THE INFLUENCE OF CURING TEMPERATURE AND STRESS CONDITIONS ON MECHANICAL PROPERTIES OF CEMENTING PASTE BACKFILL

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ABSTRACT

Cemented paste backfill (CPB) has been observed to achieve greater cemented strength when cured *in situ* compared with equivalent mixes cured and tested in a laboratory environment. This is in part due to the development of effective stress and generation of elevated temperatures by exothermic cement hydration reactions occurring during curing in a typical underground stope environment. This differs from curing in typical laboratory environments, where little or no effective stresses are generated and curing occurs under constant temperature conditions. This paper outlines the development, calibration and testing of a temperature-controlled hydration cell which provides closer representation of *in situ* conditions by controlling the rate and final amount of specimen temperature increase, in addition to curing under effective stress. The temperature-controlled hydration cell was used to examine the effect of curing under combined effective stress and temperature conditions on the development of small strain stiffness over a seven day curing period and the unconfined compressive strength at the end of this period. Curing with both elevated temperature and effective stress was found to significantly increase the mechanical properties of CPB compared with curing at elevated effective stress or ambient temperatures alone.

Key words: paste backfill, laboratory testing, curing technique, temperature, effective stress

INTRODUCTION

Cemented paste backfill (CPB) has been observed to achieve greater ultimate strength when cured *in situ* compared with equivalent mixes cured and tested in a laboratory environment (Revell, 2004; le Roux et al., 2005, Fahey et al., 2011). There are two significant differences between *in situ* and laboratory curing: 1) CPB cured *in situ* in an underground stope experiences effective stress due to both self-weight consolidation and the self-desiccation mechanism, and 2) the *in situ* environmental conditions include high humidity and higher temperatures due to the heat generated from exothermic hydration reactions occurring as the CPB cures. Effective stress and temperature increases do not typically occur in a laboratory-cured specimen due to the small specimen size (typically 50mm in diameter and 120mm in height) and atmospheric curing conditions.

The self-desiccation mechanism and its role in effective stress generation and associated enhancing of CPB mechanical properties has been explored in depth (Helinski et al., 2007; Grabinsky & Simms, 2006; Simms & Grabinsky, 2009 and Fahey et al., 2011). The development of a hydration cell apparatus (Helinski et al., 2007) allows CPB specimens to generate effective stress during curing in a laboratory environment, allowing the self-desiccation behaviour for a particular CPB mix to be examined. However, Helinski's hydration cell has no provision for *in situ* temperature replication.

Temperature is known to play a crucial role in the process of cement hydration of both cement pastes and concrete (Klieger, 1958; Brooks et al., 1990; Kim et al., 1998). Numerical modelling and laboratory studies (Fall et al., 2007, 2010; Fall & Samb, 2008a, 2008b; Nasir & Fall, 2009, 2010; Fall & Pokharel, 2010) as well as *in situ* data recovered from field studies (Thompson et al., 2011, 2012) indicate these benefits also extend to CPB material, despite lower cement content compared with cement pastes or concrete.

The size of the *in situ* CPB mass, as well as the insulation and higher ambient temperatures provided by the underground environment, allow for temperature increase resulting from exothermic hydration

reactions. Adiabatic testing can be used to determine such temperature increase (heat of hydration) (Gibbon et al., 1997; Morabito, 1998). However, it is expensive to conduct due to the high level of insulation and temperature feedback control required to measure the heat generation and prevent its dissipation. Instead, isothermal testing has been used to evaluate the increased strength development in CPB at early ages (< 28 days) due to higher curing temperatures (~35 - 50°C) (Fall et al., 2007, 2010), similar to those occurring in an underground environment (Grabinsky & Thompson, 2009; Thompson et al., 2011, 2012).

This paper examines the thermal behaviour of *in situ* and laboratory CPB at early ages (< 7 days), making use of semi-adiabatic laboratory testing techniques and *in situ* temperature data. Guided by these results, Helinski's hydration cell was modified to incorporate isothermal temperature control capabilities, allowing replication of *in situ* temperature conditions, in addition to effective stress generation. Details of the design, development, calibration and testing of this modified hydration cell are provided. The experimental work presented in this paper provides the first opportunity to examine the combined effects of curing temperature and effective stress on CPB properties in a laboratory environment.

THERMAL BEHAVIOUR OF CPB

To allow successful integration of temperature control into Helinski's existing hydration cell set-up, semi-adiabatic testing of CPB laboratory specimens was conducted and compared with *in situ* temperature data, to examine the differences in heat generation and dissipation between the two environments. CPB mixes were prepared in the laboratory using:

- Nickel tailings and process water from the Savannah Nickel Mine (SNM) located in the northern Kimberley region of Western Australia, mixed with Minecem binder, a proprietary binder especially developed for use with CPB; and

- Gold tailings and process water from Kanowna Belle Mine (KB) located in the Goldfields region of Western Australia, mixed with ordinary Portland cement (OPC) binder.

These mixes are referred to as SNM and KB respectively. Further details regarding their composition are provided later in the paper.

Semi-adiabatic laboratory testing

Semi-adiabatic testing was conducted using an insulated polystyrene box (0.5m by 0.4m by 0.3m), within which a CPB specimen (50mm in diameter and 120mm in height) was cast and its temperature recorded for 40-50 hours of curing. Figure 1 shows the results of semi-adiabatic testing conducted on SNM and KB CPB specimens with cement contents of 1.5% (circles) and 6% (solid line) respectively. A temperature increase was observed during curing of the KB specimen, whereas only diurnal temperature variations were observed in the SNM specimen. The cement content of the SNM was increased to 3% (squares); however, temperature variation was still only diurnal. It is possible that the observed difference in heat generation between SNM and KB specimens is related to the difference in initial temperature (Figure 1) - which resulted due to minor temperature sensor and calibration and room temperature differences between tests - as a higher, initial temperature will result in increased heat generation. However given that the difference in initial temperature is only 3°C, it is more likely that this difference relates to the different in binder type and cement content (1.5% or 3% Minecem in the SNM mix versus 6% OPC in the KB mix).

The heat loss compensation method developed by Ng et al. (2008) was applied to the data to determine the full temperature increase (i.e. heat of hydration) that would occur under fully adiabatic curing conditions. The compensation method results indicate a higher and sustained peak temperature compared with the measured result for the KB specimen (dotted line in Figure 1); the method could not be applied to the SNM specimens due to negligible measured temperature variation.

The heat loss compensation method is based on the parameter λ , which represents the heat loss of the specimen due to the reduced insulation of semi-adiabatic rather than adiabatic conditions. Larger values of λ indicate faster heat loss and larger subsequent error after compensation. Ng et al. (2008) recommends $\lambda = 2.18 \times 10^{-6} \text{ s}^{-1}$ for a semi-adiabatic test setup. However, for the semi-adiabatic test setup presented here, $\lambda = 6.0 \times 10^{-2} \text{ s}^{-1}$. This value is considerably larger than recommended and indicates a lack of adequate insulation of the test setup.

Modification of the semi-adiabatic test set up was considered and geothermal, numerical modelling of the setup (Walske, 2014) indicated that the thermal control could be improved by significantly increasing the ambient temperature and specimen size. However, such modifications were not feasible, nor extendable to the steel-constructed hydration cell setup. Therefore an external temperature control was necessary to replicate *in situ* temperature conditions in a laboratory setting.

In situ temperatures

In situ temperatures generated within a SNM CPB filled stope (M. Helinski, personal communication, 6 April, 2011) during curing have been measured using similar in-stope monitoring techniques to those utilised by Grabinsky & Thompson (2009) and Thompson et al. (2011, 2012). The data in Figure 2 shows a significant temperature increase (almost 10°C) within the SNM *in situ* material following the commencement of filling ($t = \sim 530$ hours), eventually equilibrating at a temperature of 34°C. This temperature response is vastly different than that observed in Figure 1. [MW1]

No *in situ* temperature data was available for a KB stope; however, given the difference between the temperatures recorded in the semi-adiabatic testing for KB and the SNM, it is realistic to assume that a similar trend would occur *in situ*, such that the KB stope curing would produce greater temperatures than those shown in a SNM stope. Indeed, *in situ* temperature data (Walske, 2014) collected from a different gold mine in the same geographical area and using similar cement content as the KB mix,

showed an average curing temperature of 44°C within the stope - this temperature has been assumed as representative of *in situ* KB curing conditions.

THE TEMPERATURE HYDRATION CELL

To generate adiabatic curing conditions, any temperature increase experienced by a cemented specimen must be solely due to exothermic hydration reactions. The role of a temperature control system is only to minimise, or ideally prevent, heat dissipation without actively heating the specimen. The isothermal curing of specimens (Fall et al., 2007, 2010) is not representative of true thermal conditions in a stope environment during CPB curing. While the temperature maintained in the thermal chamber may be the same as the final temperature achieved in a stope, the initial heating rate of the early age specimen required to reach the desired temperature is not necessarily realistic compared with the potential rate of exothermic hydration reactions. The ultimate CPB properties are known to be highly dependent on the very early age curing temperatures (Fall et al., 2010) and so, to accurately replicate *in situ* conditions, the temperature control system should allow heating of the specimens to a desired curing temperature over a similar timeframe to that experienced *in situ* – i.e. adiabatic conditions. *In situ* stope instrumentation studies such as those in Figure 2, along with Grabinsky & Thompson (2009) and Thompson et al. (2011, 2012), have shown this to occur over a period of hours.

The following section of this paper details the development of a temperature control system for implementation with Helinski's hydration cell allowing control over rates of temperature increase and final curing temperatures. Operation of the hydration cell to control effective stress and measure stiffness remains as detailed by Helinski et al. (2007).

The temperature control system

An external heat source was provided via two electrical heating blankets, powered and controlled by a custom designed system. The main elements of this system are shown in Figure 3 and include: two heating blankets, one located around the outside of the hydration cell and the other within the void space surrounding the specimen inside the cell; three temperature sensors used to monitor the hydration cell case temperature from inside the cell, the air temperature within the cell and the internal specimen temperature. A custom-designed heater control unit and associated software were used to control power supply to the heaters. Figure 4 shows how these elements are integrated into the existing hydration cell set-up.

The hydration cell was pressurised with air allowing the internal heating blanket, as well as the case and air temperature sensors, to be used without waterproofing. The air also provides better thermal insulative properties due to its lower thermal conductivity ($0.025 \text{ J/sec/}^{\circ}\text{C}$) compared with water ($0.6 \text{ J/sec/}^{\circ}\text{C}$).

Generating desired thermal curing conditions

Temperature control of the set-up was achieved via a feedback loop from the case temperature sensor to the control system, providing thermostatic control of the system by powering the heating blankets on and off to maintain the user-defined target temperature; no intermediate power setting for the heating blankets was available. A time delay, evident in Figure 5, was found to exist between the application of heat via the heating blanket and when the heat manifested as a temperature increase in the specimen.

After approximately one hour of heating, constant temperatures were reached and maintained in the air and case temperatures, yet the specimen temperature continued to increase, reaching a constant value three to four hours later. It is due to this delay that the case temperature reading was used as the thermostat sensor for the system - waiting until the specimen temperature reached the desired level

before powering off the heaters would introduce additional heat into the system and ultimately generate higher than desired specimen temperatures. To minimise the heating delay a heat timing algorithm was implemented to prevent overheating of the specimen beyond the desired temperature, as well as allowing the specimen to generate its own heat while using the heating system to minimise heat dissipation (i.e. adiabatic conditions).

The algorithm powers the heaters on and off for durations of “T” seconds depending on the difference in temperature (“ Δ ”) between the measured and target temperatures e.g. the smaller the value of “ Δ ”, the shorter the duration “T”. However, despite this improved heater control, the temperature gap between the specimen and surrounds was still too large, regardless of the “T” value considered, and the 0.5°C accuracy temperature sensors were unable to identify any initial temperature increase in the specimen and thus the heating control system was not activated (i.e. non-adiabatic conditions). To improve this thermal response, internal fans were installed within the cell to help circulate air and independent control of the internal and external heating blankets were implemented. Unfortunately the fans were found to have no effect on any of the measured temperatures and independent control of the blankets proved too complex for the control system software – adiabatic conditions could not be achieved.

Instead, an isothermal approach was adopted (Figure 5) where the curing temperature and rate of temperature increase may be varied to be consistent with *in situ* observations. Given the heat transfer delays and temperature offsets, to achieve a desired specimen temperature within a given time period (i.e. replicate *in situ* temperature conditions) the required target temperature and timing values (“T” seconds) needed to be determined by extensive calibration testing.

It is this ability to control specimen heating over a defined time period, in addition to coupling the elevated temperature curing with generation of effective stress, that makes this experimental testing novel in its development compared with previous CPB temperature testing work (Fall et al., 2007, 2010; Fall & Samb, 2008b; Fall & Pokharel, 2010).

EXPERIMENTAL TESTING

The temperature-controlled hydration cell was used to examine the combined influence of effective stress and elevated temperature curing on two different CPB materials: SNM and KB, as previously mentioned. Specific details regarding the different material types, specimen preparation and the experimental testing program are presented next.

Materials and specimen preparation

The SNM and KB CPB mixes are defined by their solids content (C_s), cement content (C_c) and void ratio (e); for the SNM mixes $C_s = 78\%$, $C_c = 1.5\%$ and $e = 0.9$ and for the KB mixes $C_s = 78\%$, $C_c = 5\%$ and $e = 0.8$. In this paper, cement content and solids content are defined as the mass of dry cement divided by the mass of total dry solids, and mass of total dry solids over total specimen mass respectively. The particle size distributions for both SNM and KB tailings are shown in Figure 6. Specific gravities for SNM and KB tailings and both binders (Minecem and OPC) are 3.2, 2.72 and 3.2 respectively.

Chemical composition of SNM and KB tailings were examined using X-ray fluorescence (XRF), X-ray diffraction (XRD), organic and inorganic carbon and total dissolved metals analyses. A quantitative results summary for each of these tests is shown in Table 1, Table 2, Table 3 and Table 4 respectively. A chemical analysis of the SNM and KB process water used in the CPB mix was also conducted. This included analysis of total dissolved solids (TDS), electrical conductivity (EC), alkalinity, hardness, pH, anions and total dissolved metals; the results are summarised in Table 5, Table 6 and Table 7. Chemical interactions are known to play a significant role in the progression of binder hydration (Benzaazoua et al., 2004; Fall & Benzaazoua, 2005). The results of these chemical analyses have been included for completeness and may be used to facilitate further analysis of the results presented in this paper. Further discussion is outside the scope of this paper. Paste specimens were prepared for experimental testing by combining the measured quantities of water, binder and

tailings required to achieve the mix specifications detailed. The time at which first contact between cement and water occurred was recorded and used as the reference time, $t = 0$. All testing was carried out in a temperature-controlled laboratory at an ambient temperature of 23°C ($\pm 2^{\circ}\text{C}$).

Testing program

To independently identify the effects of temperature and self-desiccation, or effective stress (σ'), on the development of CPB mechanical properties, specimens were cured under four different curing conditions: room temperature preventing σ' generation (curing condition A); room temperature allowing σ' generation (curing condition B); elevated temperature preventing σ' generation (curing condition C); and elevated temperature allowing σ' generation (curing condition D). These conditions are summarised in Table 8.

The development of small strain stiffness (G_o) was monitored throughout the seven day curing period using bender elements (Dyvik & Olsen, 1991); the small strain stiffness is used as an index for stiffness and hydration progression throughout hydration, rather than as a definitive value representative of actual in-stope conditions.

The unconfined compressive strength (UCS) was tested and compared at the conclusion of curing on specimens with height to diameter ratio equal to 2. Throughout the UCS testing programme, specimens were submerged in a water bath, to negate all suction-induced strength contributions (Fahey et al., 2011; Helinski et al., 2011), and loaded at a constant strain rate of 0.1 mm/minute to determine the peak UCS and post peak strain behaviour.

Stress conditions

To generate the stress conditions applied under curing conditions B and D, undrained conditions were maintained throughout the test allowing effective stress generation due to self-desiccation. In curing conditions A and C, measures were taken to prevent effective stress generation occurring. In the SNM

tests this involved opening the top cap of the specimen to interface with the air-filled cell, forcing equilibrium between specimen pore pressure and the cell pressure; evaporation from the saturated specimen was prevented by attaching a small open-ended water-filled tube to the specimen top cap opening; at the completion of testing the tube still contained water. Due to the high permeability of the SNM material (Fahey et al., 2010) this approach was sufficient to dissipate any effective stress generation. This same approach was unsuccessful for KB specimens due to the material's low permeability (Fahey et al., 2010) such that the rate of pore fluid flow through the material matrix was significantly reduced when compared with a higher permeability fill (i.e. SNM). In the case of the KB temperature-controlled hydration cell tests, the applied backpressure was expected to replenish the pore fluid depleted by self-desiccation, in order to prevent effective stress generation. Instead, the permeability of the KB fill appears to have been sufficiently low such that the back pressure was inadequate to replenish the fluid fast enough compared with the consumption of water in the hydration process, hence effective stress was (unintentionally) generated as shown in Figure 8(a) and (c). KB and SNM permeability, measured at a vertical effective stress of 40kPa, is 1.5×10^{-3} m/day and 1.02×10^{-1} m/day respectively. CPB permeability is very variable depending on hydration and stress condition; further details relating to KB and SNM material permeability may be found in Fahey et al. (2010).

Temperature conditions

From the previously discussed *in situ* temperature monitoring during stope filling, temperatures of 44°C and 34°C for KB and SNM CPB respectively were chosen as representative of *in situ* thermal conditions for replication in the temperature hydration cell. The results of the calibration process indicated target temperatures of 53°C and 40°C were required for KB and SNM testing to achieve specimen temperatures of 44°C and 34°C respectively. Room temperature, for conditions A and B for both CPB mix types, was chosen as 23°C and provided by the temperature controlled laboratory.

RESULTS AND DISCUSSION

A number of temperature-controlled hydration cell tests were conducted on each material type under each curing condition. For each data type (effective stress, temperature, stiffness and UCS) the results are plotted for each curing condition (A, B, C or D) and material (SNM or KB), where each data set contains two or three individual test results (with the exception of SNM curing condition C), verifying reproducibility of results.

The mean of each data set was then compared between different curing conditions and material types, allowing examination of the effect of temperature and effective stress on individual material behaviour in addition to behaviour differences between the two CPB mixes.

Effective stress generation

The effective stress generated under curing conditions A, B, C and D for SNM and KB tests are shown in Figure 7(a), (b), (c) and (d) and Figure 8 (a), (b), (c) and (d) respectively. Zero effective stress maintenance for curing conditions A and C were successful for SNM tests (Figure 7 (a) and (c)), whereas the low permeability of the KB material (Fahey et al., 2010) made it impossible to maintain zero-effective stress (Figure 8(a) and (c)) as previously discussed. All SNM and KB tests conducted under curing condition B and D generated effective stress as expected.

The mean effective stress determined for each stress condition data set (Figure 7 and Figure 8) are plotted together in Figure 9(a) and (b) for SNM and KB material respectively. The magnitude of effective stress generated for both KB and SNM is greater under curing condition D, compared with B; i.e. σ' generation is larger under a higher curing temperature. This is as expected given the known effect of elevated curing temperatures on hydration progression and that hydration progression generates effective stress; this is further discussed later in the paper. The difficulty in maintain a zero effective stress condition in the KB material for curing conditions A and C is clearly shown by the

~20kPa σ' maintained in curing condition A and the even larger effective stress generated in C. Whereas the applied backpressure was not successful in preventing σ' generation in the case of A, it was able to reduce the extent to which it developed, indicated by the difference between the extent of effective stress generation in curing condition A and B. The effect of elevated curing temperature is again evident where σ' generation under curing condition C is significantly larger than that generated under A.

Effective stress generation in the KB specimens under each of the four curing conditions is considerably larger than that achieved in the SNM tests. This is likely due to the lower binder content of the SNM CPB ($C_c = 1.5\%$) compared with KB ($C_c = 5\%$), in addition to the lower KB permeability, as previously discussed.

Specimen temperature

Recorded specimen temperatures are shown in Figure 10 (a), for SNM curing condition D, and Figure 10 (b), (c) and (d) for KB curing conditions A, C and D respectively. The SNM curing condition D tests were the only SNM tests to successfully record specimen temperature and an issue with KB condition B meant no temperature data was collected for this curing condition. However, based on the accuracy of achieved temperatures in other curing conditions and confidence in the ability of the temperature controlled hydration cell setup to achieve a particular curing temperature, the curing temperatures in these tests were assumed to be as desired.

The elevated “room temperature” reading observed in the A3 test (Figure 10(b)) occurred due to the accidental activation of the temperature control system demanding a temperature of 25°C. Despite this, the effective stress generated by this test was still considered representative for this curing condition due to the minor variation between A1/A2 and A3 temperatures compared with the elevated temperature of curing conditions C and D.

Small strain stiffness generation

The small strain stiffness generated by each SNM and KB specimen under the four different curing conditions is shown in Figure 11 and Figure 12 respectively. The mean small strain stiffness determined for each stress condition data set are then plotted together in Figure 13(a) and (b) for SNM and KB respectively.

The SNM specimens cured under condition D (Figure 13(a)) show significantly greater stiffness development than specimens cured under A, B or C. It was not expected that the G_o curve for B would be so low, given the effective stress generation demonstrated in Figure 9(a) and the positive correlation between these two properties. It must again be noted that the results presented represent an average of two or three individual test results (with the exception of SNM curing condition C) and that the results shown here are reproducible.

The KB material shows greater stiffness development under both elevated temperature curing conditions C and D compared with the specimens cured at room temperature. Yet as remarked for SNM, the expected correlation between σ' and G_o is not evident, as the data for curing condition A shows greater G_o values compared with B, despite the reverse with regard to σ' . The magnitude of G_o for curing condition D is comparable between the KB and SNM mixes, which is also contrary to the difference observed between σ' development in each material. The fact that this difference in expected σ'/G_o behaviour is evident in both SNM and KB material testing indicates that it is not simply related to the difficulties in maintaining specific stress condition (i.e. $\sigma' = 0$) encountered in the KB tests.

UCS testing

The stress-strain curves from SNM and KB UCS tests for all four curing conditions are presented in Figure 14 and Figure 15 respectively. Due to the difference in stress-strain behaviour of individual

tests, the maximum stress and corresponding axial strain at which the peak stress occurred was averaged for each curing condition and marked with an 'X'.

To compare the 7-day UCS for SNM and KB, achieved by curing under each of the investigated conditions, the peak stresses indicated by the 'X' in Figure 14 and Figure 15 for SNM and KB respectively are plotted as q_u in Figure 16.

These results clearly indicate a trend of increasing strength with both effective stress and curing temperature, in addition to highlighting the positive interaction between these two variables. The q_u values for the SNM CPB, show consistent increases in peak strength from $q_{uA} = \sim 140\text{kPa}$ to $q_{uD} = \sim 220\text{kPa}$ moving from curing condition A to condition D. The results suggest that curing temperature provides a greater influence on specimen 7-day strength than effective stress generation, as q_{uC} is significantly larger than q_{uB} for both KB and SNM CPB. However, in the KB testing, unlike the SNM CPB, no further strength increase was afforded with the addition of effective stress generation, as seen by comparison of q_{uC} and q_{uD} . This is explained by a higher than expected strength from curing condition C due to the unintended effective stress generation, such that there was no significant difference between curing conditions C and D. Considering the low permeability of the KB CPB (Fahey *et al.*, 2010), it was anticipated that KB would obtain the greatest benefits from curing under elevated temperatures due to its reliance on the self-desiccation mechanism for effective stress generation and the significant effect temperature has on this mechanism. This is validated by examining strength increases achieved between curing conditions, which is greater for KB compared with SNM. However, increased binder percentage used in the KB CPB mix compared with SNM also contributes to this difference.

An indication of the comparative failure behaviour is given in Figure 17, where the axial strain level at which the peak strength (q_u) is achieved, is plotted against q_u . The peak UCS stresses (q_u) for the KB material fall within a $\sim 300\text{kPa}$ stress range over a corresponding strain range of $<0.5\%$. Comparing this with the SNM UCS tests, where the peak UCS stress range is 80kPa over 2% strain,

indicates increased ductility for the SNM material. The significantly larger strengths achieved by the KB specimens under all curing conditions compared with SNM is almost certainly due to the higher binder content of the KB mix. The difference in strain may also relate to this, whereby the lower resulting strength of SNM specimens is associated with increased specimen ductility.

Surprisingly, if the full stress strain curve is examined for specimens cured under high temperatures (curing conditions C and D for either SNM or KB as shown in Figure 14 and Figure 15 respectively) there is no significant difference in post-peak behaviour, despite suggestions in the literature that curing at elevated temperatures should promote quasi-brittle failures (Fall et al., 2010).

Elevated curing temperatures lead to increased hydration progression, in turn influencing effective stress generation and microstructure; both of which have been shown to positively influence CPB mechanical properties (Helinski et al., 2007; Fall et al., 2010). The improved mechanical performance of CPB cured under elevated temperatures is clearly reflected in the results presented here. Higher curing temperatures increase the rate of chemical hydration reaction, increasing precipitate formation within the material pores. This influences the microstructure of the specimen, resulting in a finer CPB pore structure (Pokharel & Fall, 2011; Fall et al., 2010). The progression of the chemical hydration reactions and the ultimate properties achieved are highly dependent on the chemistry involved and the temperature at which these reactions occur. Given the significantly different chemistry between the KB and SNM mixes, this may explain some of the differences observed between specimens comprising different materials and/or curing temperatures. It is recommended that examination of specimen microstructure (via mercury intrusion porosimetry, or similar) be included in future studies.

CONCLUSIONS

This paper has presented the development, calibration and testing of a hydration cell successfully adapted to include temperature control. The hydration cell was modified to include a temperature

control system allowing laboratory curing conditions to better represent *in situ* curing conditions (i.e. effective stress and elevated temperature curing) than traditional laboratory techniques.

Elevated curing temperatures were shown to promote effective stress generation and the combination of both effective stress curing and elevated temperatures (curing condition D) were found to generate greater stiffness compared with the curing conditions A, B or C.

The UCS results clearly identified an increasing trend in strength with the elevated curing temperature and effective stress generation, indicating the effect of elevated curing temperature on CPB 7-day strength is more significant than effective stress development. However, effective stress generation still has a marked effect on the ultimate strength. No significant temperature effects on the post-peak UCS behaviour were observed.

This suite of testing clearly indicated significant enhancement of laboratory-cured CPB strength with control over both temperature and stress conditions, compared with traditional curing techniques, or indeed even the use of Helinski's original hydration cell which controls only stress conditions. Current laboratory testing techniques are shown to underestimate the strength of CPB compared with curing conditions better representative of those encountered *in situ*. The modified hydration cell provides the opportunity to better understand the effect of *in situ* curing conditions on CPB hydration in a laboratory environment, with associated improvements in understanding of strength development, ultimately allowing for safer, more efficient and economical CPB design.

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FIGURES

Figure 1: Semi-adiabatic testing of KB and SNM CPB material.

Figure 2: *In situ* temperatures measured in a SNM stope.

Figure 3: Temperature control system.

Figure 4: Temperature controlled hydration cell. NB: drawing not to scale. For reference, sample and cell diameters are approximately 70mm and 200mm respectively.

Figure 5: Example temperature measurements during heating of the hydration cell.

Figure 6: Tailings material particle size distribution.

Figure 7: SNM effective stress (σ') measurements under varying curing conditions: (a) curing condition A - room temperature, no σ' generation; (b) curing condition B - room temperature with σ' generation; (c) curing condition C - elevated temperature, no σ' generation; (d) curing condition D – elevated temperature with σ' generation.

Figure 8: KB effective stress (σ') measurements under varying curing conditions: (a) curing condition A - room temperature, no σ' generation; (b) curing condition B - room temperature with σ' generation; (c) curing condition C - elevated temperature, no σ' generation; (d) curing condition D – elevated temperature with σ' generation.

Figure 9: Comparison of effective stress (σ') generation with time (t) for (a) SNM and (b) KB curing condition A - room temperature, no σ' generation; curing condition B - room temperature with σ' generation; curing condition C - elevated temperature, no σ' generation; and curing condition D – elevated temperature with σ' generation. Note: for clarity, the y axes have different scales.

Figure 10: Specimen temperatures (T_s) for (a) SNM under curing condition D – elevated temperature with σ' generation; (b) KB under curing condition A - room temperature, no σ' generation; (c) KB under curing condition C - elevated temperature, no σ' generation; (d) KB under curing condition D – elevated temperature with σ' generation.

(a)

(b)

(c)

(d)

Figure 11: SNM specimen stiffness (G_o) generation under various curing conditions: (a) curing condition A - room temperature, no σ' generation; (b) curing condition B - room temperature with σ' generation; (c) curing condition C - elevated temperature, no σ' generation; (d) curing condition D – elevated temperature with σ' generation.

Figure 12: KB specimen stiffness (G_o) generation under various curing condition: (a) curing condition A - room temperature, no σ' generation; (b) curing condition B - room temperature with σ' generation; (c) curing condition C - elevated temperature, no σ' generation; (d) curing condition D – elevated temperature with σ' generation.

Figure 13: Comparison of small strain stiffness (G_o) generation with time (t) for (a) SNM and (b) KB cured under curing condition A - room temperature, no σ' generation; curing condition B - room temperature with σ' generation; curing condition C - elevated temperature, no σ' generation; and curing condition D – elevated temperature with σ' generation.

Figure 14: Strain-strain curves from UCS testing of SNM specimens cured under various curing conditions: (a) curing condition A - room temperature, no σ' generation; (b) curing condition B - room temperature with σ' generation; (c) curing condition C - elevated temperature, no σ' generation; (d) curing condition D – elevated temperature with σ' generation.

Figure 15: Strain-strain curves from UCS testing of KB specimens cured under various curing conditions: (a) curing condition A - room temperature, no σ' generation; (b) curing condition B - room temperature with σ' generation; (c) curing condition C - elevated temperature, no σ' generation; (d) curing condition D – elevated temperature with σ' generation.

Figure 16: Comparison of peak UCS strength (q_u) for KB and SNM cured under curing condition A - room temperature, no σ' generation; curing condition B - room temperature with σ' generation; curing condition C - elevated temperature, no σ' generation; and curing condition D – elevated temperature with σ' generation.

Figure 17 Comparison of UCS and associated axial strain for (a) SNM and (b) KB cured under curing condition A - room temperature, no σ' generation; curing condition B - room temperature with σ' generation; curing condition C - elevated temperature, no σ' generation; and curing condition D – elevated temperature with σ' generation.

TABLES

Table 1: Tailings chemical analysis – semi-quantitative XRF

	Units	SNM	KB
Al ₂ O ₃	% wt.	11.1	13.1
SiO ₂	% wt.	46.9	59.3
TiO ₂	% wt.	0.578	0.378
Fe ₂ O ₃	% wt.	28.7	2.93
MnO	% wt.	0.133	0.061
CaO	% wt.	2.79	4.85
K ₂ O	% wt.	1.61	2.9
MgO	% wt.	3.66	2.97
Na ₂ O	% wt.	1.23	4.6
P ₂ O ₅	% wt.	0.029	0.168
SO ₃	% wt.	11.7	0.88

Table 2: Tailings chemical analysis – semi-quantitative XRD

	Units	SNM	KB
Actinolite	% wt.	12.8	-
Albite	% wt.	23.6	35.5
Biotite	% wt.	2.2	-
Muscovite	% wt.	14.2 *	20.2
Chalcopyrite	% wt.	-	0.5
Chlorite	% wt.	-	0.6
Coquimbite	% wt.	0.1	-
Cummingtonit	% wt.	5.3	-
Dolomite	% wt.	0	17.3
Kaolin	% wt.	2.2	0.4
Microcline	% wt.	19.4	-
Pyrrhotite-5C	% wt.	6.6	-
Quartz	% wt.	12.7	22.6
Halite	% wt.	-	2.9
Talc	% wt.	1	-

* Values are not as reliable as a large orientation correction was required.

Table 3: Tailings chemical analysis - organic and inorganic carbon

	Limit of Reporting	Units	SNM	KB
TIC	0.05	% wt.	<0.05	1.53
TOC	0.05	% wt.	<0.05	<0.05

Table 4: Tailings chemical analysis - total dissolved metals

	Limit of Reporting	Units	SNM	KB
Al	10	mg/kg	18,800	2,850
Ca	10	mg/kg	8,900	30,000
Cu	0.1	mg/kg	140	23
Fe	5	mg/kg	130,000	16,000
K	5	mg/kg	7,100	1,300
Mg	5	mg/kg	11,000	16,000
Na	10	mg/kg	830	14,000
S	5	mg/kg	28,000	3,300
Si	2	mg/kg	1,200	410
Sr	0.2	mg/kg	24	250

Table 5: Water chemical analysis - alkalinity, electrical conductivity, hardness, pH and total dissolved solids (TDS)

	Limit of Reporting	Units	SNM	KB
Alkalinity	1	mg/L	<1	52
Electrical conductivity	0.2	mS/m	429	21,000
Hardness	1	mg/L	1,700	24,000
pH	0.1		7.4	7.4
TDS	1	mg/L	3,600	210,000

Table 6: Water chemistry analysis – anions

	Limit of Reporting	Units	SNM	KB
Cl	1	mg/L	58	126,000
CO ₃	1	mg/L	<1	<1
HCO ₃	1	mg/L	<1	63
NO ₃	0.05	mg/L	<0.05	64
SO ₄	0.1	mg/L	2,530	3,730

Table 7: Water chemistry analysis – total dissolved metals

	Limit of Reporting	SNM [mg/L]	KB [mg/L]
Al	0.005	0.067	<0.025
As	0.001	<0.001	0.31
B	0.02	<0.02	0.62
Ba	0.002	0.043	0.27
Ca	0.1	488	3170
Cd	0.0001	0.0001	0.077
Co	0.005	0.007	2.4
Cr	0.001	<0.001	<0.005
Cu	0.002	<0.002	0.16
Fe	0.005	5.1	2.4
K	0.1	193	116
Mg	0.1	128	3790
Mn	0.001	1.4	0.012
Mo	0.001	<0.001	0.1
Na	0.1	244	72500
Ni	0.001	0.48	1.1
Pb	0.0001	0.0001	0.075
V	0.005	<0.005	<0.025
Zn	0.005	0.046	0.063

Table 8: Testing matrix of experimental curing conditions for temperature and effective stress testing.

		<i>Stress condition</i>	
		No σ'	With σ'
<i>Temperature condition</i>	Room temperature	A	B
	Elevated temperature	C	D