Coupled thermo-hydro-mechanical-chemical evolution of cemented paste backfill in column experiments

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ABSTRACT
Cemented paste backfill (CPB) technology has been widely used to fill underground mine voids as underground mine support and/or tailings disposal. Once placed, the CPB structure is subjected to strong coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes. An insulated-undrained high column experiment is used to understand this THMC behaviour. The columns are instrumented with various sensors to monitor the evolution of temperature, pore water pressure, suction and vertical deformation with time. These 4 columns are filled with a CPB mixture, cured at 7, 28, 90 and 150 days, and then extensive laboratory testing is carried out on the CPB samples with regards to their thermal conductivity, hydraulic conductivity, unconfined compressive strength, shear strength parameters, physical and microstructural properties, and pore fluid chemistry. The obtained results show that the THMC properties of CPB are strongly coupled and findings can be used for cost-effective, safe and durable CPB structural designs.

RÉSUMÉ
La technologie des remblais en pâte cimentés (RPC) est largement utilisée pour remplir les excavations minières souterraines afin de servir comme moyen de support des terrains et/ou stockage des déchets miniers. Une fois sous terre, les ouvrages de RPC sont soumis à de forts processus couplés thermiques (T), hydrauliques (H), mécaniques (M) et chimiques (C). Dans cette étude, des essais en colonne ont été effectués pour comprendre ce comportement THMC. Les colonnes sont thermiquement isolées et sont de grande hauteur. Les colonnes sont équipées de divers capteurs qui permettent de suivre l'évolution de la température, la pression interstitielle, la succion et la déformation verticale dans le temps. Les quatre colonnes ont été remplies avec un mélange de RPC et soumises à des temps de cure de 7, 28 et 150 jours. Après chaque temps de cure, un programme extensif d'essais de laboratoire a été conduit pour déterminer la conductivité thermique, la conductivité hydraulique, la résistance uniaxiale compressive, les paramètres de résistance au cisaillement, et les propriétés physiques et microstructurales des RPC. Les résultats obtenus montrent que les propriétés THMC des RPC sont fortement couplées. Les conclusions de cette étude seront utiles á une conception d'ouvrages de RPC économiques, sécuritaires et durables.

1 INTRODUCTION

The main process in the mining industry is the extraction of ore bodies from the earth. This activity leads to the creation of large spaces which are known as "stopes" on the surface or underground and one of the main reasons of mining area instability. In addition to this problem, only small amounts of excavated rock or soil are used and therefore, the remaining are left on the surface as waste mining materials which can cause geoenvironmental problems. Over the past few decades, cemented paste backfill (CPB) technology has been extensively used in mining operations as an effective means of underground mine support and/or tailings disposal. It has become one of the most commonly used ways in mine backfilling around the world. CPB is a mixture of dewatered tailings from the milling or processing operation of the mine, water and hydraulic binders. The backfilling of an underground mine void (stope) by using CPB is a complex geotechnical process. Once prepared and placed, the CPB structure is subjected to strong coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes or factors. An understanding of these THMC coupled processes is crucial for a reliable evaluation of the geotechnical performance and cost-effective design of a CPB structure.

A relatively large number of experimental and numerical studies have been reported in the literature which gives a better understanding of each individual THMC factor on CPB performance. However, only very few investigations on the MH (e.g., Helinski et al. 2010) and THM (e.g. Nasir and Fall 2010) coupling behavior of CPB have been addressed to date.

The mechanical properties of CPB are considered as key to designing any CPB structure. Hence, during the past recent years, research efforts have been primarily and mostly spent on understanding the mechanical properties of CPB, such as unconfined compressive strength (UCS), shear strength parameters, modulus of elasticity and stress–strain behavior. These properties are significantly influenced by several factors. The physical properties (e.g. void ratio, density, degree of saturation) as well as CPB mix design proportion (e.g. binder content, water/cement ratio, tailings fineness, cement type and tailings chemical-physical properties) can significantly affect the mechanical behavior of CPB. In addition to the aforementioned parameters, field placement conditions such as stope size, curing temperature, filling rate of stope, arching effects and external load on CPB structures can add additional complexity to strength development in CPB structures. (e.g. le Roux et al. 2005, Rankine and Sivakugan 2007, and Fall et al. 2008, 2010). Aside from these, the coupling of settlement and self-desiccation and its relation to strength development in CPB materials has become an interesting research area in recent years (e.g., Yilmaz et al. 2009).

One of the most important parameters that affect the geotechnical performance and durability of CPB is hydraulic factors, such as hydraulic conductivity. The physical properties of tailings, mix design proportion and most importantly, microstructure of CPB, strongly influence hydraulic conductivity. A strong coupling exists between mechanical and hydraulic factors of CPB at any curing time (Fall et al. 2009). In addition, the development of pore water pressure (PWP) and suction during stope filling significantly affects the applied hydrostatic pressure as well as the effective stress close to the bottom of the stope and the barricade.

The heat produced by cement hydration is the main source of heat in CPB materials which is considered as a thermal factor. Thermal conductivity is the main thermal property in CPB materials and has a direct impact on CPB heat development which itself is fully coupled with CPB hydro-mechanical evolution. The CPB mix component, curing time, curing temperature and degree of saturation can affect the thermal properties of a CPB structure. Moreover, stope geometry and filling rate have considerable effects on heat development in CPB structures (Nasir and Fall 2009, Celestin and Fall 2009).

The main chemical processes that affect the CPB strength development are cement hydration as well as precipitation of hydrated phases from the pore fluid of CPB. The hydration of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) leads to precipitation of hydration products (e.g., calcium silicate hydrate (CSH), calcium hydroxide (CH), and ettringite) in the cemented matrix of the CPB, thereby causing refinement of the pore structure and reduction in the porosity of the CPB. This reaction contributes to the development of the interaction between the strength and hydraulic properties in CPB. Furthermore, sulphide oxidation is another chemical factor that can affect the behavior of CPBs, notably can lead to destructive effects on CPS's strength development. To understand this mechanism, observations on pore fluid chemistry and microstructural properties can determine pore structure development in CPB material (e.g. Ramlochan et al. 2004 and Benzaazoua et al. 2004 and Fall et al. 2010).

Our literature review on recent studies shows that a THMC coupling interaction has not yet been addressed. Moreover, most of the experimental studies were carried out on CPB that was prepared and cured in a cast cylinder. This means that the impact of the self-weight and the coupled THMC factors on the properties and behaviour of CPB has been neglected. In field conditions, CPB normally bears highly applied overburdened stress. In addition, the CPB is an evolutive porous medium; this means that its properties and behaviour are time-dependent. There have been no studies on the coupled THMC processes that occur in CPB.

This research gap has motivated the authors to conduct the current research to study the coupled THMC evolution of CPB by column experiments. This method allows us to assess THMC behaviour of CPB in two dimensions of time and depth that correspond to the effects of curing time and self-weight, respectively. This paper includes a part of an extensive undergoing experimental and numerical study on the THMC behavior of CPB material; and efforts have been made to mostly focus on early (7 days) and advanced (150 days) ages of CPB material in this paper.

2 MATERIAL AND METHODS

2.1. Material

The materials used include binder, tailings, and water.

2.1.1 Binders

The most popular cement used in backfill operations is ordinary Portland cement type I (PCI) which is used in this study.

2.1.2 Water

Tap water was used to prepare the CPB.

2.1.3 Tailings

Commercially available artificial (silica) tailings were used to prepare the fresh CPB. These tailings are made from ground silica which contains 99.8% $Si0_2$. The grain size of the silica tailings is very similar in physical characteristics to the natural tailings available in the mining sites of eastern Canada (Fall and Samb 2007). Natural tailings can contain several reactive chemical elements and often, sulphide minerals, which can interact with cement and thus, affect the interpretation of the results. Therefore, silica tailings are used to minimize the uncertainty induced by these interactions which can significantly influence the results of the study.

2.1.4 Mixing procedures and mix proportions

In order to produce one cubic meter of CPB mixture that contains 4.5% PCI and a water to cement ratio (w/c) equal to 7.6, tailings material, cement and water were mixed and homogenized in a concrete mixer for about 10 minutes. In all of the mixes, the w/c and cement proportions were kept constant. The CPB mixtures were produced and then poured into insulated columns in 3 layers that were each 50 cm high for 3 consecutive days in order to capture the THMC processes.

2.2 Method

2.2.1 Developed column experiment set up

In order to simulate CPB undrained conditions in underground mine stopes and coupled THMC behavior, six columns were manufactured. These columns allow the simulation of stope backfilling sequences. Figure 1 presents a schematic diagram of an experimental set-up of columns.

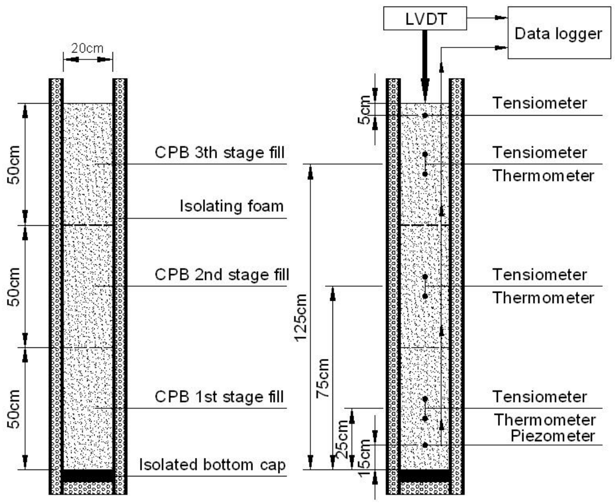

Figure 1. Schematic diagram of the experimental set-up: (a) curing columns, and (b) arrangement of sensors.

Two tubes with an external diameter of 30 cm and inner diameter of 20 cm, and height of 150 cm were used to build each column. Expansive insulation foam was used to fill the gaps between the tubes to simulate insulation and undrained conditions. Four columns were filled with fresh CPB and then cured in a controlled temperature and humidity room for periods of 7, 28, 90 and 150 days. After the specific curing time was reached, each column was dismantled over 3 days. CPB samples were then taken from different heights of the columns (e.g. 10, 25, 40, 60, 75, 90, 110, 125, 140, and 145 cm).

2.2.2 Column instrumentation

Two columns were fixed with various sensors, including a temperature sensor, vibrating wire piezometer and tensiometer at different depths, with a linear variable differential transformer (LVDT) at the top. These sensors allow us to monitor the evolution of temperature, positive PWP, and suction within the CPB during its curing as well as its vertical deformation. The temperature sensor and tensiometer were installed in the middle of each layer at heights of 25 cm, 75 cm and 125 cm from the bottom. A tensiometer was also used which was placed close to the CPB surface (5 cm below the surface) to assess the evolution of the suction due to water loss by evaporation and self-desiccation. The piezometer was installed 15 cm from the bottom of the experiment column.

2.2.3 Experimental program

2.2.3.1 Physical and engineering property tests

All of the sampled CPB samples were tested in terms of their thermal properties (thermal conductivity), hydraulic properties (hydraulic conductivity and water retention curve (WRC)), mechanical properties (UCS, shear strength parameters and modulus of elasticity) and chemical properties (degree of cement hydration and pore fluid chemistry). In addition, extensive physical testing and observation of microstructural properties were conducted to understand the evolution of the index properties and pore structure of the CPB from early to advanced ages. Gravimetric water content (ω%), volumetric water content (θ%), degree of saturation (Sr%), void ratio (e), porosity (n) and wet/dry density (ρ) were determined for the entire column. Moreover, a microstructural analysis which includes the examination of the pore structure and evolution of binder hydration products was also carried out. The microstructure of the studied CPB samples was investigated by mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) observations. Prior to the MIP testing, all samples were first oven dried at 50^oC until mass stabilization. MIP tests allow the evaluation of pore size distribution to be measured. SEM observations were conducted with a Hitachi S4800 FEG–SEM. The samples were observed in backscatter electron mode. MIP testing and SEM imaging were implemented on 4 samples taken from a column at heights of 10 cm, 60 cm, 110 cm and 140 cm at 7, 28, 90 and 150 days of curing.

A pore fluid chemistry analysis was performed to understand the evolution of pore fluid characteristics for different heights on a column and at different curing times. Three samples were taken at column heights of 25 cm, 75 cm and 125 cm, and tested for concentration of various cations (e.g., magnesium ion (Mg^{2+}), potassium ion (K^+), Al^{3+}, calcium ion (Ca^{2+}), sodium ion (Na^+), Fe^{2+}), anions (e.g., OH^-, SO_4^-, $HSiO_3^-$) and pH.

Unconfined compression tests were performed on the CPB specimens after 7, 28, 90 and 150 days of curing at different heights. A minimum of two samples were tested at each level according to the standard ASTM C39 by using a computer-controlled mechanical press. The compression tests were carried out at a constant deformation rate of 1.14 mm/min.

Despite some inherent problems (e.g., principal stress rotation, stress non-uniformity, failure plane definition), a direct stress shear apparatus was used for mechanical shear testing because of its simplicity and efficiency in fulfilling all of the testing of samples from each layer on the same day. The tests were performed according to ASTM D3080-04 at a controlled strain rate of 1.0 mm/min. A minimum of 4 specimens were tested, each under a different normal load, to determine the effects on shear resistance and displacement, and strength properties, such as Mohr strength envelopes.

Hydraulic conductivity tests were performed by using TRI-FLEX II on the CPB specimens for each curing time and at different heights. The flexible wall technique was used to determine the hydraulic conductivity of the CPB.

The procedure for this method is described in ASTM 5084-00 and was conducted in the constant head mode equal to 10 kPa. Two samples were tested and at least 3 readings were done, and the average value was the saturated hydraulic conductivity of the sample tested.

A WP4-T dewpoint potentiometer device was used to measure the WRC of the CPB samples. The WP4-T was adopted in order to obtain all results of samples from each layer on the same day to avoid any significant changes in the microstructure of the CPB as hydration proceeded. This device is capable of measuring total suction from 0 to 60 MPa with an accuracy of ±0.1 MPa from 0 to 10 MPa and ±1% from 10 to 60 MPa. The WP4-T was placed in a temperature and humidity control room. CPB samples were cut and trimmed with a spatula into a diameter close to 37.80 mm and less than 5.5 mm in height, and then placed into the machine to measure their water potential. In order to construct the WRC, CPB samples were air dried in room temperature for about 15-20 minutes and then the next reading was carried out. To accelerate moisture loss in the samples, a small fan was installed above to increase the evaporation rate. Eventually, the CPB samples were oven dried, and the solid mass and gravimetric water content were calculated during each drying step.

A KD2 thermal properties analyzer was utilized to measure the thermal conductivity of the CPB samples obtained from various heights of the column. The device computes the values of thermal conductivity and resistivity by monitoring the dissipation in heat from a line source given a known voltage. To carry out the measurement of thermal conductivity of CPB, holes that were 2.80 mm in diameter were first drilled in the centre of the CPB sample and then a thermal probe was inserted. Special care was taken to fill the gaps between the needle probe and walls of the hole so that proper contact could be made during the readings. For this purpose, a high thermal conductivity silver polysynthetic compound (k=8 w/m.k) was used.

2.2.3.2 Instrumentation methods used in the development of the column experiments

Column instrumentation allows the measurement of the evolution of temperature, suction, PWP and vertical deformation at different heights of a column with time. The monitoring of suction development with time was conducted by using a dielectric water potential sensor-MPS-1. This sensor is capable of measuring the soil water potential between 0 and -500 kPa with good accuracy. Four manufactured calibrated sensors were installed at column heights of 25 cm, 75 cm, 125 cm and 145 cm. The sensor ceramic tips were soaked in water prior to use and placed at the center of each layer before casting.

In order to understand the temperature evolution due to cement hydration at various heights of a column, TH-T temperature sensors were employed. They use a 3 kΩ standard chip thermistor. The thermistor is encapsulated and sealed into stainless steel housing. Three temperature sensors were calibrated by thermometers and then installed in the middle of each layer at column heights of 25 cm, 75 cm and 125 cm, and temperature evolution was monitored by time.

The evolution of PWP is critical in the designing of barricades in mine stopes. The applied hydrostatic pressure normally reaches the highest value at the bottom of the stope. A vibrating wire piezometer was employed in order to understand the evolution of PWP with time especially after placing fresh CPB in the column as well as monitor the consequences of the sequential filling of PWP evolution. For this purpose, a WP2100 piezometer with ±70 kPa pressure range and ±0.5% accuracy equipped with a low air entry value ceramic filter was calibrated and installed at a height of 15 cm from the bottom of the column. The piezometer was connected to a data logger and readings were collected for each minute up to 5 days after CPB placement.

The vertical deformation of fresh CPB has not been fully understood until now. Soon after the placement of fresh CPB, the CPB is subjected to vertical deformation. This vertical deformation was measured by an LVDT that was placed perpendicular to the CPB surface located at the top of the column. The LVDT measures an electrical output proportional to the position of a solid core in a cylindrical shaft. The LVDT was connected to a small circular plastic plate that was located on the top of the fresh CPB. This plate was heavy enough not to float on the CPB's bleed water, yet light enough not to sink farther into the fresh CPB. The sensor was connected to a data logger to monitor settlement with time.

3 RESULTS AND DISCUSSION

3.1 Evolution of mechanical properties with time

Figures 2 presents the variations in UCS against different heights on a column, for columns cured at 7 and 150 days. It can be observed that the variations in UCS seem to be dictated not only by the curing time and the self-weight pressure, but also by the sequencing of filling. The first layer of filling shows lower values of UCS compared to the second layer of filling. This could be due to the fact that, after the second layer of filling (50-100 cm), the CPB material can drain its water through the CPB sub-layer and therefore, behaves as a drained (or partially drained) material.

Shear strength parameters that include effective friction angle (φ), and effective cohesion (c) were found from direct shear testing and have been plotted in Figure 3. It can be seen that there is no significant change in φ after 150 days of curing compared to 7 days which was also previously reported based on triaxial test results by Rankine and Sivakugan (2007). However, effective cohesion considerably changes with curing time and reaches a higher value in the middle of the column which could be partially attributed to faster draining conditions, higher bonding particles and more strength gain.

The result of the variations in UCS versus degree of saturation is shown in Figure 4. This clearly demonstrates that the strength performance of a material is significantly influenced by the degree of saturation. This can be attributed to the development of suction due to self-desiccation in CPB material, especially at advanced ages and therefore, increases in strength of material.

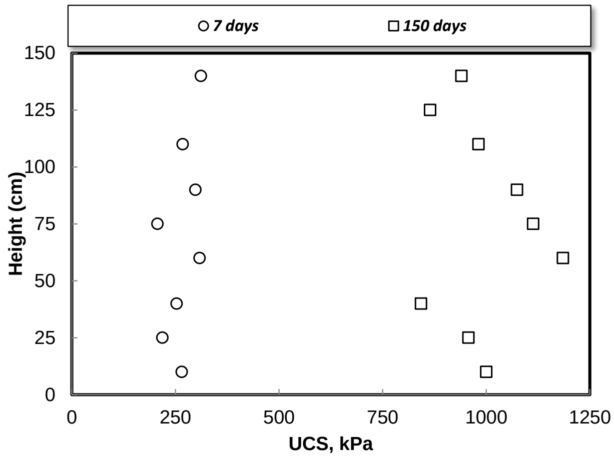

Figure 2. Variations in UCS against different heights on a column

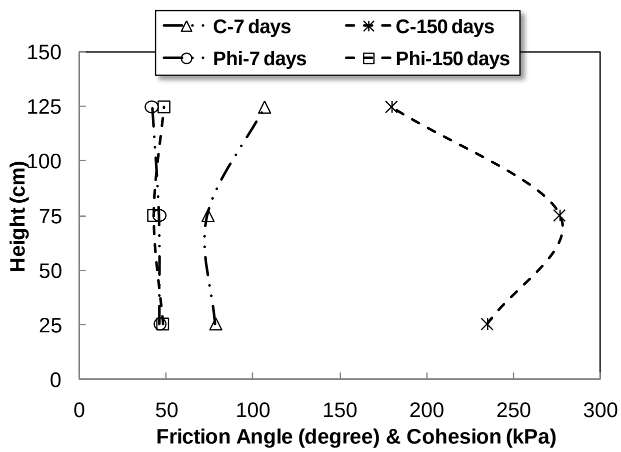

Figure 3. Variations in shear strength parameters against different heights on a column

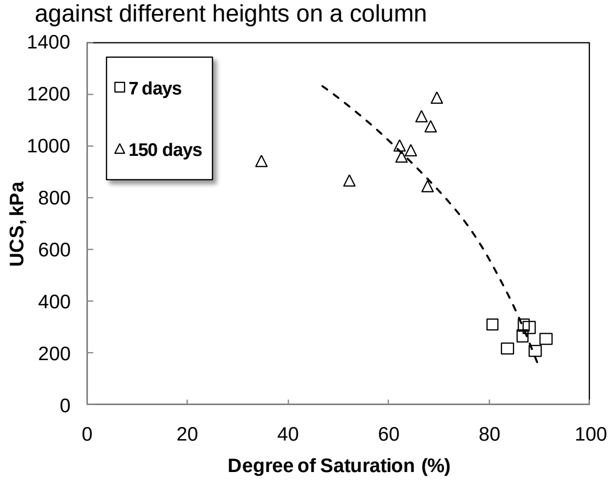

Figure 4. Variations in UCS against degree of saturation

3.2 Evolution of suction and water potential properties of CPB

The development of suction in CPB material and consequence of gradual stope filling have not been completely investigated. This phenomenon has been studied in this research and the result is shown in Figure 5. Right after CPB placement, the PWP increased up to 9.6 kPa which is even higher than the hydrostatic pressure of 3.5 kPa. The excess pore water pressure ratio ($r_u = \Delta u/\sigma'_v$) is about 3.4 at this point which is a significant amount; however, due to self-desiccation as a result of cement hydration, the PWP drops to a zero value after 2.8 hrs. Then, development of negative PWP (suction) considerably starts with time. As expected, after placement of the second layer, water drains into the sub-layer and then the PWP starts to increase, but lower than the value which has been experienced before. This finding strongly supports the drained behavior of CPB material in the middle part of the column. Moreover, from this graph, it can be noticed that the slope of each PWP reduction curve is higher than that of the next one (e.g. S1>S2>S3). This slope clearly demonstrates high self-desiccation in early ages after CPB placement which is fully coupled with the heating rate generated from cement hydration. This coupling behavior can be seen from a temperature-time graph (Figure 7). The rate of cement hydration start to decrease with time and therefore, a lower slope of the PWP can be expected.

Figure 6 illustrates the variation of WRC of CPB at early ages. No significant changes in water potential behavior were observed with column height. However, it is interesting that high air entry value (around 400 kPa) is noticed for CPB material which can be attributed to the very fine pore structure and reduction of the porosity of the CPB materials by means of filling the pores in the cemented matrix of the CPB by cement hydration products (Fall et al. 2009).

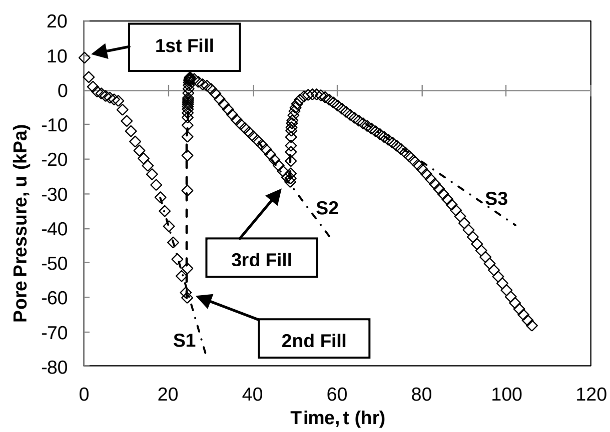

Figure 5. Evolution of PWP with time at a depth of 1.35 m

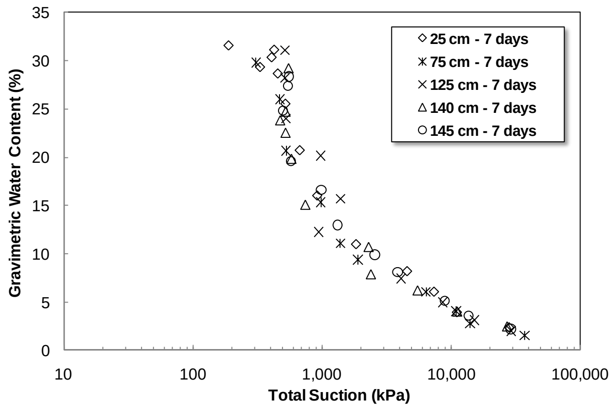

Figure 6. Water retention curve of CPB at early age versus depth

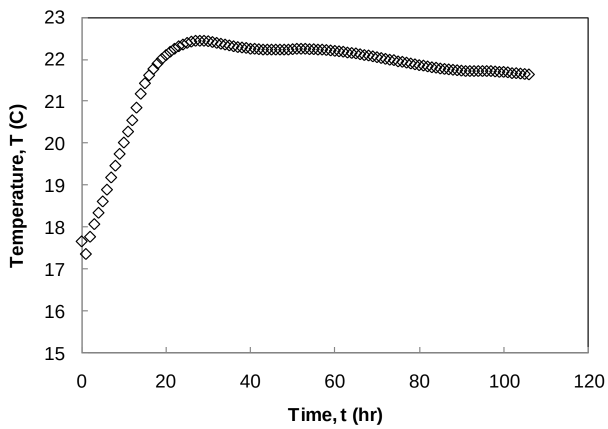

Figure 7. Evolution of temperature with time at the depth of 1.35 m

3.3 Evolution of thermal properties and heat development

Temperature development with time during cement hydration at the depth of 1.35 m is demonstrated in Figure 7. The results show that heat from cement hydration starts to develop with CPB placement and almost reaches a steady condition after 22 hrs. This heat development is the key parameter in CPB strength development and self-desiccation behavior as discussed before. The variation of thermal conductivity with degree of saturation has been plotted in Figure 8. It can be observed that the thermal conductivity of CPB decreases with a decrease in degree of saturation. Poor thermal property can be expected for advanced age CPB materials due to high development of desaturation as the result of the coupling of self-desiccation and surface evaporation.

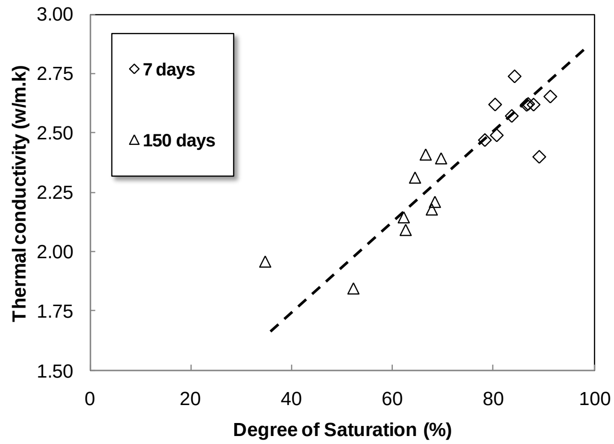

Figure 8. Variations in thermal conductivity against degree of saturation

3.4 Vertical settlement

Figure 9 demonstrates the results of vertical settlement with time soon after finishing CPB placement. The settlement reaches the highest value (4.3 mm) after 2.5 hrs when CPB placement occurs, following with lower increments up to 8 hrs and eventually keeps a straight line with time. This behavior can be attributed to the combined effect of self-desiccation in the entire column and surface evaporation at the top of the column with self-weight pressure. Self-desiccation is when during cement hydration, the resulting hydrated volume is less than the combined volume of uncemented constitutes (cement and water). This volume reduction would give rise to the development of suction and desaturation of CPB (Helinski et al. 2007). At very early ages, due to the high development of excess pore water pressure ($r_u = 3.4$), effective stress stretches to a very low value, and the resulting self-weight of CPB material can consolidate (far away from conventional consolidation mechanisms) the pore voids generated due to self-desiccation. This coupling process leads to high development in vertical settlement in very early aged CPB. After strength gain of CPB material due to cement hydration and dissipation of the PWP, and instead, very rapid development of negative water pressure (suction) by self-desiccation, CPB mechanical properties start to build up again and can no longer be affected by the self-weight pressure of the CPB material. This will result in considerable decrease in vertical settlement.

3.5 Pore fluid chemistry and evolution of physical properties with time

The analysis of the chemical composition of the pore fluid supported the data gained from mechanical tests. The cement hydration process with time was reflected in the changes of Na, K, OH, S and Ca concentrations in the pore fluid. The dominating cations of CPB pore fluid were Na, K and Ca during the first days of hydration process. Analysis of pore fluid solution shows that Ca concentration decreased from 8.2 mM for 7 days sample to 4.1 mM for 150 days sample due to formation of cement hydration products which cause refinement of the pore structure and hence higher CPB strength. In contrast, K and Na concentrations increased slightly from 80.4 mM to 88.3 mM and 91.3 mM to 97.9 mM respectively with time.

The strength and performance of CPB materials are influenced by their physical properties, such as void ratio (e), density (γ), and degree of saturation (Sr). Hence, evolution of these properties with column height and time has been investigated. Figure 10 demonstrates the variation of void ratio versus degree of saturation of CPB at early and advanced ages. Two different behaviors can be observed from this figure for different curing times. The data obtained from the sample cured for 7 days show that the degree of saturation is dependent on the void ratio that develops in the sample. A higher degree of saturation means lower void ratio. Le Roux et al. (2005) attributed this behavior to the entrance of air bubbles into the CPB material during the mixing, transport and placement processes which lead to an increase in void ratio and decrease in degree of saturation. However, Aubertin et al. (2003) credited this phenomenon to the pore size distribution (PSD) of the CPB material and ability of drainage of the CPB in stopes. Yet with regards to CPB cured at 150 days, no significant variation of void ratio versus degree of saturation was observed. CPB material at this age has reached the end of cement hydration and ultimate pore size distribution has been achieved. Therefore, there is no considerable change in void ratio across the column. However, samples close to the column surface show a marked decrease in void ratio along with loss of water content as a result of evaporation. Figure 11 shows the variations in gravimetric water content against column height. Water content is controlled during CPB preparation and hence, the measured values for CPB cured at early ages are relatively constant for column height and very close to the value obtained for fresh CPB. However, this parameter shows a significant decrease after 150 days and reaches 21.1-23.3% (associated with 62.3-69.7% degree of saturation). The variations in water content in a column demonstrate a slight increase in the middle of the column and then a significant reduction towards the surface of the column. It is interesting to note that around 30% of the column height is affected by evaporation which can be important in acid mine drainage (AMD) management. Generally speaking, oxygen diffusion can significantly increase by desaturation. Obtained experimental findings show the susceptibility of the upper part of CPB filled stopes to oxygen diffusion and likely AMD potential, although this issue should be investigated and proven by experimental and field studies. Figure 12 presents the variations in both wet and dry densities in the columns for 7 and 150 days of curing time. The column with the CPB mixture that is cured at an early age of 7 days shows a higher wet density in comparison to the one cured at 150 days due to higher water content. This value significantly decreases near the top of column as a result of evaporation. However, the dry density at 150 days of curing shows a higher value in comparison to 7 days of curing. This can be due to the refinement of the pore structure and reduction of the porosity of the CPB materials as the pore structure is filled by cement hydration products in the cemented matrix, which will eventually produce a CPB material with a higher dry density.

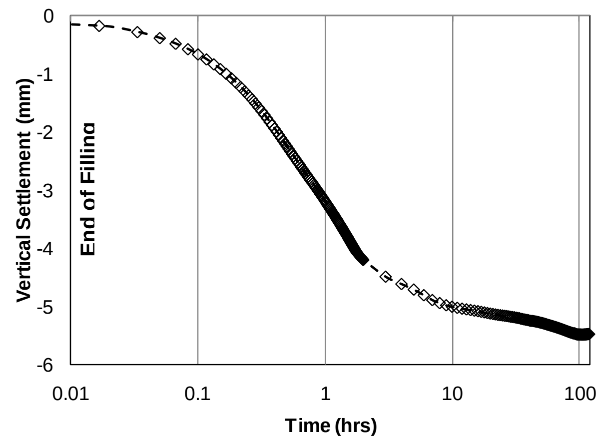

Figure 9. Evolution of vertical settlement with time

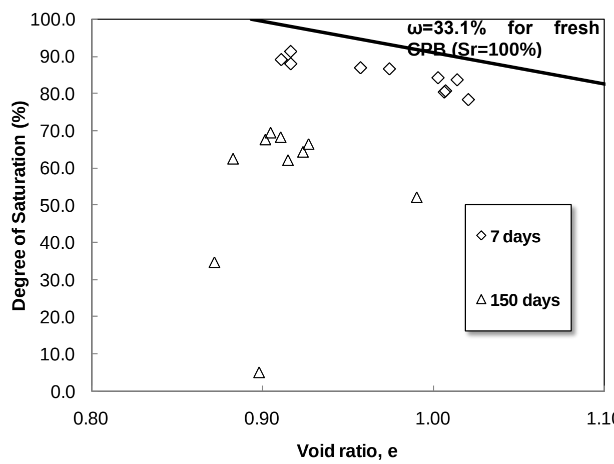

Figure 10. Variations in void ratio against degree of saturation

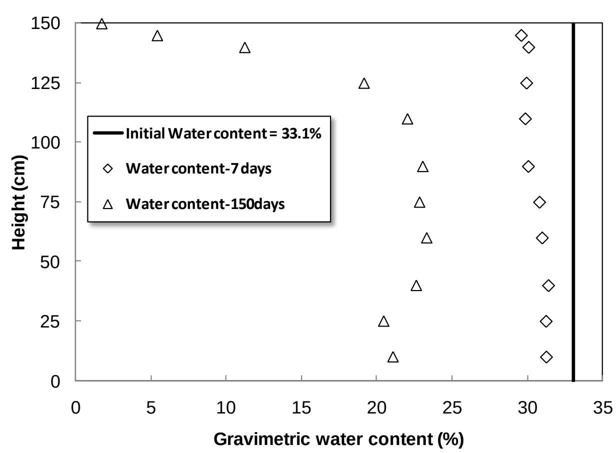

Figure 11. Variations in water content against column height

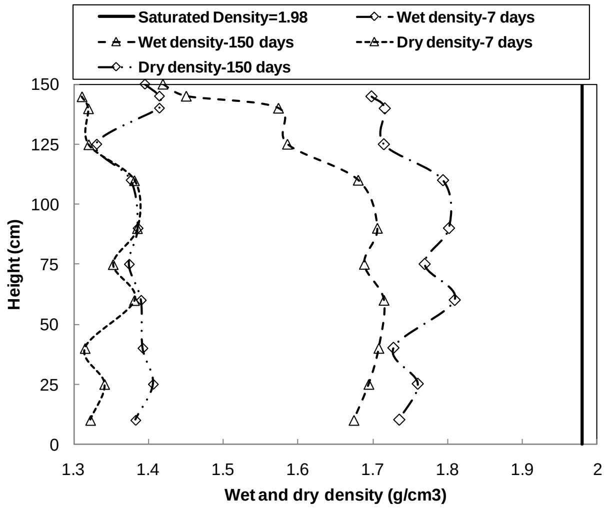

Figure 12. Variations in wet and dry densities with column height

4 SUMMARY AND CONCLUSION

This paper has presented the results of the THMC evolution of CPB material with a column experiment. Pore pressure monitoring presents that CPB structure can experience high pore water pressure soon after placement in the stope. In addition, suction development with time can be considered as a significant factor in CPB strength evolution. Thermal conductivity measurement of 7 and 150 days shows that this property is strongly dependent on CPB's degree of saturation. Surface evaporation can influences hydro-mechanical and physical properties of CPB structure. The obtained results show that the THMC properties of CPB are strongly coupled. This THMC behavior is fully dependent on cement hydration processes in CPB material. Self-desiccation, heat development and self-weight pressure can be considered as important internal mechanisms that can affect short-term THMC behavior of CPB structure. In addition, current study shows that variations in the studied parameters are not uniform with time and in height of column. This study has demonstrated that the coupled effect of THMC factors on CPB performance is important for consideration in the designing of cost-effective, safe and durable CPB structures.

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