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Constrained thermal expansion as a causal mechanism for in situ pressure in cemented paste and hydraulic backfilled stopes

BD Thompson *Mine Design Engineering, Canada*

D Simon *University of Toronto, Canada*

MW Grabinsky *University of Toronto, Canada*

DB Counter *Glencore Canada Inc., Canada*

WF Bawden *Mine Design Engineering, Canada*

Abstract

In situ pressures are compared within cemented paste backfill (CPB) and cemented hydraulic backfill (CHB) at five mines. Pressures are initially controlled by backfill rise rates, and subsequently moderated as the backfill transitions from a fluid to a soil-like material and gains shear strength. At Kidd Mine, significant pressure increases were measured within the CPB during backfilling shutdowns. A positive correlation is found between pressure and temperature, with pressure increasing by ~30 kPa/°C. In one location, temperature increased by 11°C, corresponding to a 300 kPa pressure increase. Extrapolating the rates of pressure increase to the end of backfilling suggests up to 50% of the vertical pressure measured was thermally-induced. Similar magnitude pressures that are apparently thermally-induced were measured in CHB. As noted by others, a component of pressure increase measured by a total earth pressure cell (TEPC) due to differential thermal expansion of the TEPC constituent materials and the stiffening surrounding medium should be expected. However our calibrations (physical and theoretical) suggest the instrument calibration to be significantly smaller than the measured, thermally-induced pressure increase in the various backfills. Constrained thermal expansion of CPB/CHB within the stope is the suggested causal mechanism for the measured thermally correlated pressure changes. This interpretation is supported by laboratory tests that demonstrate CPB expands, and can induce pressure increases of ~200 kPa when the backfill materials are heated to mimic the in-stope thermal conditions. Increased sample air content minimises thermally–induced pressure increase, making it difficult to accurately replicate in situ conditions in the laboratory. Limited in situ pressure changes at Cayeli Mine also appear to correlate with temperate increases during downtimes in backfilling. This was not observed at Williams Mine, possibly due to low binder contents. Therefore, constrained thermal expansion potential as a mechanism for pressure generation in CPB is not common to all mines but should be considered when interpreting field data. The interpretation of thermal expansion of backfill emphasises the requirement to better understand the response of TEPCs to changes in temperature while under load, in order to isolate the effects of instrumentation and physical backfill behaviour.

1 Introduction

CPB is a type of backfill that utilises cemented total mine tailings, and is gaining popularity throughout the mining industry due to rapid in-stope delivery, engineered strength properties and diversion of tailings from surface disposal (Henderson et al. 2005; Landriault 2006). The University of Toronto (U of T) conducted a large scale CPB fieldwork program in partnership with Cayeli Mine (Inmet Mining Corporation), Kidd Mine (Glencore Canada) and Williams Mine (Barrick Gold Corporation). The work was motivated by the relative lack of understanding of the in situ geotechnical properties of CPB and is described in detail by

Thompson et al. (2011, 2012). Mine Design Engineering (MDEng.) has applied this approach to CHB as detailed by Thompson et al. (2013).

In order to predict containment barricade pressures it is important to understand how backfill-induced pressures and temperatures evolve within a stope. Pressures can significantly vary even within the same mine due to the interplay of several variables (Hassani et al. 1998; Yumulu & Guresci 2007; Thompson et al. 2011, 2012). Initially, CPB rise-rate controls pressure, but as the binder hydrates and the initially fluid CPB gains shear strength, then pressures are moderated through arching (i.e. Mitchell et al. 1982; Li & Aubertin 2009). Rate of binder hydration therefore is critical in minimising barricade pressure and is influenced by binder content, tailings chemistry, water content, and other factors. Stope geometry has a significant effect on the extent of arching, and barricade pressures can be reduced by increasing a barricade's distance from the draw point/stope brow (Li & Aubertin 2009; Thompson et al. 2012).

Within Kidd Mine CPB, total earth pressures (measured using TEPCs) were measured to increase throughout the high binder content CPB volume (but not in the low binder volume) during extended periods in which backfill did not enter the stope. Such pressure changes correlate with temperature increases, the largest being a 300 kPa pressure increase over an 11°C temperature increase. Pressures also decrease with decreasing temperature. Thermally correlated pressure increases were measured at the Cayeli Mine during downtimes in backfilling, albeit to a much lesser extent (i.e. 20 kPa over a 16°C temperature increase). They were not observed during the Williams Mine fieldwork, possibly due to relatively limited temperature change (6°C) during backfilling. Recent fieldwork in CHB at two mines in Sudbury, Canada (Thompson et al. 2013) also detected increases in total earth pressure during down times in backfilling that appear to correlate with temperature increases. The CHB thermally correlated pressure increases were of a similar magnitude to those measured at Kidd.

This paper presents data from Kidd Mine to summarise the in situ pressure response at this site, and to demonstrate the thermally correlated pressure change in CPB. The proposed causal mechanism is constrained thermal expansion potential of the CPB. A brief literature review is provided for the thermal expansion of materials, including cement pastes. Finally, laboratory experiments using Kidd CPB materials are presented. These tests do not seek to exactly reproduce the field data, as critical differences exist between laboratory and field prepared samples, and in our capacity to reproduce boundary and field heating conditions in the laboratory. Rather the laboratory experiments demonstrate that pressure increases in CPB due to thermal expansion can be measured in a controlled laboratory environment, and highlight some controlling factors within the limitations of the laboratory apparatus. There is also discussion of the effect of temperature on TEPCs based on previous research including field, laboratory and theoretical considerations. Understanding TEPC response to temperature is a critical requirement in order to separate instrument effects from the physical behaviour of a backfill.

2 In situ pressure measurements

Total earth pressures, pore water pressure and temperatures were extensively measured in numerous longhole stopes at three paste backfilling mines. This paper considers data from Kidd Mine, measured using TEPCs and Piezometers produced by RST Instruments (models LPTPV-V and VW2100). The selection procedure of the TEPCs is discussed in detail in Grabinsky and Thompson (2009). TEPCs were deployed in orthogonal clusters to measure vertical, and two horizontal pressure axes. Full details on installations and results for each mine site are reported by Thompson et al. (2011, 2012). Confidence in the results is increased by the spatial extent of instrumentation within each stope, and the ability to compare data from a range of different stopes.

A summary of the instrumentation used in the 67-SL1 stope is shown in Figure 1 from the Kidd Mine. Identical instrumentation was deployed in the 88-947 Kidd stope. The cross-section illustrates approximate instrument locations (Figure 1(a)) within the stope. For deployment, instruments were attached inside cages (Figure 1(b)) and then suspended vertically from the back (roof) of the stope via pulleys and cables that were installed prior to the stope being blasted (Figure 1(c)). Additionally, instruments were positioned either side of the stope brow on a 'T' structure (Figure 1(d)) to measure pressure differences from arching close to the stope wall, and in drifts. Finally, instruments were directly positioned on the barricades. Both stopes tested at Kidd contained CPB with 4.5% binder content in the lower portion of the stope, and 2.25% binder in the higher stope volume. Binder comprises a ratio of 90:10 blast furnace slag to Portland cement (PC). A full description of installation and results is contained in Thompson et al. (2009).

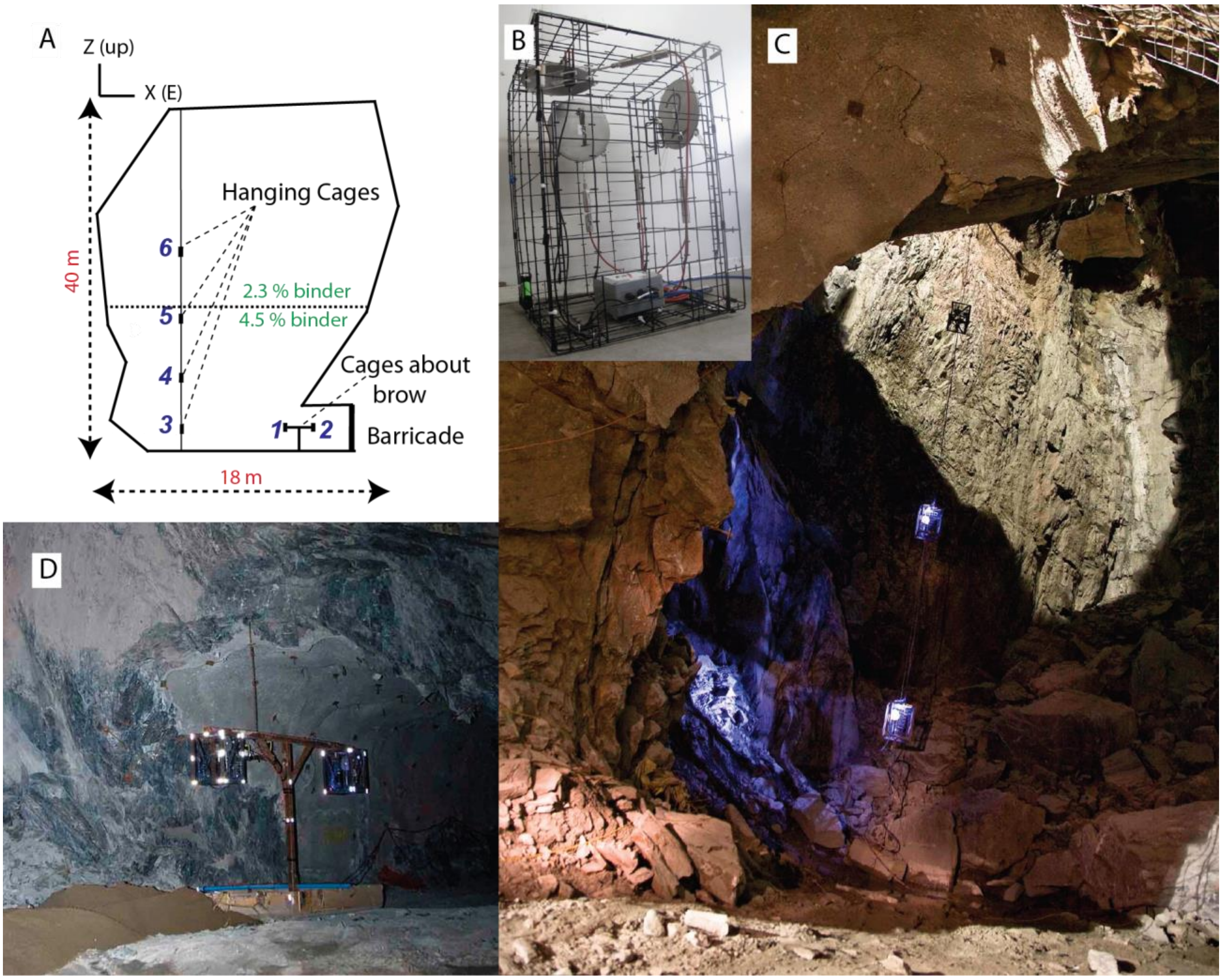

Figure 1 (a) Cross-section of stope; four instrument cages (b); are suspended vertically in the stope (c); and two cages span the undercut brow (d)

Backfilling of the Kidd Mine 67-SL1 test stope was completed in 6.4 days. Its undercut dimensions were 28 × 12 m, with floor to floor height of 32 m. The transition from 4.5 to 2.25% binder CPB was at a fill height of 8 m. Figure 2 shows total earth pressure, pore pressure and temperature data at 3 m elevation (cage 3) and 15 m elevation (cage 5). Both cages hung vertically in the central area of the stope ((Figure 1(c)). Cage 3 was covered by the 4.5% binder content CPB at 0.6 days. Hydrostatic loading (where the CPB behaves as a fluid with all total earth pressure axes being equal) was measured for 0.5 days. Cage 5 was covered by 2.25% binder content CPB at 2.9 days, and loading was hydrostatic for 2.2 days. As expected, pore pressures were equal to total earth pressure for the duration of the hydrostatic loading period, which provides confidence in the suitability of the TEPCs for this application. The break in hydrostatic loading is interpreted to signify the development of shear strength in the CPB. Horizontal pressures had reached a plateau, or were decreasing by the end of the pour for both cages. The shorter hydrostatic loading period for cage 3 demonstrates the influence of higher binder content in moderating strength development and hence pressure gain. The temperature measurements also reflect this, as cement hydration is an exothermic reaction and more rapid temperature gain is observed for cage 3 than for cage 5. The temperatures at the end of backfilling were 37 and 27°C, respectively, increasing from ~19 to 20°C at the start of the pour.

Backfilling was halted on three brief occasions during the 6.4 day backfilling period for operational reasons. For the cage 3 horizontal (east) component, pressures continue to increase during the backfilling shutdowns. Indeed, the shutdowns induce no deviation in the rate of pressure increase. In the vertical orientation, the rate of pressure increase was reduced, but an increase was still measured even though no backfill was entering the stope. For cage 5 in the lower binder content CPB, pressures remain constant during periods of backfilling downtime. This may be due to the lower change in temperature-induced by the 2.25% binder.

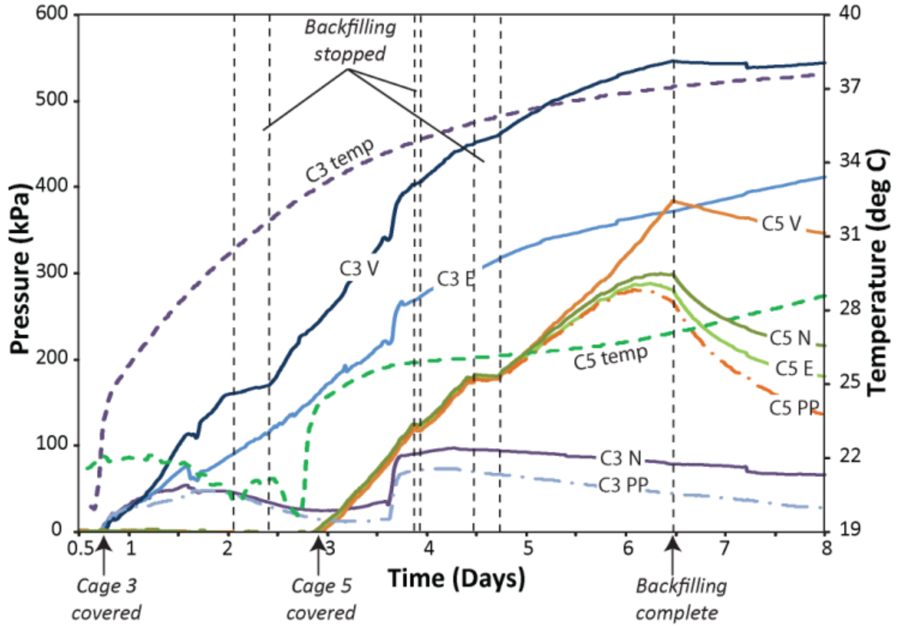

Figure 2 Total earth pressures for cage 3 (C3) and cage 5 (C5) in the vertical (V), and horizontal axes; horizontal axes are labelled north (N) and east (E) and pore pressures labelled PP; cage 3 was suspended at 3 m and cage 5 at 15 m heights in the 67-SL1 stope

The 88-947 stope had undercut dimensions 18 × 11 m, with a floor to floor height of 40 m. CPB with 4.5% binder content was poured to a height of 16 m, with 2.25% binder content used above this level. Backfilling was conducted for 2.3 days, to a height of 17 m, when an extended shutdown occurred for operational reasons. Three orthogonal total pressures (vertical, horizontal 1 and horizontal 2), pore pressure, and temperatures are presented for cages 3 and 5 (at 3 and 15 m vertical height in the stope) in Figure 3(a, b). Two short downtime periods, and the extended shutdown at 2.3 days defining the end of the 'first pour' are marked. Pressures continued to increase following the shutdown at 2.3 days. Figure 3(c, d) shows the change in pressure is plotted against the change in temperature for cages 3 and 5 from the time the first pour ends to the time of peak temperature. Vertical pressure at cage 3 increased by ~120 kPa and temperature increased by 3.3°C. Rates of pressure increase are in the range 31-35 kPa/°C. Cage 5 measured an 11°C increase following the shutdown, with a ~300 kPa pressure increase providing an average increase of 27 kPa/°C. However, as shown in Figure 3(d), the gradient is not linear for cage 5. The entire heating and cooling episode for cage 3 is presented in Figure 3(e). The peak temperature at cage 3 was 47°C, measured at 15.4 days. Backfilling resumed at 21.8 days. This 'second pour', as indicated on Figure 3(e), induced a 72 kPa pressure increase in the vertical orientation of cage 3 and a 20 kPa increase in the horizontal pressure axes. A production blast-induced a pressure increase of ~60 kPa in the horizontal pressure axis in the stope, which is probably due to the stope walls converging into the fill. Subsequently, pressures decrease to within ± 50 kPa of the original pressure (at the end of pour 1) as the CPB cools to its original 'end of first pour' temperature, demonstrating again that temperature change has a positive correlation with pressure. As will be reviewed, laboratory experiments were conducted to examine the effect of temperature on the TEPCs, suggesting a 0.5 kPa/°C calibration factor is required to adjust the measured pressures to account for the instruments' sensitivity to temperature (Grabinsky & Thompson 2009). This is significantly below the approximately 30 kPa/°C pressure change measured at Kidd Mine, indicating that the results reported above cannot be explained simply by incorrect instrument calibration.

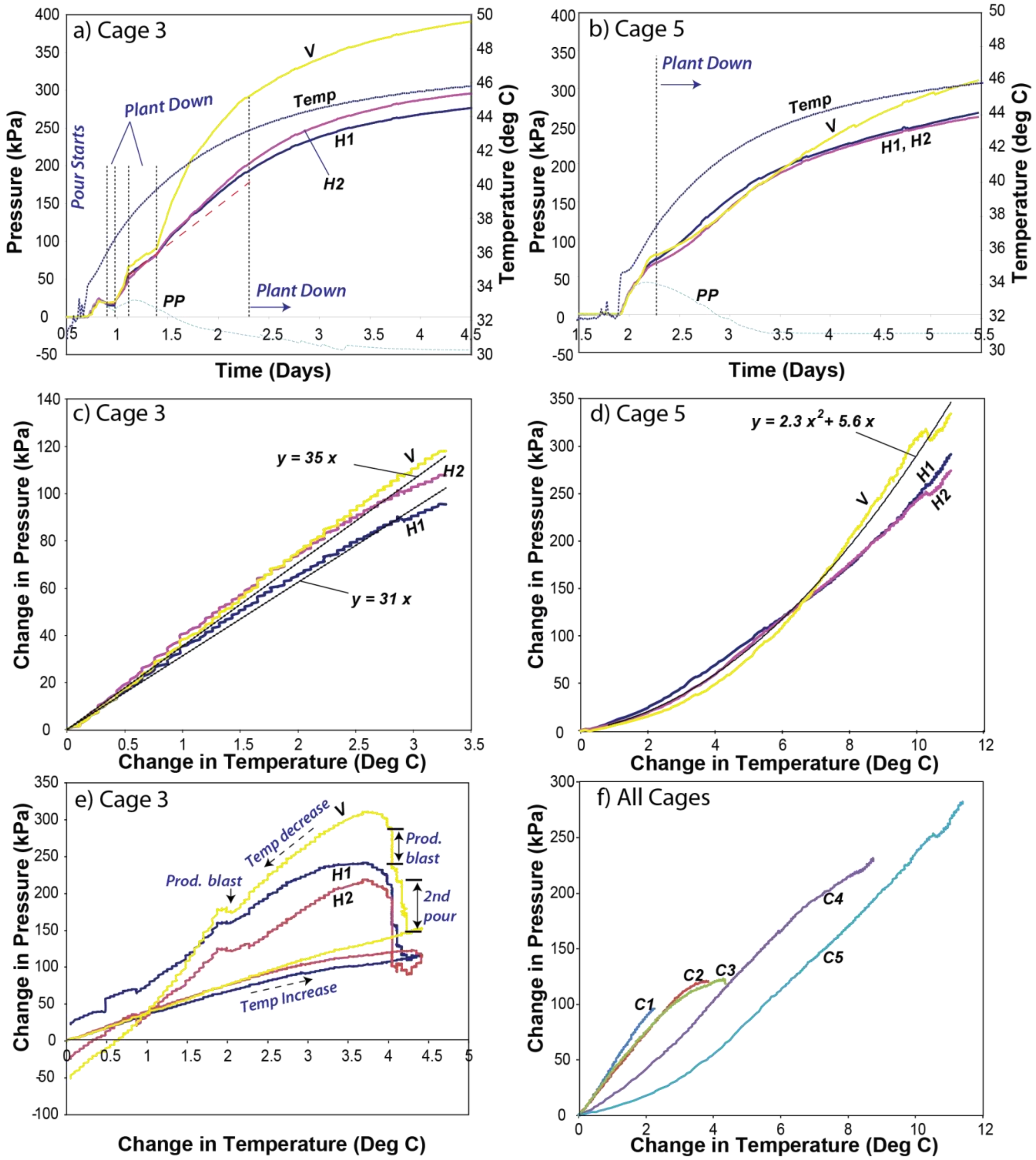

Figure 3 (a, b) total pressures in the vertical (V) and horizontal axes (H1, H2), pore pressures (PP) and temperatures for cages 3 and 5 in Kidd's 88-947 stope; (c), (d) change in temperature versus change in pressure from the time backfilling was halted (2.3 days) to peak temperature; (e) continuation of (c) showing heating and cooling phases; (f) pressure versus temperature relationship (after shutdown) for cages (C) 1-5

The pressure – temperature relationships for the other locations in the 88-947 stope are indicated using data from cages 1-5 from the time of the 2.3 day 'extended' shutdown to the time of peak temperature (Figure 3(f)). Pressures in the 'horizontal 2' axis are shown. The magnitude of the (thermally correlated) pressure change after the first pour was greater for cages 4 and 5. Whereas cages 1-3 underwent significant temperature increase (and so expansion potential) during the first pour, cages 4 and 5 were at a relatively early phase of binder hydration and so undergo significant temperature increase after the backfilling shutdown.

Cages 1-3 experienced significant thermally correlated pressure increases during backfilling, as observed during the backfill shutdown between 1.1 and 1.4 days in Figure 3(a). It is useful to consider the relative magnitudes of pressures at cage 3 that are induced by weight of backfill, and pressures that apparently correlate with temperature increases. Therefore, we assume the thermally correlated pressure increase began at the start of the 1.1-1.4 day shutdown (when it is first clearly observed), and the 54 kPa pressure measured before this period is due to weight of backfill. Between 1.1 and 1.4 days, pressures increased in all axes by 28 kPa. Extrapolating this gradient, as shown by the dashed red line in Figure 3(a) to the start of the extended shutdown gives a total pressure of 175 kPa, and so 121 kPa can be attributed to 'thermally correlated' pressure rather than weight of backfill. Thus, the 121 kPa pressure increase corresponds to 63% (121/200 kPa) of the final measured horizontal pressure (200 kPa) at the end of the first pour. Vertical pressure at this time was 293 kPa. Following the same approach, 41% of vertical pressure (121/293 kPa) measured at the end of the first pour, i.e. start of the extended shutdown, is interpreted to be due to the thermal loading effect.

As will be discussed in the following section, it is proposed that the thermally correlated pressure increase is caused by constrained expansion potential of the CPB within the confined stope volume. This phenomenon has only been measured within high binder CPB at Kidd mine, i.e. the 2.25% binder material did not exhibit similar behaviour. At Williams Mine, temperatures within 3% binder CPB (50:50 flyash: PC ratio) increased by 6°C and no temperature–pressure correlation was observed during downtimes in backfilling. At Cayeli, pressure increases were measured during downtimes in backfilling, with temperatures increasing 16°C and pressures increasing less than 20 kPa (Thompson et al. 2012). The thermally correlated pressure increase is therefore likely to be dependent on the properties of the backfill materials. Significant pressure generation through constrained thermal expansion potential of CPB is not a universal phenomenon for all mines but as demonstrated for Kidd Mine, it requires consideration as a mechanism that can induce substantial pressure increase within CPB. Similarly, its occurrence has been documented in CHB, i.e. at Vale's Coleman Mine. As described in the companion paper (Thompson et al. 2013), instruments similar to the Kidd installation were installed at the brow, centre-stope, and barricade in a 10:1 ratio solids to binder stope. As shown in Figure 4, significant pressure increases occurred during down−times in backfilling (backfilling periods P1-P7 are indicated by the dashed lines in the figure).

3 Temperature effect on TEPCs and required calibrations

3.1 Previous work

A TEPC comprises two circular steel plates, welded together, and containing some relatively incompressible fluid, connected via a long stem to a pressure transducer. Manufacturers typically provide a thermal calibration value for the pressure transducer, but not for the steel plates and oil that comprise the 'head' of the instrument. The differential thermal coefficients of the steel and the fluid will result in apparent stress−induced by a change in temperature. Further, this calibration will be affected by a surrounding medium applying load on the cell, and the stiffness of the material, in resisting the expansion of the TEPC.

Daigle and Zhao (2004) performed calibration of TEPCs in a soil-filled calibration chamber. They mostly featured small diameter cells (76 mm) that are acknowledged to have an aspect ratio exceeding the recommended minimum value required to minimise over/under registration of pressures through stiffness contrasts. TEPCs of diameter 228 mm were also considered, but they comprised a relatively minor component of the test program. The calibration chamber was designed for the small diameter cell, rather than the larger, 228 mm cells and so their results should be considered at best, preliminary for the larger cells. In terms of the sensitivity of pressure to temperature changes, their calibration data shows that the larger cells perform much better than the small diameter cells. When loaded to 238 kPa, the 228 mm cell exhibited an 80 kPa 'apparent pressure' variation (i.e. pressure-induced by the temperature change) over a 40°C temperature range, i.e. ~2 kPa/°C. The manufacturer of the cells tested are not stated in Daigle's work, but based on dimensions, they do not correspond to the 241 mm diameter cells featured in this in situ backfill testing. There is likely variation in the construction quality of the various manufacturers, for instance, in terms of de-airing the cells, and other construction details that will have an effect on the thermal response.

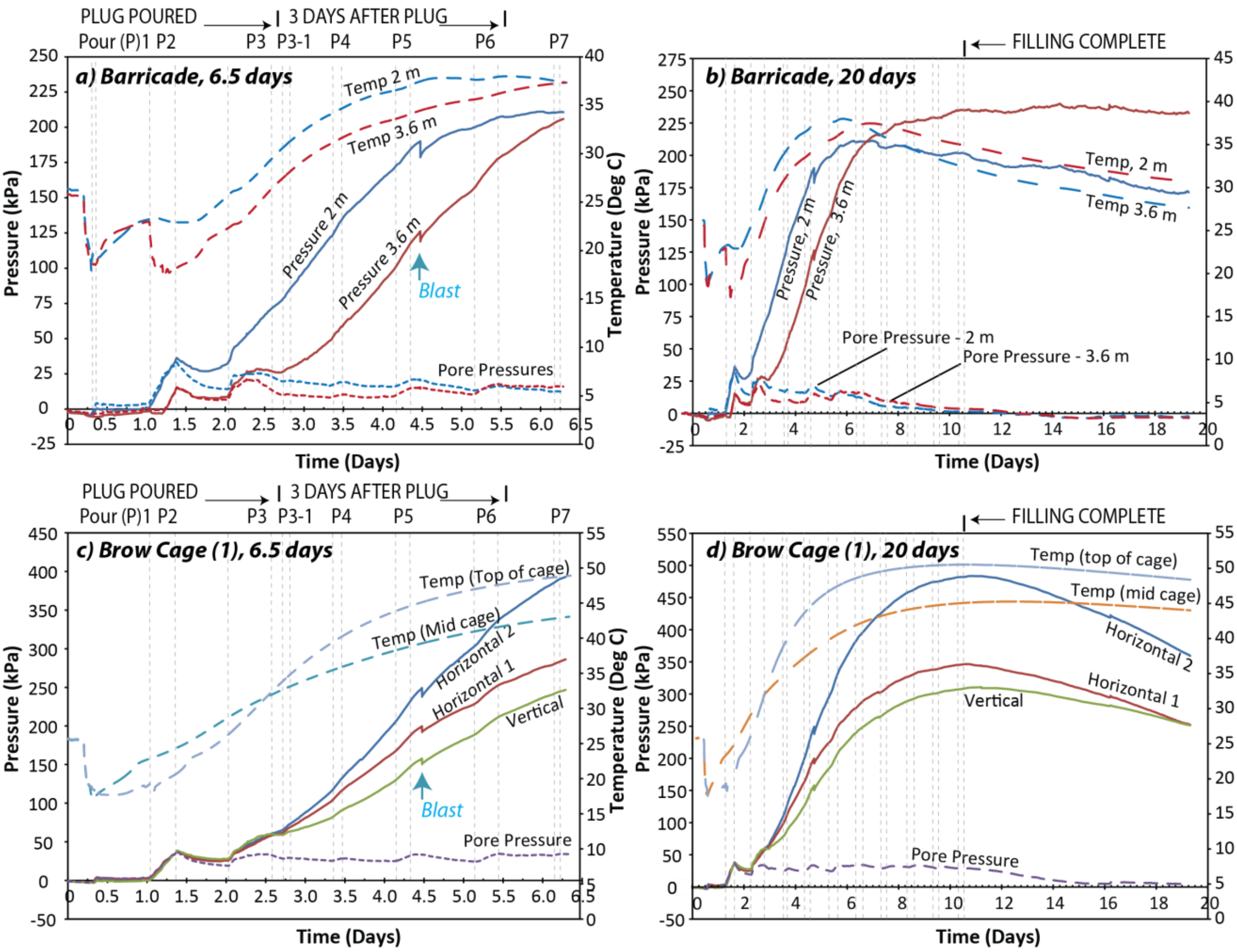

Figure 4 Total pressures, pore pressures and temperatures measured in Coleman's 3510 1814 stope. The height of barricade instruments are annotated and cage data shows orientation of pressure axes (taken from Thompson et al. 2014)

Tesarik et al. (2006) measured pressures with TEPCs in various backfill types and considered the effect of temperature changes on the registered pressures. They considered empirical (i.e. pressure changes during downtimes in backfilling) and theoretical (i.e. after Sellers 2000) correction factors to remove the 'effect' of temperature on pressure measurements. Tesarik et al.'s work provides very valuable background to the present paper, especially in the conclusion that temperature calibration (additional to that provided by the manufacturers) is required for TEPCs. However, we propose an additional mechanism neglected by Tesarik et al., should be considered as a cause of the thermally-induced pressure changes, i.e. thermal expansion of the fill. The majority of data presented by Tesarik et al. are from cemented rock fill. This fill type is a more challenging medium for pressure measurements, relative to our measurements of CPB and CHF. This is evidenced by Tesarik et al.'s needing to pre-cast or embed the TEPCs in grout or backfill, and shotcreting the instruments before backfilling the stope, which would add additional stiffness contrast issues into the measurement 'system'.

In relation to our work, the most comparable data from the Tesarik et al. (2006) work comes from CPB in the Lucky Friday Mine. Theoretical correction factors of between 4.86 and 6.39 kPa/°C were proposed based on seven day and 28 day elastic modulus values. However, peak temperatures manifested at three days when stiffness would be reduced. The Young's modulus values (and so calibration values) are quite high compared to our values measured from Kidd laboratory data, as discussed below. Further, significant pressure changes are induced by local mining, which further complicates interpretation.

Tesarik et al. (2006) applies the theoretical approach of Sellers (2000) to estimate the magnitude of the thermal calibration required for a TEPC, which is based on the geometry, material properties of the cell, and elastic modulus of the surrounding medium. Using the equivalent TEPC radius, R (similar to that used in our fieldwork), thickness of liquid film within the TEPC, D, and coefficient of thermal expansion of the liquid, K, i.e. 700×10^{-6}/°C, the correction factor C is defined as:

$$C = 1.5 \times E \times K \times D/R \tag{1}$$

As part of the U of T research, Galaa et al. (2012) measured the elastic modulus, E, for Kidd Mine material, which evolved to 200 MPa at 48 hours, and 300 MPa at 100 hours. These measurements suggest the thermal correction factor should evolve from 0.9-1.4 kPa/° C, at Kidd during this time period.

3.2 Calibration of TEPCs

In order to provide some basic thermal calibration factors for the RST TEPCs under an applied load, simple laboratory tests were performed. An optimised calibration is still a research objective, as per the method of Daigle and Zhao (2004), albeit in an adequately sized load chamber. TEPCs were placed in a water bath and loaded using steel weights to provide loads equivalent to those measured in the undercut region of Kidd stopes (Figure 5(a)). Hot (tap) water was continually circulated into the water bath, and the temperature was allowed to equilibrate, over a period of 30 minutes. Once the peak temperature was achieved, the water circulation was halted and the water bath was allowed to cool to room temperature. This provided a gradual temperature transition from 43 to ~18°C. Representative data is shown in Figure 5(b) and (c), for a TEPC loaded to induce pressures of 94 kPa and 138 kPa respectively. The rate of pressure and temperature gradients for the two tests indicates the pressure changed at a rate of between 0.4 and 0.5 kPa/°C.

Although relatively basic, this apparatus suggests that the effect of temperature on the TEPCs used in the Kidd and Vale fieldworks is limited to ~0.5 kPa/°C. The theoretical analysis (after Sellers 2000) suggests that in the initial 100 hours, the Kidd material has stiffness that should require a thermal calibration in the order ~1-1.5 kPa. Although definitive calibration using more elegant apparatus is still required, the initial physical and theoretical calibration approaches suggest the thermally-induced pressure increases in the field, which are of order 20-30 kPa/°C require alternative explanation.

4 Thermal expansion and pressurisation in other materials

The interpretation that thermally-induced pressure increases in backfill are due to thermal expansion within the confined (rock) volumes has not previously been proposed, to the authors' knowledge. This is in part due to the lack of previous in situ data and uncertainties in TEPC thermal calibration factors. However, thermal expansion caused by increasing temperature is a well-known phenomenon in other materials. The magnitude of expansion, i.e. coefficient of thermal expansion (CTE) differs for each material. For example, at standard temperature the CTE for water is about 2.20×10^{-4}/°C, while for silica based solids, such as quartz sand and Portland cement, the CTE is between 2.0×10^{-5}/°C and 50×10^{-6}/°C, respectively. Constraining the thermal expansion potential of a material will induce a pressure increase. The influence of temperature on soil and porous rock behaviour is well documented, for instance, Palciauskas and Domenico (1982) modified the Biot's constitutive relation for a porous medium as follows:

$$\varepsilon = \left(\frac{\sigma}{K}\right) + \left(\frac{P}{H}\right) + \alpha_b (T - T_o) \tag{2}$$

Where:

- ε = volumetric strain.
- σ = mean stress.
- K = bulk modulus.
- P = pore water pressure.
- H = Biot's elastic constant.
- α_b = the coefficient of volumetric thermal expansion of the porous body.
- T = temperature.
- T_o = the initial temperature.

The coefficient for thermal expansion of water is temperature dependant, ranging between 3.03×10^{-4} (at 30°C) and 4.54×10^{-4} (at 50°C) for the temperatures experienced at Kidd. Campanella and Mitchell (1968) showed that large pore pressures develop in saturated clay as a result of heating in un-drained conditions. For further background, Ghabezloo and Sulem (2009) provide detail on thermal expansion in porous rocks and Sellevold and Bjontegaard (2006) in PC pastes. The effect of air on thermal pressurisation and expansion was demonstrated by Qian et al. (2009), who showed that PC paste mixed with an air-entraining agent, containing 6% air, exhibits 25% less thermal expansion as compared to PC paste without the air–entraining agent if the paste is heated from 35 to 75°C. DeWall et al. (1996) showed that the presence of air in a closed water system causes a decrease in the magnitude of temperature-induced pressure as compared to pressure values measured in water with no air, as the void space allows the accommodation of internal strain.

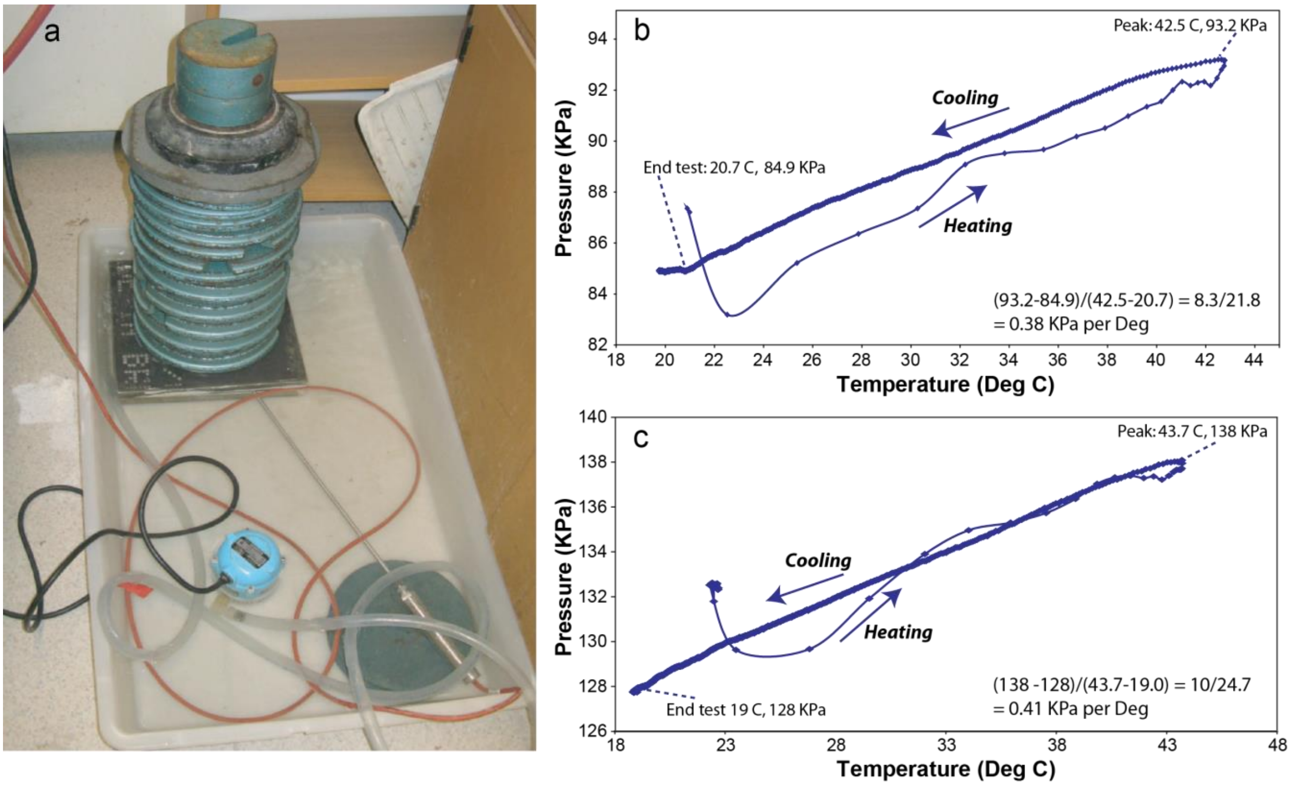

Figure 5 (a) loaded TEPC in heated water bath; and (b), (c), results for TEPCs under 287 and 415 kg weights

5 Thermally-induced pressure increase of CPB in the laboratory

In order to demonstrate the extent of thermal expansion and pressurisation of CPB, laboratory tests have been conducted.

Kidd Mine CPB was prepared in the laboratory with 200 mm slump. The control sample was 4.5% binder CPB, containing 22% water and 78% solids, replicating as far as possible, the material surrounding cages 1-5 from the 88-947 test stope. The solid components included 4.5% binder (90:10 slag:PC) and 95.5% aggregate mix, which consisted of 55% sand (passing sieve no. 6) and 45% tailings. All of the constituent materials were mixed thoroughly for 2 minutes before being poured into the specimen holder (a stainless steel container). The volume of the control specimen was 200 mL (200 cm^3). The total volume of the sample holder was 1,112.4 mL, and so the remaining space was filled with de-aired water. This de-aired water acts as a buffer, separating the sample from the pressure transducer. The total volume of water in each container was kept constant at 998.2 mL, where 912.4 mL represents the water in a buffer zone and the reminder represents the water contained in the control specimen (i.e. CPB). The bulk density and water content was measured for the freshly-mixed samples at the beginning of each test for quality control. Additional mixtures tested in this study included: 2.2% binder CPB, a sand-water mix, a mine tailings-water mix, and a sand and mine tailings mix. The volume of each mixture was adjusted accordingly to reflect the changes in specimens' water content and to ensure there was a constant volume of water of 998.2 mL in each experiment.

The experimental setup was inspired by the ASTM International standard method for chemical shrinkage of hydraulic cement paste (ASTM International 2007). Immediately after mixing, CPB was poured into a stainless steel container and the remaining volume was filled with de-aired water. Some CPB samples were kept under vacuum for 1 hour to remove entrapped air bubbles before the cylinders were assembled and placed in the oven. The container was then closed with a Plexiglas lid and O-ring that provided an air tight seal. The Plexiglas lid had two built-in valves (Figure 6). The valves were used to fill the remainder of the specimen container with de−aired water, and to evacuate any air bubbles entrapped during sample preparation. To ensure equal initial stress conditions, all specimens were initially pressurised at approximately 10 kPa before they were exposed to an elevated temperature. The assembled containers were then placed in the oven, while pressure transducers were placed outside of the oven and were connected to the containers with tubing that ran through the hole at the top of the oven (Figure 6). To measure sample temperature, a control container of a similar volume was filled with water and placed in the oven and its temperature change was recorded using a thermistor. All specimens were heated at a rate of ~5°C per hour, and no volume change of the CPB was allowed.

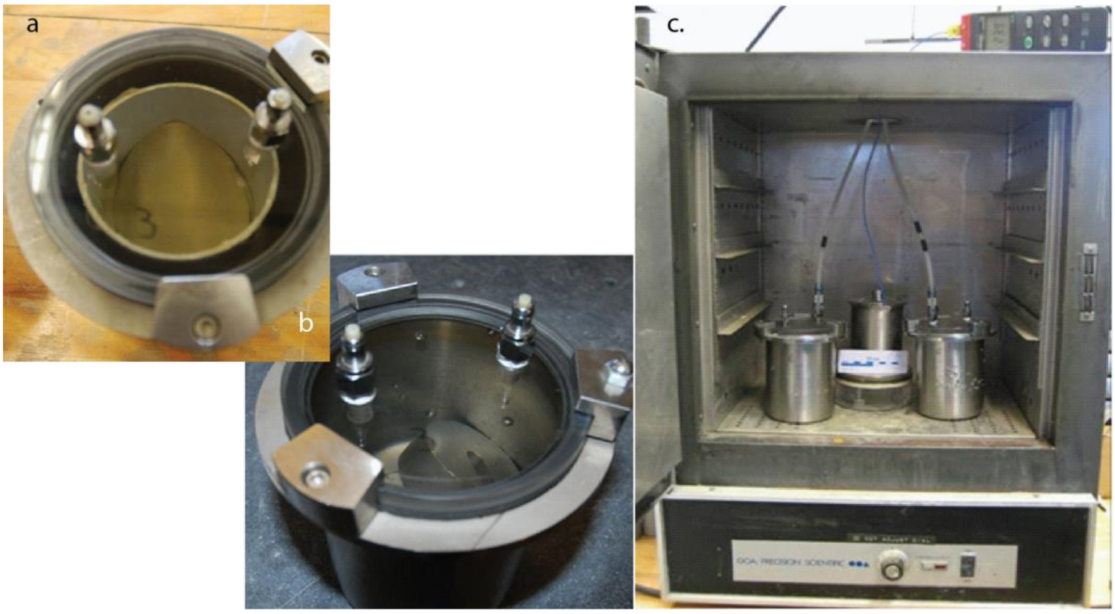

Figure 6 (a, b) specimen container with built-in fittings; (c) experimental setup: specimen containers, oven, pressure transducers, and TE probe

The results of a series of temperature-induced pressure measurement tests are shown in Figure 7. All specimens were heated from ~24 to ~49°C. Pressures in sand–water mixtures increased to 140 ± 30 kPa in non-de-aired specimens and to ~270 kPa in de-aired specimens (Figure 10 (a), (b)). For tailings-water mixtures, pressures increase to ~180 ± 10 kPa in non-de-aired specimens (Figure 10 (c), (d)). Pressures in 4.5% binder CPB (Figure 10 (e), (f)) increased to ~100 kPa in the non-de-aired specimens and to ~200 kPa in the partially de-aired specimens. Entrapped air increases the compressibility of the CPB and so reduces the magnitude of a thermally-induced pressure increase. The variation in induced pressure measured for similar samples containing different amounts of air indicates the importance of air content in constraining the induced pressures.

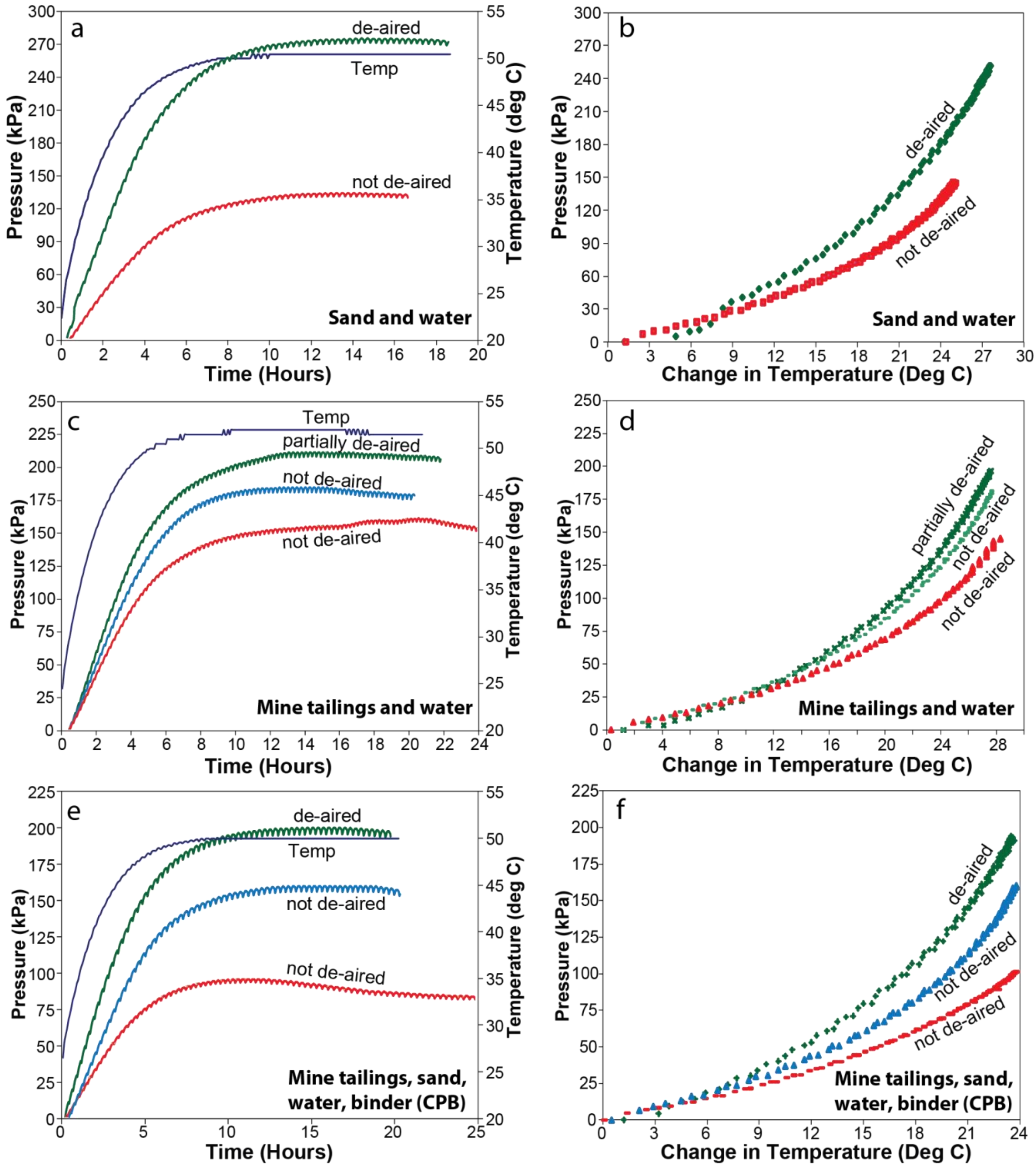

Figure 7 Pressures versus time during the heating of various samples, and the corresponding pressure versus temperature relationship

6 Discussion

The evolution of pressure with increasing temperature in 4.5% CPB is shown in Figure 8 for field (cage 5, 88–947 stope) and laboratory samples. An 11°C temperature increase-induced a ~300 kPa pressure increase in the field, whereas in the laboratory, a 25°C temperature increase-induced a pressure increase of 200 kPa. The difference between field and laboratory values could be due to numerous variables. The most significant may be the difference in stiffness of CPB. For instance, the heating rate used in the laboratory was much higher than in the field, and therefore the field CPB is able to gain stiffness through binder hydration whereas the laboratory CPB is relatively fresh. There will also be differences in the boundary conditions that constrain the in situ and laboratory samples. The boundary conditions acting in the stope will vary depending on the height of CPB overburden.

There are also differences resulting from mixing CPB on the industrial/field scale and the laboratory scale that will affect the air content. This was shown by le Roux et al. (2004), who measured index properties of in situ and laboratory-prepared CPB from the Golden Giant Mine. The degree of saturation was shown to decrease from 100% in the laboratory to 90-80% for in situ CPB, while the void ratio increases from approximately 1.0 for laboratory CPB to between 1.15-1.3 for in situ CPB (Figure 9). Le Roux et al. attributed the increase in void ratio (and a consequent decrease in degree of saturation) of in situ CPB to entrapped air bubbles that could be incorporated during the paste's mixing and transport to the stope. Such air bubbles are apparent in CPB subsequently retrieved from a test stope (Figure 9(a)). Even the relatively small difference in air content observed for laboratory prepared samples resulted in a 125 kPa difference in pressure for the 4.5% binder CPB (Figure 8). A more sophisticated laboratory set up would be required to ensure constant air content for the laboratory samples. As stated above, there are inherent differences between laboratory and in situ bulk properties, and difficulties in obtaining such in situ measurements pose additional problems. For this reason, the development of a more sophisticated laboratory approach is beyond the scope of this paper. Indeed, even with constant laboratory air contents, the results would be extremely difficult to directly apply and compare with the field data due to the inherent differences between the laboratory and field conditions.

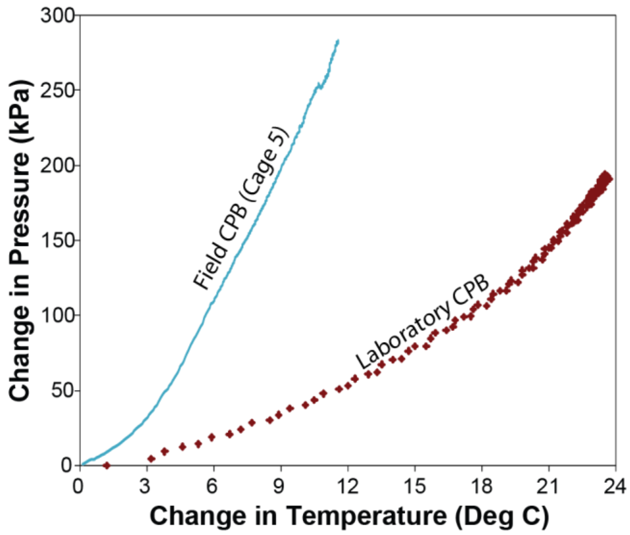

Figure 8 Temperature-induced pressures in laboratory prepared, and in situ 4.5% binder CPB

For Kidd Mine, the implications of a significant amount of load within backfill being due to thermal expansion are important. For instance, the backfilling strategy at Kidd is advanced in comparison to many mines using CPB, with barricade pressures being routinely measured and used to control whether backfilling can be continuous or whether a cure period is required. Binder hydration causes the temperature increase that induces the expansion driven pressure increase, but it also requires CPB to have gained shear strength and so a component of pressure will be arched. Indeed, arching will be enhanced through the expansion of CPB. Whether the thermally expanding CPB has sufficient strength to resist flow in the case of barricade breach, and whether the load induced by the thermal expansion should be considered in the same manner as fluid backfill weight when rating barricade strength require further consideration. At least, Kidd engineers should be aware the high pressures measured on barricades for 4.5% binder content CPB could be due to a mechanism other than large fluid head pressure.

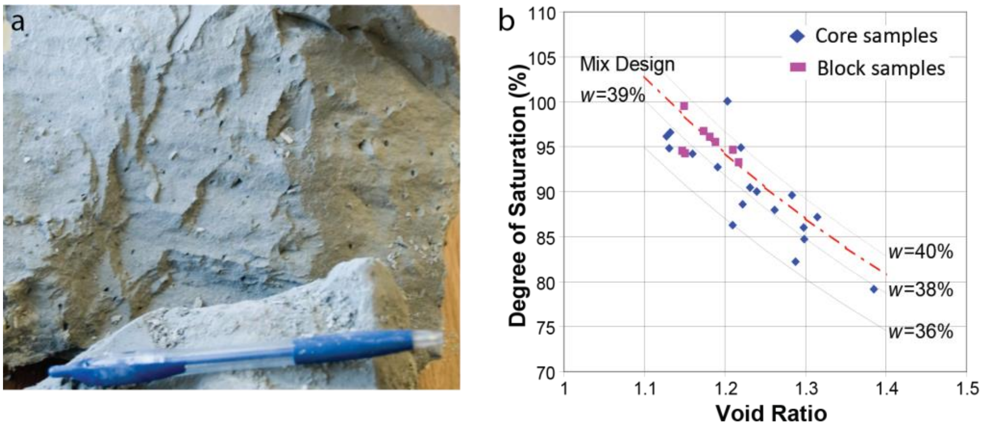

Figure 9 (a) variations in degree of saturation of CPB with void ratio for different levels of moisture content (adapted from le Roux et al. 2004); (b) CPB sample with entrapped air bubbles

7 Conclusions

Significant in situ pressure increases that correlate with temperature increases caused by binder hydration, during periods of backfilling downtime have been attributed to the constrained thermal expansion effect of CPB. For a stope at Kidd Mine, the thermal expansion-induced pressures are estimated to comprise 50 and 63% of the vertical and horizontal pressures measured at the end of the first pour based on extrapolation of pressure gradients during downtimes in backfilling. Rates of pressure increase in the order of 30 kPa/°C were measured, whereas the TEPC calibration required to correct for temperature change was estimated at 0.5 or ~1.5 kPa/°C based on theoretical calibration. Heating of confined CPB in the laboratory can induce thermal expansion-induced pressures of up to 200 kPa for the approximate temperature range that was measured at Kidd Mine. In situ, a temperature increase of 11°C induced a 300 kPa pressure increase. The higher pressure increase in the field can be explained by greater stiffness of in situ CPB due a slower rate of heating allowing more cement hydration, and differences in material properties. Indeed, the laboratory study demonstrated the dependence of the magnitude of pressure increase on air content. This is an important conclusion as inherent differences between laboratory and field prepared CPB in terms of void ratio prohibit a direct comparison of thermal expansion driven pressures between field and laboratory. The geometry of the bulk volume of fill and the location of the pressure sensors is also suspected to influence the magnitude of the temperature/pressure relationship.

Similar field testing measured pressure increases during downtimes in backfilling at the Cayeli Mine, albeit to a much lesser extent. At Williams Mine, no pressure increases were observed during backfilling downtime, although the ambient temperature, and temperature range was significantly smaller, likely due to the difference in the exothermic properties of the Portland/fly ash binder and the lower binder content. At Kidd Mine, thermal expansion-induced pressures were only measured in the higher binder content CPB. Therefore, thermal expansion of CPB appears to be material and temperature dependant and further work is required to better understand the phenomena. However, as shown at Kidd Mine, it can represent a significant component of in situ pressure and its recognition is of great importance to field engineers measuring in situ pressures, and consultants and academics using field data for laboratory and numerical modelling calibration. Careful interpretation of the mechanisms generating pressures in a specific stope is required, and thermal loading should be considered alongside the overburden weight, arching mechanisms, and wall closure. This work demonstrates the importance of instrument calibration, in order to differentiate instrument and 'real' material behaviour, and additional work to better calibrate TEPCs is required. Field observations of CPB shrinkage through desiccation also require future consideration.

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