRC of the cemented sample is used, the pore-pressures are then dissipated at a greater rate, as it takes only a relatively small amount of water removal (either due to drainage or self-desiccation) to dissipate PWP or generate suction.

Figure 7 illustrates an important point with respect to the relative importance of drainage and self-desiccation in alleviating pore pressures. While the post-curing simulation with sink generates the most negative pore-water pressures, the post-curing simulation without a sink generates the least: this is due to the lower saturated hydraulic conductivity of this material, which reduces the amount of drainage.

This case is a good target for this kind of modelling. Temperatures were not elevated in this mine, though in some mines the rise in temperature due to hydration can be significant enough to affect the hydraulic properties of the CPB. This case has also relatively low total stresses. In deeper stopes with a fast rate of filling, the total stress may be sufficient to compress the pore matrix of the CPB and alter its water retention characteristics. This effect, however, may be suppressed in many mines by the increase in stiffness. Compression of the CPB will naturally result in further excess PWP generation, though arching effects must also be taken into account in the field.

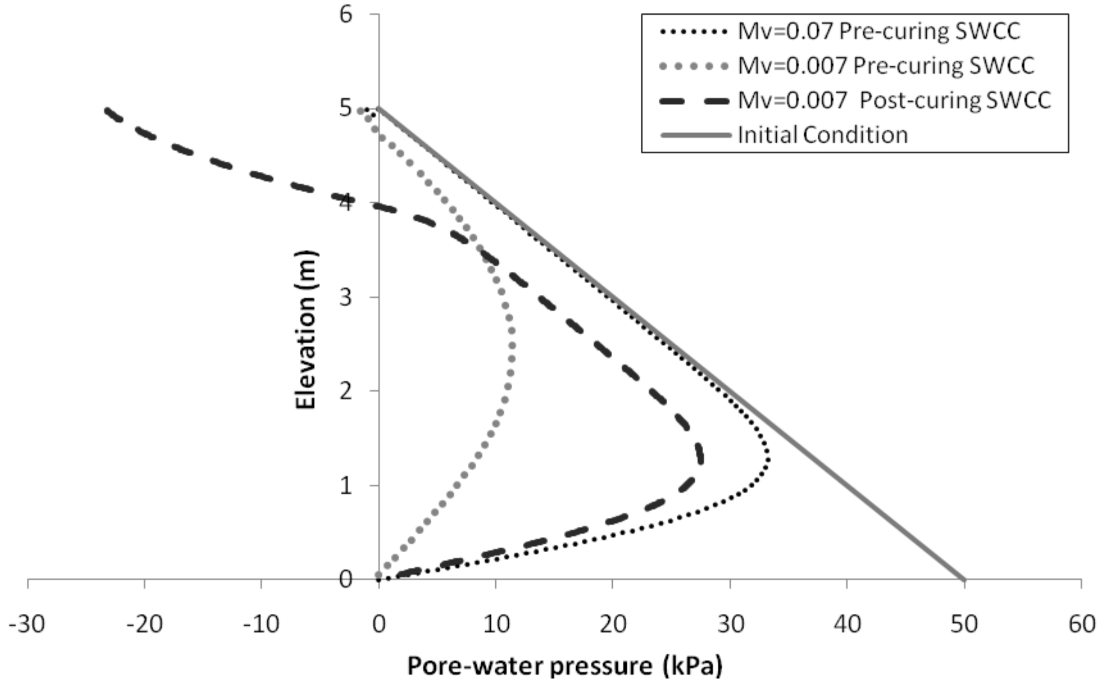

Figure 6 Simulations of pore-water pressure drawdown after 20 hours, varying compressibility and the WRC

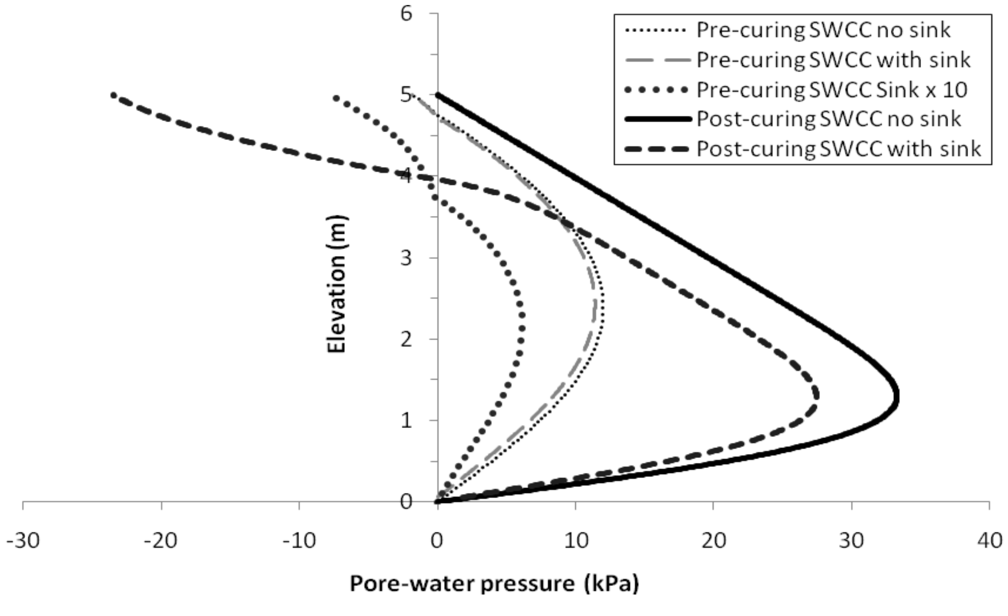

Figure 7 Simulations of pore-water pressure drawdown after 20 hours, showing the relative contributions of drainage and hydration

5 Conclusions and future work

This work has established a framework to simulate pore-pressure drawdown by both drainage and self-desiccation in CPB in the context of unsaturated flow modelling. Ongoing work is focusing on (i) tracking the evolution of the WRC and saturated hydraulic conductivity over time by analysing the evolution of pore-size distribution, (ii) incorporating transient compressibility obtained by bender element tests (such as those undertaken by Helinski et al., 2007) into the modelling, and (iii) studying the effects of temperature and total stress on the water retention properties of the material. This work forms part of a larger study incorporating field measurements from three mines using varied stope deposition schemes. Measurements of PWP and suction in these stopes will serve as validation and calibration data for the modelling approach shown in this paper.

Whereas the dissipation of pore-water pressure is crucial to optimising backfill placement, this research would also apply to surface deposition schemes incorporating layers of CPB. The effect of self-desiccation on drying and potential desaturation of surrounding tailings would be very important to the performance of the whole stack.

Acknowledgements

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References

Acker, P. (2004) Swelling, shrinking and creep: a mechanical approach to cement hydration, Materials and Structures/Concrete Science and Engineering, 37, pp. 237–243.

Belem, T., Bussiere, B. and Benzaazoua, M. (2001) The effect of microstructural evolution on the physical properties of paste backfill, In Proceedings Tailing and Mine Waste 2001, A.A. Balkema, pp. 365–374.

Belem, T., Harvey, A., Simon, R. and Aubertin, M. (2004) Measurement and prediction of internal stresses in an underground opening during its filling with cemented fill, In Proceedings 5th International Symposium on Ground Support in Mining and Underground Construction, pp. 619–630.

Belem, T. and Benzaazoua, M. (2008) Design and application of underground mine paste backfill technology, Geotechnical and Geological Engineering, Vol. 26(2008), pp. 147–174.

Decagon Devices Inc. (2007) Operator's manual for models WP4 and WP4-T, Dewpoint PotentiaMeter.

Fourie, A., Helinski, M. and Fahey, M. (2006) Filling the gap – a geomechanics perspective, Australian Centre for Geomechanics, Perth, Australia, Newsletter 26, pp. 1–4.

Grabinsky, M. and Simms, P. (2006) Self-desiccation of cemented paste backfill and implications for mine design, In Proceedings Ninth International Seminar on Paste and Thickened Tailings, Australian Centre for Geomechanics, Perth, Australia, pp. 323–336.

Grabinsky, M. and Bawden, W.F. (2007) In situ measurements of geomechanical design of cemented paste backfill systems, In Proceedings Minefill 2007 (Paper No. 2456), [CD-ROM].

Helinski, M., Fourie, M., Fahey, M. and Ismail, M. (2007) Assessment of the self-desiccation process in cemented mine backfills, Canadian Geotechnical Journal, Vol. 44, pp. 1148–1156.

Hilf, J.W. (1956) An investigation of pore-water pressure in compacted cohesive soil, Ph.D. thesis, Technical Memorandum 654, U.S. Department of the Interior Bureau of Reclamation, Denver, Colorado.

Hua, C., Acker, P. and Ehrlacher, A. (1995) Analyses and models of the autogenous shrinkage of hardening cement paste, Cement and Concrete Research, Vol. 25(7), pp. 1457–1468.

Kim, J-K. and Lee, C-S. (1999) Moisture diffusion of concrete considering self-desiccation at early ages, Cement and Concrete Research, Vol. 29, pp. 1921–1927.

le Roux, K. (2004) In situ properties and liquefaction potential of cemented paste backfill, PhD thesis, Graduate department of civil engineering, University of Toronto, Canada.

Li, L., Aubertin, M. and Belem, T. (2005) Formulation of a three dimensional analytical solution to evaluate stresses in backfilled vertical narrow openings, Canadian Geotechnical Journal, Vol. 42, pp. 1705–1717.

Simms, P. and Grabinsky, M. (2009) Direct measurement of matric suction in triaxial tests on early-age cemented paste backfill, Canadian Geotechnical Journal, Vol. 46, pp. 93–101.

Umwelt-Monitoring-Systeme (UMS) (2009) User Manual: T5/T5x pressure transducer tensiometer, Ver 12/2009, UMS GmbH Munchen.