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In situ behaviour of cemented hydraulic and paste backfills and the use of instrumentation in optimising efficiency

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Abstract

Better understanding of in situ backfill behaviour can allow mines to optimise backfilling efficiency. To this end, a significant quantity of fieldwork has recently been conducted by University of Toronto (U of T) and Mine Design Engineering (MDEng.), focused on in situ measurements in cemented paste backfill. Using these 'production friendly' instrumentation approaches, new fieldwork data from two of Vale's Canadian operations are presented, to demonstrate how instrumentation can be applied to better define the behaviour of cemented hydraulic backfills. Instrumentation consists of clusters of total earth pressure cells, piezometers (for pore pressure) and thermistors that are placed remotely in open stopes, and mounted on barricades. Backfilling with cemented hydraulic fill requires consideration of drainage and potential segregation affects, which are not associated with paste. In situ data demonstrates the transition of the backfill from a fluid to soil-like material at various locations in backfilling stopes. Within a relatively coarse grained (i.e. sand) cemented hydraulic fill, this transition occurred relatively quickly (after three hours). For a sand and tailings blend of cemented hydraulic fill however, the hydrostatic loading condition persisted for between 12 and 24 hours. During backfilling, this information, combined with barricade pressure data, was used to optimise requirements for the post-plug cure period, saving up to three days of stope cycle time. The measurements in hydraulic fill are contrasted with previous fieldwork data from cemented paste backfill. Strength gain mechanics differ between the fill types, through the requirement for drainage in hydraulic fills, whereas cement content and self-desiccation mechanisms appear to dominate in situ measurements in paste. Hydraulic fills exhibit particle size segregation which results in spatial variation in cement content, and so spatially distinct pressure and temperature responses for the interpreted coarse and fine grain zones were measured. A measured low temperature zone was interpreted to represent a coarse grain size fill with an at rest earth pressure coefficient similar to that of a dense sand. A high temperature zone was interpreted to represent a fine grain size fill which features higher cement content. The significantly greater temperature measured in the binder-rich areas are thought to induce 'thermal expansion' generated pressure increases. This work demonstrates the potential for instrumentation to feature as part of a considered quality control policy (that includes barricade construction and drainage checks) to safely optimise backfilling efficiency.

1 Introduction

Backfilling is a critical component of the mining cycle for many underground mines, providing ground support to maintain stability in active mining areas, and maximising ore recovery through reduced requirement for pillars between stopes. The principal backfill types are rock fill, hydraulic fill and paste fill, as described in detail by Hassani and Archibald (1998) and Potvin et al. (2005). This paper focuses on hydraulic and paste mine fills. Both fill types are transported via boreholes and pipe networks from surface plants to the active mining area, where they are deposited into stopes. Figure 1(a) is a schematic diagram of a typical long hole stope being backfilled. Figure 1(b) and (c) show photographs of cemented hydraulic fill and paste fill being poured into long hole stopes.

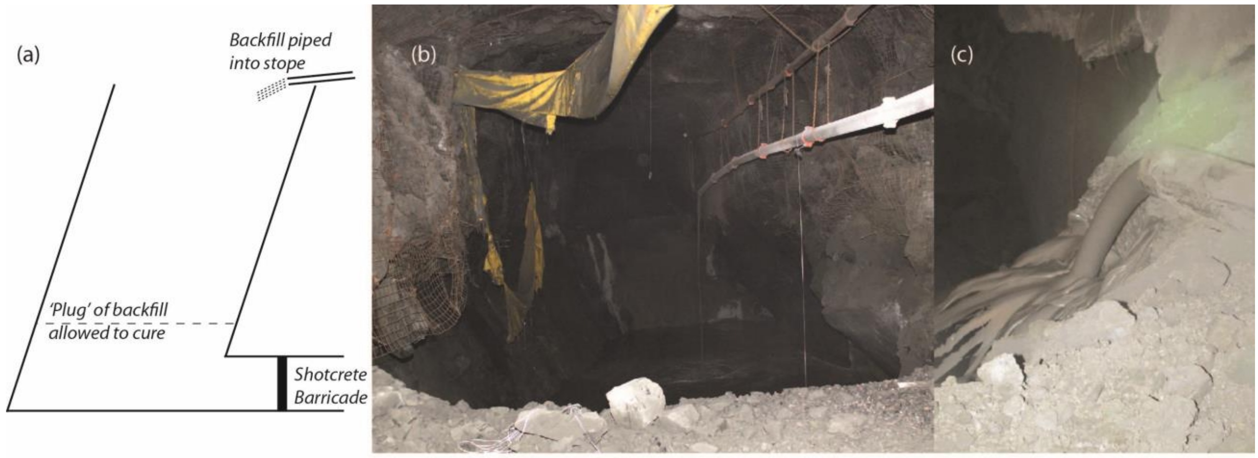

Figure 1 (a) schematic diagram of backfilling and backfilling with cemented; (b) hydraulic; and (c) paste fill

Cemented paste backfill, comprising cemented, high density thickened tailings has a solid content (by weight) of 75-85%. Cemented hydraulic backfill has particle size between clay and coarse sand, with a solid content generally in the range 68-72%. Once deposited, hydraulic fills require significant drainage in order to gain strength via consolidation, and this requirement is reflected in the material design; typically no more than 10% of solids are finer than 20 µm and a gravitational percolation rate greater than 10 cm/h is expected. Conversely, paste backfill requires more than 15% of solids to be finer than 20 µm to facilitate the material's pipeline flow and this fines content serves to retain water and eliminate or greatly reduce the in situ drainage requirement.

The procedure by which stopes are backfilled varies from mine to mine. Generally the rationale is to backfill a stope as quickly as possible while ensuring safe load on barricades that are constructed to confine fill at undercut accesses. Without measuring the pressures induced by backfill on barricades, a mine must pour in a conservative manner, whereby a plug of backfill is poured and allowed to cure for up to seven days, prior to the remainder of the stope being filled (Figure 1(a)). Recent fieldwork (Thompson et al. 2011a, b, 2012) demonstrates that instrumentation can be used to; (a) characterise the in situ behaviour of backfill, and (b) determine the necessity or length of a cure period for a specific stope. For instance, if backfill gains strength at a sufficient rate, then the plug may have cured enough to isolate the barricade from the effects of continued pouring, and so eliminate the requirement for a cure period. Such an instrument approach, coupled with appropriate quality assurance/quality control (QA/QC) procedures, can allow an operation to safely optimise the efficiency of backfilling by accelerating the filling process and so enabling faster stope cycle times.

Understanding backfill behaviour through in situ measurements is important from an operational and academic perspective, as previously shown by Hassani et al. (1998), Yumlu and Guresci (2007) and others. Building on this previous work, the U of T, in partnership with Barrick Gold Corporation, Inmet Mining Company, and Xstrata Copper Canada (Grabinsky 2010; Thompson et al. 2012) conducted extensive fieldwork at three mines, in order to better understand in situ backfill behaviour and to evaluate backfilling efficiencies at the partner mines. Key contributions of the previous work are detailed in Thompson et al. (2011a, b, 2012), and the field data has provided basis for modelling and laboratory studies, as reported in this volume by Grabinsky et al. (2014a, 2014b) and Veenstra et al. (2014a, 2014b). Blast vibrations in backfill were also monitored (Mohanty & Trivino 2014).

MDEng. have refined the 'production friendly' fieldwork approach developed during the U of T work, and in partnership with Vale, have applied backfill monitoring techniques to hydraulic fill at two Sudbury operations. Such data is valuable given the lack of similar published data in this backfill type. In this paper, we demonstrate the application of instrumentation to characterise in situ hydraulic backfill behaviour, and present representative data from two mines. Using this and previous data from our earlier studies, we compare in situ measurements in cemented hydraulic fill and cemented paste fill, and show how instrumentation can be used to safely maximise backfilling efficiency in long hole stopes.

2 Instruments and installations

In order to assess the filling strategy of a mine, in terms of the length of, or requirement for cure times during backfilling, it is first necessary to understand how the backfill behaves in situ. This can be achieved by measurement of total earth pressure, pore pressure and temperature data. Displacement transducer data are not reported in this paper, but can be valuable, especially in calibrating barricade design models. In the case of the current fieldwork at the Vale operations, a limited number of 'whole stope' installations aim to characterise the general in situ fill behaviour. Following this, routine barricade monitoring is used as a QA/QC procedure to ensure barricade pressures are safe and the material is behaving as expected.

It is relatively simple to measure barricade pressures during backfilling. Such data however, likely will not be representative of fill behaviour in the main stope body, as geometric complexities at stope boundaries enhance arching potential, and improved drainage may act to reduce pressures at the barricade location. Further, barricade pressures are generally limited to measurement in one axis (i.e. acting towards the barricade) which prevents more qualitative interpretation, as will be discussed. The optimum approach for a mine seeking to understand a backfill behaviour is to measure; (a) pressures in the centre stope location, i.e. where the maximum pressures will likely be measured, (b) under the brow where pressure will likely be somewhat reduced relative to the stope centre due to the effects of arching and finally, (c) at the barricade. Once a mine has an understanding of typical backfill pressures and factors that may cause higher than usual barricade pressures, then the backfilling 'strategy' can be reviewed to consider potential increases in backfilling rates. This is reviewed in more detail in Thompson et al. (2011a). Appropriate QA/QC controls, such as routine barricade pressure monitoring should be a requirement if backfilling rates are increased based on such work. Awareness of the cause of previous barricade failures is also important (i.e. Grice 1998; Revell & Sainsbury 2007; Yumlu & Guresci 2007).

The fieldwork reported herein, consists of 'whole stope' installations featuring instrument clusters populated with orthogonally oriented total earth pressure cells (TEPC) and piezometers (for pore water measurements). These instruments were supplied by RST or Geokon, with ranges of 350 kPa or 1 MPa. The instruments are installed in wire cages, and protected by larger steel frames (Figure 2). In the initial U of T fieldwork, multiple cages were suspended vertically in the centre stope, and sequentially covered as the stopes were filled. Instruments were also positioned at the stope brow, and at barricade locations. The data resulting from these tests provided (a) confidence in the instrumentation approach, and (b) very detailed information on the in situ behaviour of paste (Thompson et al. 2011b; Thompson et al. 2012).

Subsequent fieldwork, including the Vale work, featured a more 'production friendly' approach, where instrumentation was installed in undercut locations. This allows fast installations, with minimal (i.e. one day) delay to the regular production cycle. Such an installation is shown in Figure 3, with instruments in the centre stope and under the brow. Typically the field tests at Vale operations have also consisted of TEPC and Piezometers mounted at the 1/3 and 2/3 height of each barricade tested. Such an installation is shown in Figure 3(d) and (e), with TEPCs and piezos either mounted on a cage, or attached directly onto the screen. Our current preferred method is the former, as it offers some disconnect between the barricade and the TEPCs, and ensures the instruments are embedded in backfill.

Data is recorded and relayed to surface or safe locations, to allow scrutiny of pressure data in real time. Thus, decisions on the backfilling strategy can be made on a stope by stope basis (i.e. length or requirement for a cure period after the plug) based on barricade pressures. For routine barricade monitoring at Vale, the Minetrax wireless network is used to communicate real time data to surface. It is also important to visually monitor barricade condition, especially with hydraulic backfill stopes, via remote video footage.

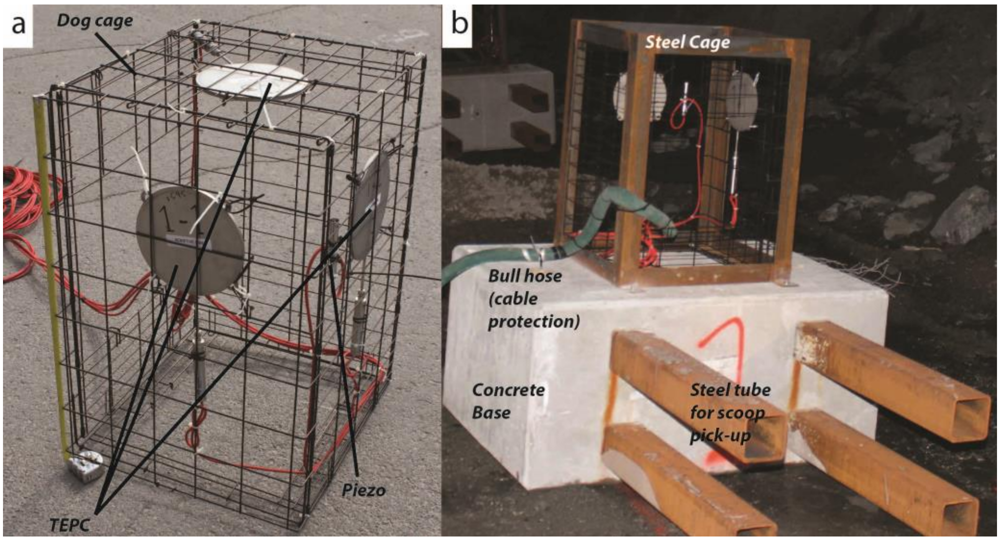

Figure 2 (a) TEPCs and piezometers are installed in wire cages, which are subsequently (b) protected by robust steel cages and attached to concrete blocks for remote deployment in stopes

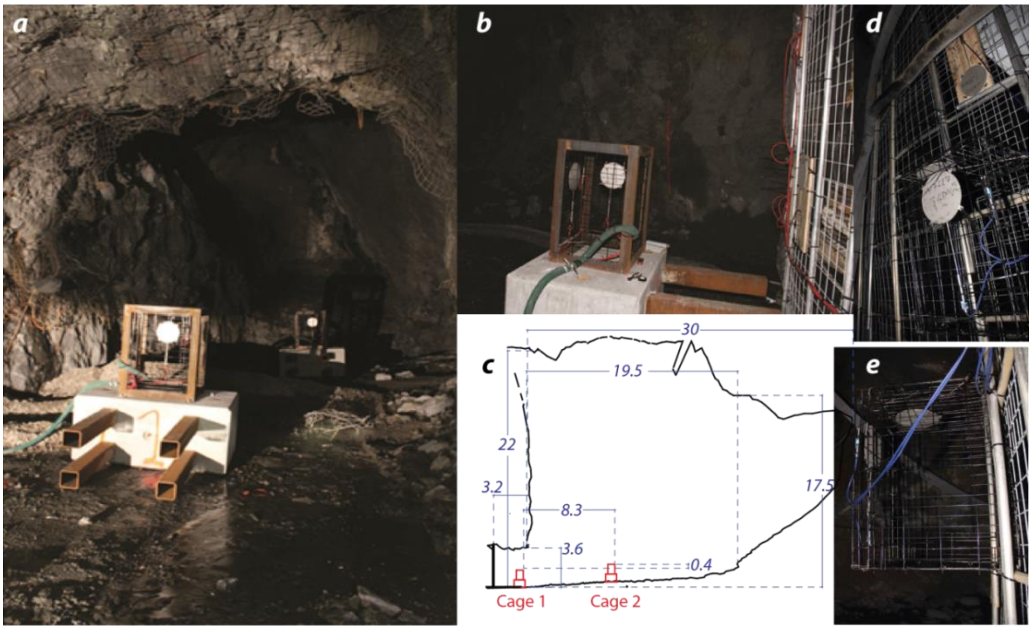

Figure 3 (a) and (b) instrument clusters are positioned in the undercut of stopes (i.e. centre stope and brow location); (c) stope and instrument section view (in metres); (d) and (e) instruments attached to barricade

3 Controls on in situ pressures in paste fill

The combination of fieldwork, laboratory studies and modelling analysis have enabled better understanding of the in situ behaviour of paste fill in recent years. Some general concepts and controls on paste behaviour and barricade pressures are reviewed, which to an extent, apply equally to hydraulic fill.

Initially, both hydraulic and paste backfills are in a fluid state upon deposition, and so pressures exerted by the weight of backfill are equal in all orientations, and theoretically, will be a product of the height and density of the backfill. The rise rate of backfill in a stope is defined by plant output and horizontal area (per metre height) of a stope. Rise rate controls the initial rate of pressure increase, as shown in Figure 4(a), for vertical pressure measured at 3 9 m elevations in a Cayeli Mine stope (Thompson et al. 2012). The vertically narrowing stope geometry caused rise rates that were lower at the bottom of the stope than at the top (i.e.

31 cm/h compared to 42 cm/h) as reflected by the different rates of pressure increase. Operations may limit allowable rise rates to avoid over-pressuring barricades.

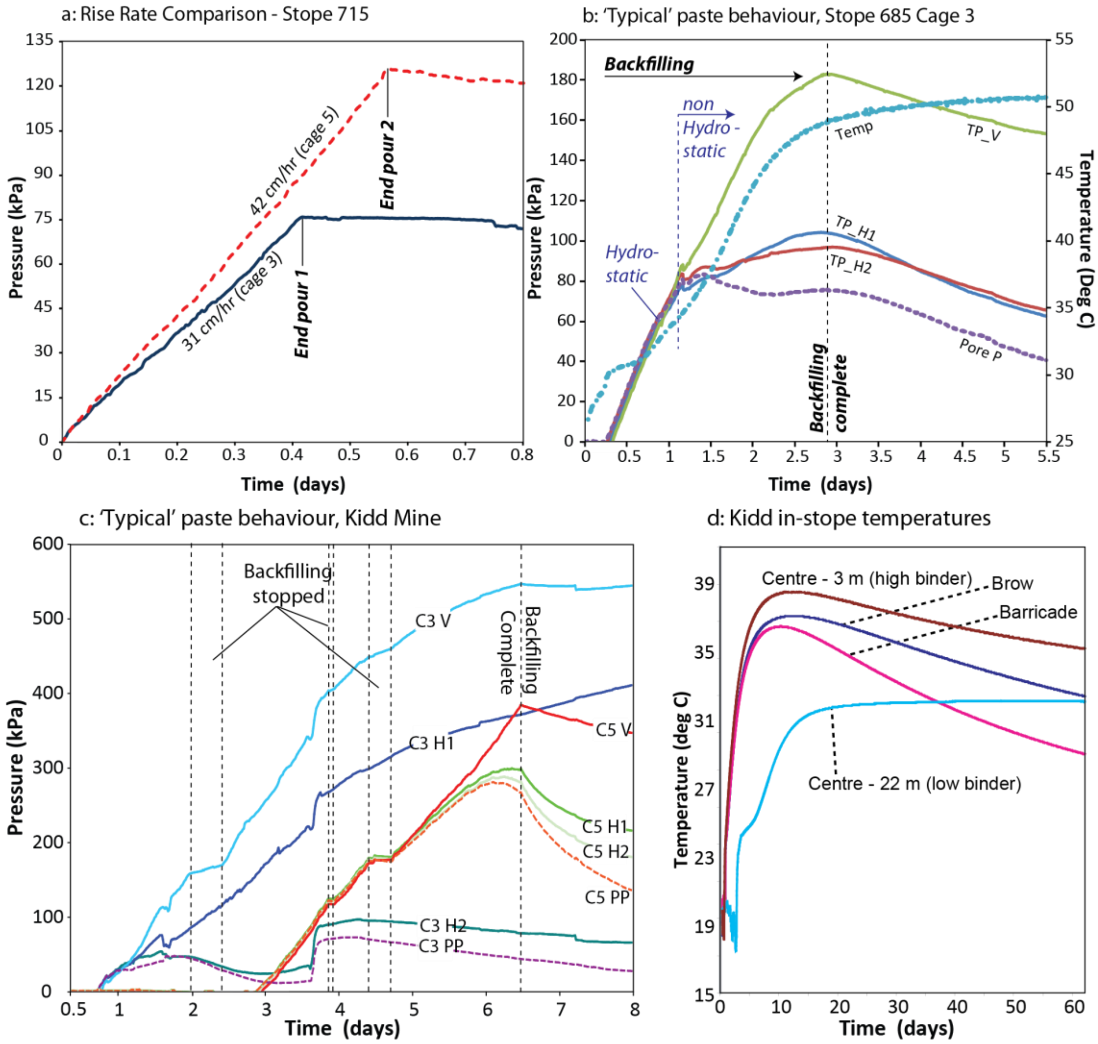

Figure 4 (a) vertical total pressures measured at two elevations in a Cayeli stope. Times are adjusted so 'time zero' corresponds to the fill height reaching individual cages; (b) vertical total pressure (TP_V), horizontal total pressures (H1, H2), pore pressure and temperature indicate 'typical' paste behaviour; (c) total pressure and pore pressure (PP) data from high (C3) and low binder (C5) fill in the same stope; (d) temperatures at various locations within the Kidd Mine stope (adapted from Thompson et al. 2011b)

The initial rate of pressure increase is moderated as shear strength develops, i.e. as the backfill transitions to a soil-like material. The time required to reach this transition from a hydrostatic (i.e. total pressure is equal in all orientations and equal to pore pressure) to non-hydrostatic loading condition is an important control on expected barricade pressure. This transition can be assessed by comparison of horizontal and vertical pressures at a point. Another means of interpreting in situ backfill mechanics is by measuring total earth pressure (σ), and pore pressure (u), to calculate effective stress (σ') (i.e. the stress carried by the solid phase of a material), as below. The importance of this approach is highlighted by Fourie et al. (2007).

$$\sigma' = \sigma - u \quad (1)$$

The strength gain mechanism for paste and hydraulic fills are different (or at least the interplay of drainage, consolidation and binder hydration will likely vary between the two fill types), and so the 'signature' of the strength gain in terms of pressure response, could also be expected to differ. An example of 'typical' paste backfill behaviour is shown from an instrumented stope at the Cayeli Mine in Figure 4(b) (Thompson et al.

2012). The ~15 m high stope was poured continuously, and orthogonally oriented total pressures and pore pressures were measured. There is an abrupt transition from hydrostatic to non-hydrostatic loading, which is interpreted to define the onset of shear strength development in the fill. After this point, a minimal increase in horizontal pressure was measured. This relatively abrupt transition to non-hydrostatic loading was a consistent observation from all three paste backfilling mines featured in Thompson et al. (2012).

Binder content was demonstrated as a controlling factor in the length of hydrostatic loading periods at the Kidd and Cayeli mines. Higher binder contents correlated with faster strength gain and lower barricade pressures. For instance, Figure 4(c) shows pressures from a Kidd stope, from the 4% binder plug (Cage 3), and the 2% binder 'main' pour (Cage 5). The 4% binder fill is shown to deviate from hydrostatic loading within 12 hours, whereas the 2% binder fill requires 48 hours before a gain in shear strength was measured. Such in situ data implies that binder hydration is the critical strength gain mechanism in paste fill. The 'self–desiccation' effect of the binder hydration is thought to be the causal mechanism of this strength gain, whereby the hydration reaction consumes water and induces negative pore pressures within the stiffening material (as shown experimentally by Helinski et al. 2007; Simms & Grabinsky 2009).

Another important feature of the Kidd data is the measurement of total pressures that continued to increase during pouring downtimes in the higher binder fill (i.e. Figure 4(c)). Pressure increases correlate with temperature increases that are generated by the exothermic binder hydration. The pressure increase was interpreted to be due to thermal expansion of the fill in the confined environment (Thompson et al. 2011b), as supported by laboratory tests and instrument calibrations, as described in a companion paper in this volume.

Temperature data from Kidd is shown in Figure 4(d), with as expected, highest temperatures being recorded in the centre of the high binder mass. Temperatures are reduced with proximity to the stope boundaries where greater heat loss is experienced. The lower binder fill measured relatively low temperature increase.

4 In situ measurements in cemented hydraulic backfill

To investigate potential improvements in backfilling efficiency, Vale and MDEng have conducted in situ testing of cemented hydraulic backfilling of long-hole stope mines in Sudbury, Canada. Data from this fieldwork are considered in this paper. Specific backfilling practices are summarised for each site. Vale's barricade design features 30 cm (minimum) thick, arched, shotcrete walls. Weeping tile/wick drainage pipes are installed around the barricades, and from the overcut to the barricade to facilitate drainage. Ponding height on top of backfill is monitored to ensure adequate drainage of the fill. Both mines follow a plug and main pour strategy, with an extended cure period after the plug is complete.

4.1 Backfilling at the Garson Ramp

Garson Ramp uses cemented hydraulic backfill with sand sourced from a local pit (i.e. no tailings). The ratio of sand to binder ranges between 15:1 and 30:1, with binder comprising 70% blast furnace slag, 25% cement kiln dust, and 5% normal Portland cement (NPC). Pouring is generally conducted during four days per week, on a 12 hours per day basis. One test was conducted with barricade instruments only, after which a 'whole stope' test was performed.

4.1.1 Stope 880-6514, initial barricade pressure test

The initial barricade monitored at the Garson Ramp Mine was at the 880-6514 stope, with one TEPC and piezometer. This was conducted to provide preliminary data with which to plan the subsequent 'whole stope' installation. Stope dimensions were 16.7 m height, 8.2 m wide and 27.8 m length. The barricade size was 4.6 m wide by 5.4 m high. The TEPC and piezometer were located at 1.6 m height at the centre of the barricade.

Pressure and temperature data is displayed in Figure 5, and provides a useful illustration of 'typical' backfilling practice at the mine. Pouring periods are illustrated by the dashed lines. Total earth pressure and pore pressures were equal during the first pour (Figure 5(a)), showing similar decreases as the fill drains. During the second pour, total pressure increased at a greater rate than pore pressure. This suggests that the fill gained shear strength during the cure period, i.e. was no longer in a fluid state. There was very little change in pore pressure for the remainder of the pour. There was an increase in total earth pressure during each pour period, although the magnitude of this increase was reduced as the height of the fill increased.

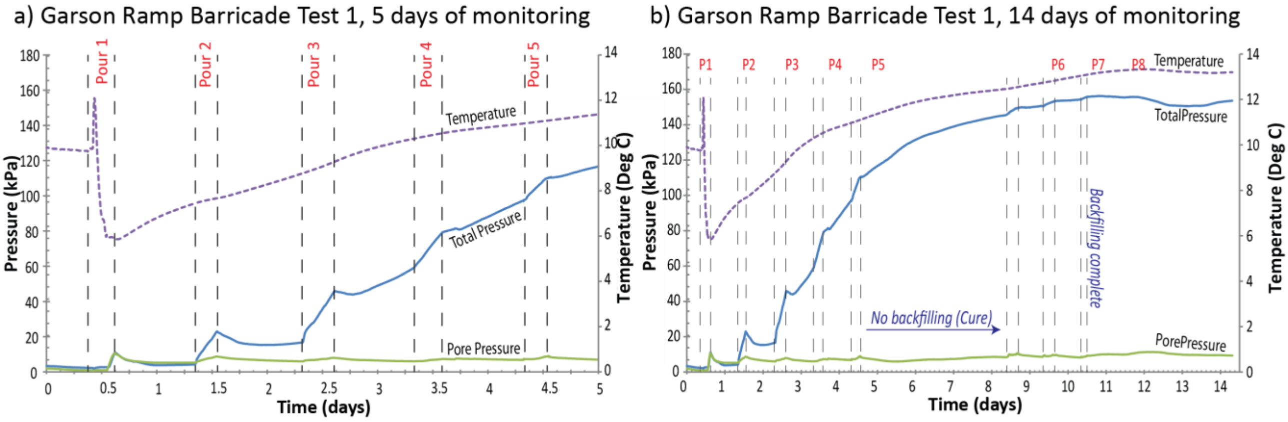

Figure 5 Total earth pressures, pore pressure and temperature measured for the 880-6514 stope at the Garson Ramp for five and 14 day periods

During the cure period following pour three, there was an increase in total earth pressure even though no backfill entered the stope. This pressure increase persisted for the remainder of backfilling, and is similar to that previously reported (i.e. at Kidd), which was interpreted as due to thermal expansion of the backfill in a confined area. Temperature (Figure 5) shows that backfill temperatures increased to a peak, shortly after backfilling was complete. The initial transient temperatures were due to flushing. The backfill temperatures at the barricade increased from ~5 to 11°C, with total pressure peaking at 106 kPa during the plug, and 152 kPa at the end of backfilling. Pore pressures peaked at 9.6 kPa.

4.1.2 Stope 880-6514, stope test

The 880-6514 stope featured instrument clusters under the brow (Cage 1) around 3 m from the barricade, and 10 m into the stope (past the brow, Cage 2), with vertical heights 1.5 m (brow) and 1.9 m (open stope). Two pairs of TEPCs and Piezometers were mounted at the 1.5 and 2.7 m height of the 4.4 m high barricade. The cross section of this stope and photos of the cages in position are shown in Figure 3.

Data was networked to a remote location and so fill behaviour could be interpreted in real time, which minimised the risk of over-pressuring the barricade. Also, access was prevented to the undercut region, with video footage of the barricade allowing its observation. Based on these safety measures, the decision was made to accelerate the usual pouring schedule for the plug, to determine backfill response under more aggressive filling conditions. The plug usually takes three days to pour, but in this case was poured continuously (except for a temporary shutdown) after which, normal pouring schedules were resumed.

Pressure and temperature data for this stope are presented (Figure 6). The initial 1.25 days of data includes the plug pour, and start of the cure period. The data are consistent with previous tests; at the barricade, total pressure and pore pressure initially increased at an identical rate. Pore pressures reduced in comparison to total pressure and peaked ~12 hours after the start of backfilling, at 26 kPa. By 22:00, fill levels had reached the top of the barricade, from where water was observed to be leaking as an imperfect seal had presumably been created during the shotcreting process. This escape in water (as observed from the remote camera footage) correlates with the fall in pore pressure and reduction in total pressure. Filling was halted for two hours, to allow the excess water to drain, and by the restart (23:00), the water leak had choked itself and the remainder of the plug was completed. This illustrates the effect drainage has on pressures. At the end of the plug pour, the total pressure at the barricade reached 68.5 kPa. Total pressures continued to increase during the cure period, and again, the thermal expansion hypothesis is proposed.

The under-brow and open stope data present more complete data on fill behaviour, as the orthogonally oriented TEPCs provide additional information compared to the single axis-pressures measured at the barricade. At the brow (Figure 6(b)), hydrostatic loading persisted for three hours. Pore pressures then began to plateau, and horizontal pressures increased at a reduced rate, compared to the vertical pressure, which shows the onset of shear strength gain. At the completion of the plug pour, vertical pressure was 63 kPa, and horizontal pressures were 43 and 57 kPa (H1 and H2, towards the barricade respectively). Pore pressure was 24 kPa, with effective stresses therefore 19-39 kPa (for the H1 and H2 axes).

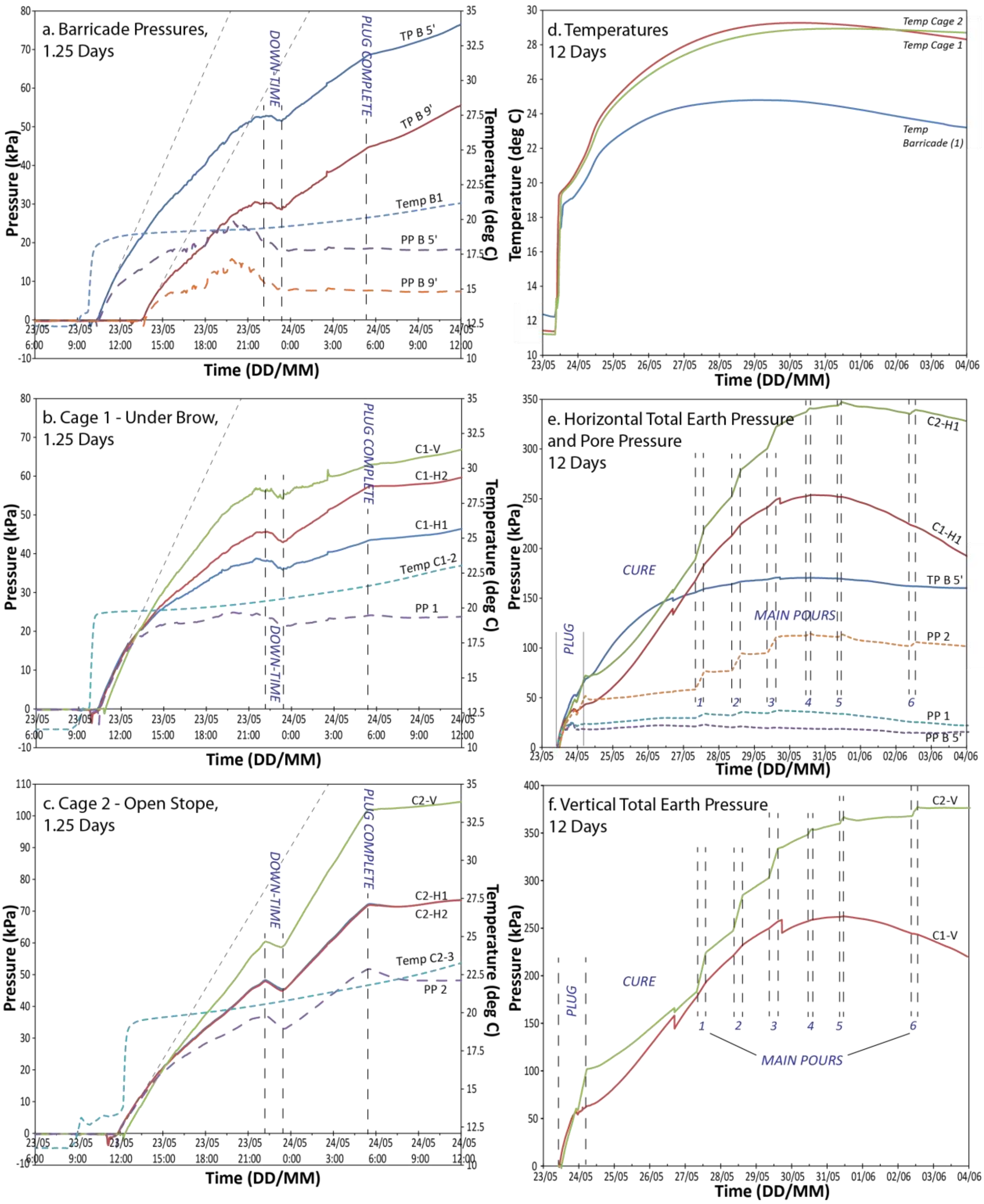

Figure 6 Total pressure, pore pressure (PP) and temperature data measured during the Garson 880-6514 stope. (a) total pressures at the barricade (TP B) are measured at 1.5 m and 2.7 m elevations; (b)-(f) show vertical total pressures (V) and horizontal total pressures (H1 and H2) for instrument cages (C1 or C2)

The open stope location (Figure 6(c)) shows a similar trend, with initially hydrostatic conditions transitioning after three hours. Total pressure at the completion of the plug was 102 kPa in the vertical axis, and 72 kPa in the two horizontal axes. Unlike the brow location where pressures were presumably affected by more complicated geometry, the horizontal pressures were equal in the centre of the stope. Whereas pore pressure measured at the brow had essentially plateaued midway through the plug pour, pore pressures at the centre stope location continued to increase throughout the plug pour, to peak at 52 kPa. Temperature data displayed in Figure 6(d) are consistent with the paste measurements shown in Figure 4(d).

The evolution of horizontal pressures acting towards the barricade is shown in Figure 6(e) for the duration of backfilling (i.e. six pouring periods after the plug). Total pressures increased during the three day cure period and at the brow (C1) and open stope location (C2). This pressure increase persisted until the temperatures had peaked, and is interpreted to be due to thermal expansion of the fill in the confined area. The peak horizontal pressure was 347 kPa in the centre of the stope, and 253 kPa under the brow. Pressure increases above the 'background' increase (i.e. induced by weight of backfill, rather than the proposed expansion pressure effect) were measured at the centre stope during backfilling periods. Much smaller pressure increases were evident under the brow, and pressure increases induced by additional backfilling were negligible at the barricade. Pore pressure data (Figure 6(e)) shows increases at the centre stope location (peak pore pressure was 115 kPa) during backfilling, and smaller pore pressure increases being measured under the brow (peak pore pressure was 37 kPa). Negligible changes in pore pressure were measured at the barricade after the plug pour. Vertical pressures at the brow (C1) and centre stope (C2) are compared for the same 12 day period in Figure 6(f), and they exhibit consistent behaviour to that described for the horizontal pressures.

This result was consistent with the 880-6415 barricade test, and considered very positive in demonstrating that the fluid loading phase of backfilling was relatively short for this stope, indicating the rapid onset of strength gain. The proposed mechanism of thermal expansion inducing pressure increases in the confined region appears responsible for the majority of pressure measured both in the stope and at the barricade. This mechanism inherently requires strength gain through the cement hydration reaction that induces the temperature increase, and the low pore pressures indicate high effective stresses have developed in the fill.

The work at Garson Ramp was conducted to test the instrument concept in hydraulic fill. There was no requirement to increase backfilling rates from an operations perspective. The focus of the fieldwork shifted to the Coleman Mine, where the benefits of more efficient backfilling are significant. The Garson data provides an excellent case study for a relatively coarse grained, fast draining hydraulic backfill, and highlights the requirement to better understand the mechanics of the thermally induced pressure increase.

4.2 Backfilling at Coleman Mine

Hydraulic fill at the Coleman Mine consists of a 2.3:1 ratio of sand to tails. The tailings grain size distribution is shown in Figure 7. Binder is a mixture of 70% iron blast furnace slag, and 30% NPC. The ratio of dry weight of solid to binder is typically 10:1 in the plug of a stope. Standard backfilling procedure at Coleman is to fill stopes during one shift per day, with the following 12 hours reserved as a cure time. A plug height of 1.5 m above the stope brow is defined. A plug is required to cure for three days. A restricted volume of waste rock can be dumped into the stope during the main body pour. The main motivation of this fieldwork is to measure fill behaviour and evaluate if the three day cure is required, or if the 12 hours per day cure periods provide sufficient drainage time. The stopes tested at Coleman have had similar dimensions, typically with height 33 m, width 16 m and length 23 m.

Undercut access for personnel was prevented during backfilling for Coleman stopes featuring 'accelerated backfilling' as part of this trial. In addition, all data was networked to a remote location to allow constant interpretation of fill behaviour in order to intelligently control backfilling and minimise risks of over−pressuring barricades.

Similar to Garson Ramp (Figure 3), the first Coleman stope (3510 1814) was instrumented with TEPCS and piezometers under the brow (Cage 1, which was 3 m from the barricade) and open stope (Cage 2 was located 13.3 m from the barricade). Barricade TEPCs and piezometers were located at 2 and 3.7 m heights on the 4.5 m high barricade (these are shown in Figure 3(e) and (f)). The stope floor topography meant that the instrument heights for Cages 1 and 2 were ~1.4 and 1.8 m respectively.

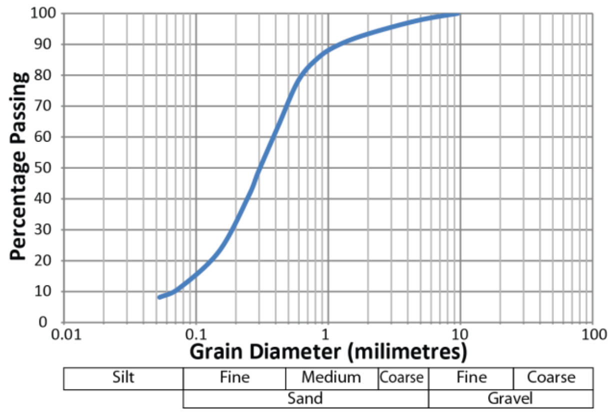

Figure 7 Grain size distribution for tailings used in backfill at Coleman

Total earth pressure, pore pressure and temperature data are shown for both the initial 6.5 day and the complete, 20 day recording periods in Figure 8. Pour periods are labelled P1-P7 on the 6.5 day figures, and dashed lines indicate their timing on 20 day figures. 13 pour periods were required to fill the stope. The initial pour (P1) brought the fill height to the base of the 1.5 m elevation barricade and brow instruments. During P2, the pressure data from the three locations show hydrostatic loading. During the following P2 cure, pressures fall as the fill drains. At the barricade (Figure 8(a)), the 2 m elevation instrument shows a separation of pore pressure and total pressure during the cure, whereas the 3.6 m elevation instruments measure total pressure equal to pore pressure. It is likely that the lower instrument at this point was within a more consolidated zone, or at least, that the higher instrument was within a fluid layer. Indeed, the 2 m barricade TEPC measured an increase of pressure before the end of the P2 cure, and a relatively constant rate of loading was observed, through pour and cure periods to the end of P5. This is interpreted as thermal expansion related pressure increase. After 2.75 days, a similar increase in pressure began at the 3.2 m barricade TEPC, which again, was relatively constant, irrespective of whether the stope is pouring or curing. The 20 day data (Figure 8(b)) at the barricade shows that total pressures appeared to peak shortly after the temperature peaked. Pore pressures at the barricade peaked at 1.4 days (33 kPa) and 2.4 days (22 kPa) for the 2 and 3.6 m instruments respectively.

The pressure data from the brow region is shown in Figure 8(c) and (d). As at the barricade, loading was hydrostatic for P2 (the instruments were not covered during P1) and drainage was measured (based on pressure reductions) during the P2 cure. During P3, the first indication of strength gain (i.e. 24 hours after the fill covered the instruments) is shown with total pressures increasing while the pore pressure remained relatively stable. Indeed, pore pressures peaked at 37 kPa during P1 and no significant increase in pore pressures were observed after P1. The loading rate increased at a relatively constant rate following the P3 pour, which suggests that some of the loading during the P3 was in fact due to the thermal expansion rather than the weight of backfill.

The thermal expansion interpretation may explain why magnitudes of total pressures at the brow location were not as expected based on weight of fill, with the horizontal '2' axis acting towards the barricade, being smaller than the horizontal '1' axis, and with vertical pressure being the minimum pressure measured at this location. The peak total pressure was 483 kPa, acting across the drift rather than towards the barricade, and so is the 'most' confined axis. The temperature data indicates that heterogeneities in fill exist, even at a relatively localised scale. For instance, the temperature at the brow cage (Figure 8(c) and (d)) was measured at points separated by ~30 cm vertical distance (i.e. see instruments in Figure 2(a)), and at 6.5 days, almost 5°C temperature difference had developed. Initially the temperature at the mid-height of the cage increased faster than the temperature at the top of the cage, i.e. at 1.5 days on Figure 8(c), which could be explained by the instruments being either side of a fluid transition height. However, temperature at the top of cage shows a faster increase from this point, which could be explained by the enveloping fill having a relatively higher cement content due to settlement and washing out of binder from the coarser grained fraction of the fill. The total temperature increase at the brow was 28°C.

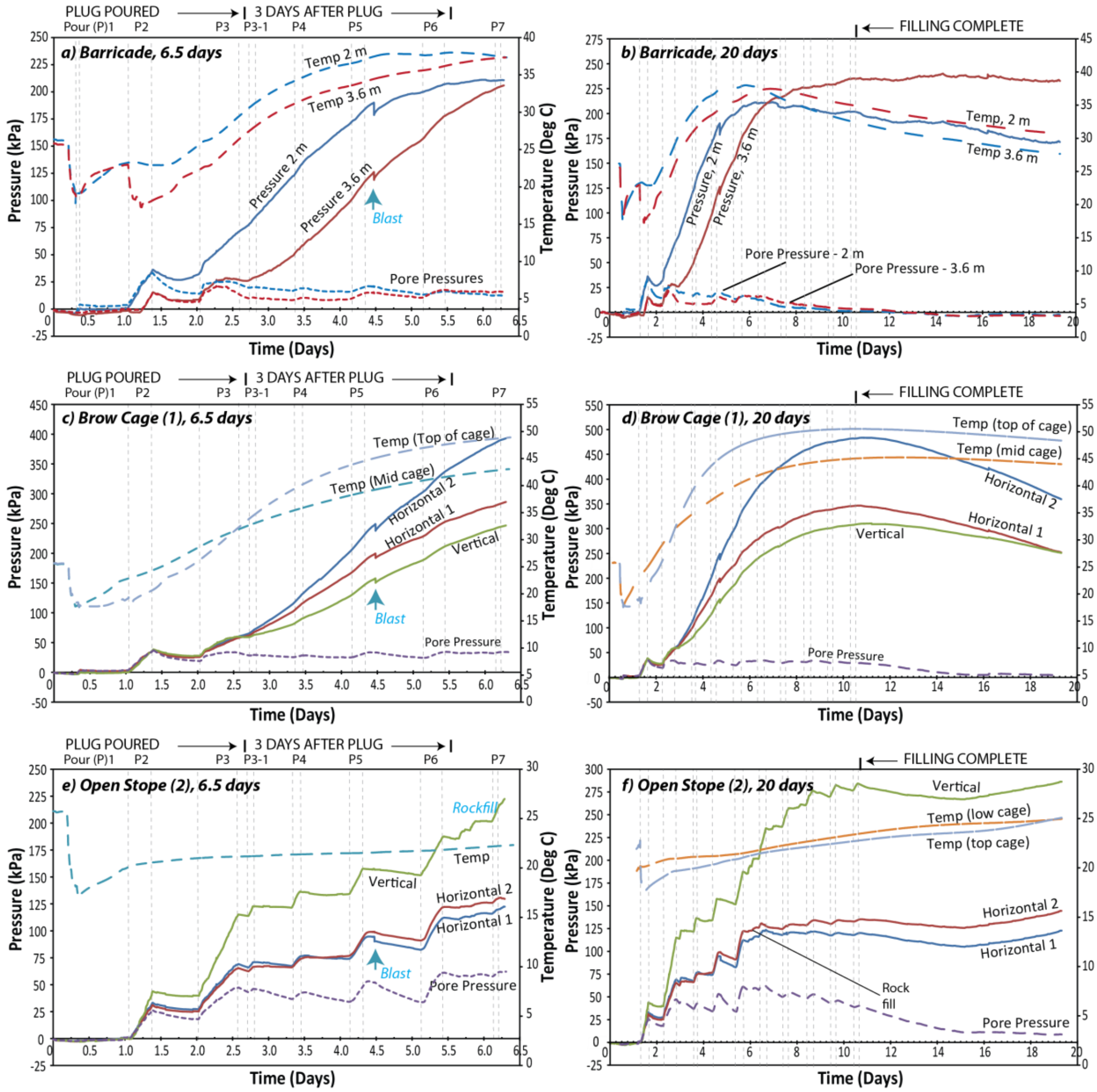

Figure 8 Total, pore pressure and temperature data measured at Coleman's 3510 1814 stope. (a)-(b) the heights of barricade instruments are annotated; (c)-(f) cage data shows total earth pressure measurement axes

By the end of the plug pour, total pressures at the barricade and brow were measured to increase whether or not the stope was backfilling, due to the interpreted thermal expansion effect. It was concluded that additional backfilling did not have any effect on the barricade pressures, and so it would be safe (in this zero-risk to personnel stope) to continue pouring without the three day cure period (the 12 hours per day cures were maintained). Therefore, interpretation of real time in situ data allowed an informed decision on fill behaviour and so the stope's cycle time was accelerated by three days. Peak total pressure on the barricade was 85 kPa at the end of the plug pour, with the ultimate total pressure measuring 211 and 240 kPa on the 2 and 3.2 m elevation instruments respectively. Again, it is highlighted that these pressures were largely induced through the interpreted thermal expansion mechanism, and the pore pressure data indicates that the fill had developed significant effective stress.

At the open stope cage location (Figure 8(e) and (f)) the instruments were covered during P2, and even during the first pour, some gain in shear strength was measured, based on vertical total pressure being greater than horizontal pressures, which are greater than pore pressure. Strength gain, likely through drainage and/or consolidation occurs during P2 and subsequent cure periods, as shown by the reduction in total and pore pressure. Peak pore pressure was measured at ~60 kPa between the P6 and P7 pours. This value is higher than at the brow and barricade locations, indicating improved drainage potential at the brow, presumably due to proximity to stope walls and drainage pipes. Total pressures increased during each pour, and are not observed to increase during cure periods, until the P6 cure, when rockfill is dumped (Figure 8(e), 5.75 days). This indicates the thermally correlated pressure increase does not occur at Cage 2. Horizontal total pressures had nearly plateaued (~125 kPa) by P7, but vertical pressures continued to increase until filling was complete. Peak total pressure was 285 kPa at the end of backfilling, at which point the at-rest coefficient of earth pressure (K_0) was 0.39 (effective horizontal stress/effective vertical stress). The temperature increased by less than 5°C, which is significantly less than at the brow and barricade.

5 Discussion

Clearly, there are two significantly different behaviours being measured in the Coleman stope. At the centre stope location, there is a small temperature change, with backfill behaviour consistent with response to self-weight pressures, which are minimised in the horizontal orientations by the material transition from a fluid to a soil like material. The K_0 value is consistent with a dense sand (Craig 2006). As in Figure 4(d), paste fill stopes consistently feature higher temperatures in high binder pours, i.e. plugs, compared to lower binder pours, i.e. main pours, and therefore it is a logical assumption that this low temperature location has relatively small binder content compared to elsewhere in the stope.

It is well known that hydraulic fills can experience grain size segregation, with the formation of a shallow angle beach sloping away from the fill point. As detailed in Falconbridge Ltd. (1990) and references therein, three zones will form in this beach. Initially, particle size is representative of the overall size distribution. The second zone features mostly coarse particles and the third features mostly fine particles. The segregation is a result of differential settling rates based on particle sizes.

The fine grained binder will therefore be concentrated more in the fine grained zone, and less in the coarse grained zone. This is consistent with the in situ temperature and pressure data measured in the 3510 1814 stope. Subsequent analysis shows that Cage 2 was located closer to the fill point, and temperature data suggests relatively small binder content existed, compared to the more distant brow location which experienced large temperature increases. For this backfill at least, the temperatures resulting from the cement hydration reaction appeared to increase total pressures, at least in the confined environment. These higher pressures should not necessarily be a concern as the pressure increases are as a result of strength gain (as demonstrated by the required cement hydration) and pore pressures remain low. Indeed, this proposed thermal expansion mechanism appears to operate irrespective of the rate of pouring and curing. The weight of historical evidence in terms of a lack of barricade failures indicates the additional pressure induced does not present a concern in terms of barricade stability. Coring, and physical measurement of fill strength will be conducted in a subsequent test to better define the magnitude of early age strength gain. It is important to note that barricade strengths are generally considered in terms of a fluid pressure, under which condition, if a barricade is caused to displace then the fluid pressure will be maintained. It is important to recognise that the fill at this stage of curing is not in a fluid state, and so deflection of the barricade would result in a reduction of total pressure, as the soil like material was permitted to relax. Clearly, the worst case situation should be considered for barricade design, i.e. fluid loading, but modelling of barricade strength based on the observed loading, which is similar to a soil−structure interaction situation would also be useful.

Falconbridge Ltd. (1990) considers how fill segregation may reduce fill strength through planes of weakness, and how fill points should be considered to manage the segregation effects in terms of exposing faces. The present fieldwork however, appears to show also that fill point location should be acknowledged in terms of potential variation in barricade pressures. Indeed, several further tests have been conducted at Coleman and although measurements generally correspond to the high temperature barricade results, examples of low temperature and low pressure barricades, consistent with the Cage 2 data (Figure 8) have been measured and could be explained by the location of the fill point with respect to the barricade.

In situ tests in pastefill generally result in data that is consistent with a homogenous fill material under self-weight loading condition, which is moderated by arching, and stope geometry, binder contents, geotechnical material properties and other factors. Thermal expansion of fill in confined areas is also proposed as a mechanism for pressure increase at some, but not all operations. Data from two hydraulic backfill operations exhibits many similarities, although the coarser grain (i.e. faster draining) material at Garson Ramp appeared to gain strength more rapidly than the Coleman operation, presumably due to faster drainage. Compared to paste, the hetrogeneous in situ material properties of hydraulic fill add a additional variable in understanding in situ pressure response.

Thermal expansion was first proposed as a pressure gain mechanisms following the Kidd Mine fieldwork, where it was only measured in relatively high binder stopes (Thompson et al. 2011b). Laboratory tests were then conducted and were able to replicate the temperature induced pressure increases in confined fill, and instrument calibration was considered as further discussed in a companion paper in this volume.

6 Conclusions

This paper has shown how instrumentation can be applied to better understand in situ backfill behaviour in backfilled stopes. In paste, the behaviour reflects a homogenous material. The initial rise rate moderated by strength gain as the fill transitions from fluid to a soil-like material are the initial controls on induced pressures. Pressure increases during periods of down-time that correlate with temperature increase are interpreted to be due to expansion of fill in confined environments, following careful consideration of laboratory simulations of field conditions and instrument calibration requirements, although concurrent low pore pressures demonstrate the fill develops relatively large effective stresses under this condition. The heterogeneous nature of hydraulic fills has been shown to determine localised in situ pressure response, with coarse grained, low temperature zones interpreted as having reduced binder content, and fine grained zones recording high temperatures indicative of high binder contents. Generally, this work has been successful in defining in situ behaviour, and work to incorporate instrumentation into routine backfilling practice at Coleman, and therefore manage backfilling on a case by case basis continues.

It is important to note that field measurements are of site-specific benefit as differences in tailings properties and chemistry can influence backfill behavior even on the same site (Thompson et al. 2012) and so it would be improper to apply results from one site across other operations.

Caution must be applied when using instrumentation to monitor hydraulic fill barricades as the piping mechanism that was reported to induce several barricade failures (Grice 1998), generally during the 1990s, would not necessarily be detected using a TEPC. Piping failures can occur where fine particles leak from the stope to enable pipe-like structures to gradually be extended to the fill surface. The presence of ponded water on top of the fill subjected the barricades to hydrostatic loads even though plugs had cured and so punching failures occurred (Grice 1998). Grice (1998) highlighted that raising slurry density above 70% solids (by weight) largely eliminates such risk, and Vale's hydraulic backfilling operations exceed this slump density. However, control of filling strategies for hydraulic backfilling should not rely on pressure measurements alone. Proper water management and drainage of fill is also a requirement, as is rapid attention to leakage of fill material through the barricade.

With some exceptions, the binder content of backfill is usually defined by fill strengths that are required to mine against or under fill rather than a focus on short term strength gain in the plug to minimise barricade pressures. Generally there is an understandable focus on reducing binder costs. Mines should consider however, that increasing binder content in backfill plugs may result in faster cycle times through elimination or reduction of cure periods and so result in savings through increased production rates.

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