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Monitoring barricade performance in a cemented paste backfill operation

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Abstract

Efficient barricade design and construction practices can have an important impact on mining cycle time and therefore on the economic performance of the mining operation as a whole. However, standardised procedures have yet to be developed that will allow the mining engineer to reasonably predict barricade performance and assess the actual behaviour of the barricade during filling, curing, and subsequent mining of surrounding stopes. A case study will be presented in which a reinforced shotcrete barricade is instrumented to measure pressures exerted on the barricade and its corresponding deformation. Various points within the fill mass are also instrumented to measure total and effective stresses and to assess hydration progress in situ. The study provides important insights regarding the mechanisms of backfill curing and the establishment of an initial stress state within the fill mass and on the barricade. General recommendations are developed so that other mine sites may follow similar procedures to optimise their barricade design and construction practices.

1 Introduction

The use of cemented paste is becoming more widespread as a backfill material in underground mining. This is due to rapid in-stope delivery, engineered strength characteristics, and advantages associated with diversion of tailings from surface to underground storage. Mining operations may adopt varying backfilling strategies that ensure pressures induced by the cemented paste backfill (CPB) do not exceed the capacity of fill barricades, erected to contain the backfill during its (semi-)fluid phase. However, without in situ measurements of CPB behaviour, it is difficult to constrain the expected loads, and so backfill strategies may be conservative, but to an unknown degree. The economic potential of a reduction in stope cycle times (for instance, where multi-stage pouring strategies are adopted to minimise pressures) or a reduction in binder contents is significant. Furthermore, all operations wish to enhance the safety of workers and equipment, which can only result from a better understanding of potentially hazardous backfilling situations.

A research project is in progress to better understand the geomechanical behaviour of CPB. A total of five stopes have been comprehensively instrumented at three mining operations. Such programs aim to determine the temporal and spatial evolution of pressures induced during and after backfilling. The ultimate aims are to contribute to the backfilling strategies at the three operations through a more complete understanding of in situ CPB behaviour. Information, such as balancing of rate of filling versus cement hydration rates to limit barricade pressures, arching of pressures at stope boundaries and into drifts, long term pressure development, and the potential for positive correlation between pressures and temperatures have been considered. Here, the first of two stopes tested at Inmet's Cayeli Mine in North Eastern Turkey is described. Specific instrumentation and installation methods are summarised. Results are presented to show a detailed record of how pressures and temperatures manifest during and following backfilling.

2 Methods

2.1 Cemented paste backfill design, stope geometry and pouring strategies

The ore body at Cayeli has complex geology, with the mill processing ore in two streams; 'clastic' and 'non clastic', resulting in two types of tails. This paper presents the first of two stopes tested at Cayeli, in which non-clastic tailings were used. The second stope featured clastic tailings. Initial results from the two stopes suggest the chemistry of the tails may influence cement hydration. Work is ongoing to better understand these differences.

The test stope, 685 N 20, is a primary stope that will be undercut by future mining. The undercut area is 26 × 10 m, and the overcut area is 23 × 11 m, with floor to floor height of 16 m. The standard paste filling design for such a stope is to pour CPB with binder content 8.5%, to a height of 8 m. The remainder of the stope is filled with CPB with binder content of 6.5%. The binder consists of 100% Portland cement. To prevent generation of excessive barricade pressures, stopes are filled in two stages, with an intermediate curing period of between three and seven days. Further, the filling rates are limited to approximately 37 cm/hr below, and 45 cm/hr above a height 8 m respectively.

For this stope, we deviated from the mine's conventional two stage filling strategy. Previous work by mine staff and consultants provides confidence that fill barricades at the mine can withstand pressures up to at least 100 kPa (Yumlu and Guresci, 2007). In this fieldwork, the data logger was connected to the Ethernet. This allowed real time scrutiny of pressure data at the fill barricade. As pressures did not exceed 100 kPa on the barricade during backfilling, the pour was completed continuously. As with all stopes at the mine, access to areas in the vicinity of a fill barricade is restricted as a safety precaution during backfilling.

2.2 Rationale for instrumentation

Pressures in cemented paste during backfilling are essentially controlled by the rise rate of the CPB (i.e. the amount of overburden load applied) and the hydration rate of the binder, which contributes to shear strength and causes pressure to be arched to the stope sidewalls (Mitchell et al., 1982; Mitchell, 1992; Li and Aubertin, 2009). The geometry of a specific location controls the extent of arching, i.e. reduced pressures have been measured at fill barricade locations at the Williams and Kidd Mines (Grabinsky et al., 2008; Thompson et al., 2009). The stope was instrumented with total earth pressure cells (TEPC) to measure total earth pressure, and piezometers to measure pore water pressure, in addition to further transducers to be considered shortly.

Total earth pressure and pore water pressure can be combined to interpret the development of effective stress within the CPB, i.e. the load carried by the solid skeleton of the CPB. The development of effective stress in CPB is generally indicative of a reduced risk of barricade failure and liquefaction susceptibility. In the laboratory, negative pore water pressures have been demonstrated in CPB (Grabinsky and Simms, 2006; Helinski et al., 2007; Simms and Grabinsky, 2009), the presence of which inherently increases the stability of CPB. The featured piezometers are thought to allow the measurement of negative pore water pressure up to the air entry value of the piezometer tip, approximately -20 kPa. To capture suctions beyond this range, heat dissipative sensors (HDS, Campbell Scientific model L229) are used, as described by Grabinsky (2010).

With the ultimate goal of predicting pressures at a given location, it is a requirement to know the approximate time of binder hydration for a given CPB mix design, in order to account for the moderating effect of binder hydration on the applied overburden load. The development of shear stress, and arching of pressure, as a function of cement hydration, can be determined by a deviation from hydrostatic loading. Temperature can also be used as an indicator of cement hydration, and so in this test, the thermocouple channel output from each piezometer and TEPC was recorded. Further, changes in the chemistry of the CPB result from cement hydration, inducing a change in the electrical conductivity of the material. Electrical Conductivity (EC) probes were included in the emplaced instrumentation clusters in order to elucidate cement hydration information. The application of this probe for CPB research has been considered by Simon et al. (2010) and is beyond the scope of this paper.

From an operational standpoint, the primary focus of the Cayeli fieldwork was to measure and interpret pressures at fill barricades. Ultimately, the ability of the fill barricade to withstand the loads induced by a given filling strategy (i.e. loading rate for a given CPB mix design) determines whether backfilling can be continuous or performed in stages, with inherent economic implications. However, rather than looking at pressures induced by CPB only at the barricade, it is preferable to measure pressures throughout the stope. This enables the entire stope to be considered as a system, and pressures at specific locations considered as a function of the local geometry. Such an approach is essential if analytical modelling is to be applied, and the results extended to other stope geometries and CPB mix designs. To achieve this goal, instrument clusters were suspended vertically in the centre of the stope. Instrument clusters were also positioned either side of the brow at the draw point of the stope, and additional TEPC and Piezometers were installed directly on the fill barricade. To assist in evaluating barricade response to applied load, displacement was measured using an array of potentiometers at the free face.

For ease of installation in the stope, three orthogonal TEPC, one piezometer, one HDS and an electrical conductivity probe were installed in (dog) cages. The cages also contained compasses and tiltmeters to determine any change in the measured pressure axes should the cages suffer movement during backfilling. Minimal movement of the cages was detected. The instrument cages were subsequently placed in external, protective cages, for installation in the stope, as shown in Figure 1. The position of the instrumentation is indicated in the cross section (Figure 2).

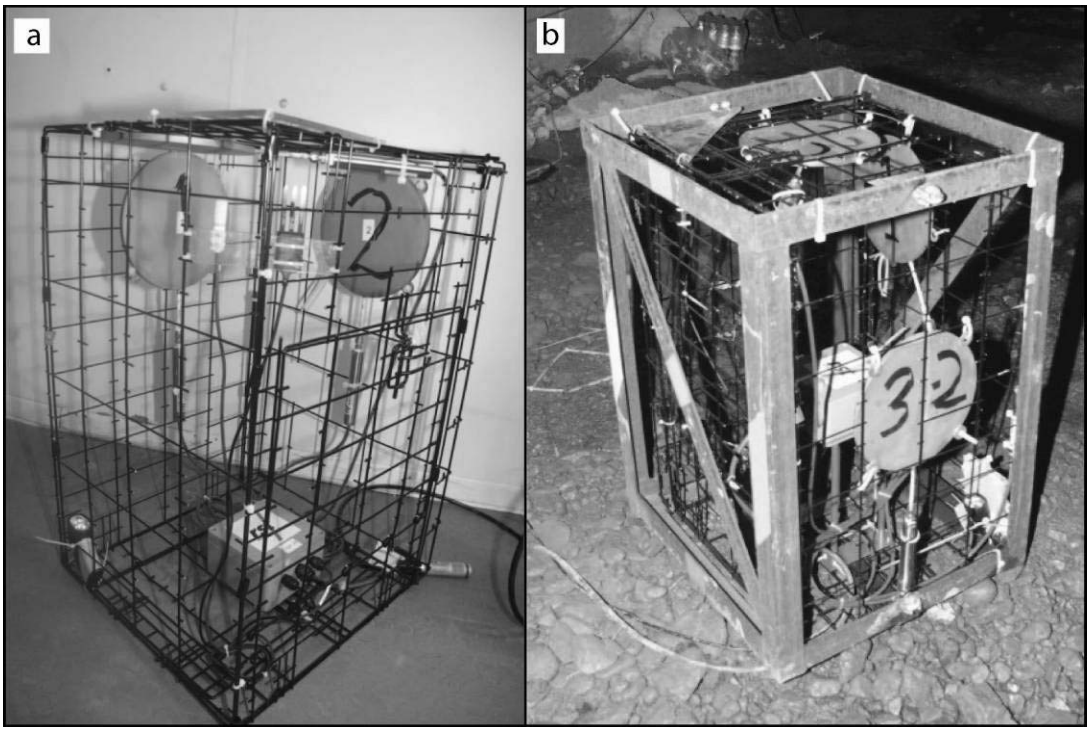

Figure 1 (a) Example of instrument cage with TEPC, Piezometers, EC probes, tiltmeter and compass installed; (b) instrument cage is inserted into a protective cage ready for installation in the stope

2.3 Installation of instrumentation

Three instrument cages were installed vertically, in the centre of the stope, using a pulley and anchor block system. Before the stope was blasted, two pulleys were welded to cable bolts in the overcut back (roof). Cables were threaded through the pulleys and pulled, tight to the back, out of the stope's perimeter. Subsequently, the stope was blasted and mucked. The cables were then lowered into the stope. In the overcut, the cables were attached to winches (Figure 3(a)). In the undercut, the cables were attached to the chain of three cages and tied onto an anchor (Figure 3(b)). Then, the cages were hoisted into the stope using the winches in the overcut, with the anchor being driven into the stope in the bucket of a remotely controlled scoop. The final position of the hanging cages is shown in Figure 3(c). Previous experience has demonstrated the importance of covering the data cables with sand as protection from falling rocks, as shown in Figure

3(c). The cages were positioned at 2, 6 and 10 m height in the stope, measured from the TEPC measuring vertical pressure, at the top of each cage.

Two instrument cages were installed at the draw point of the stope, on a 'T' structure with height 1.8 m, as shown in Figure 4(a). The cages were separated by 3.5 m. Cage 1 was 2.5 m from the fill barricade, with the brow opening to a height of 6 m above the cage. Cage 2, 6 m from the fill barricade, was in the open stope, as shown in Figure 4(c). This photograph, taken using a remote boom, looks directly into the stope, with Cage 2 visible approximately 1.5 m into the stope.

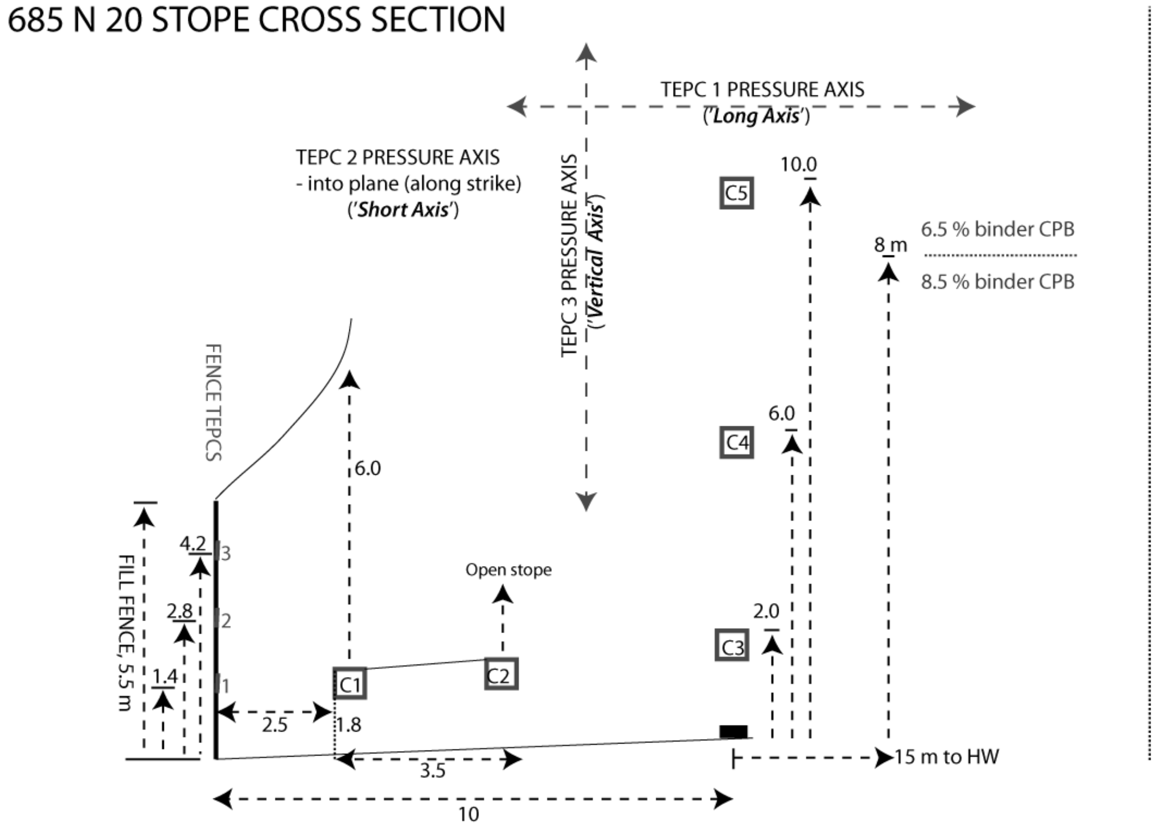

Figure 2 Cross section of 685N20 stope showing stope dimensions (in metres), and cage (C) and fill barricade instrument locations. The vertical, long and short TEPC axes are indicated

2.4 Fill barricade instrumentation and construction

Three total pressure cells and piezometers were attached directly to the fill barricade as shown in Figure 5(a). The instruments were positioned at the centre of the barricade, at heights of 1.4, 2.8 and 4.2 m. Barricade construction consisted of rebar drilled into the perimeter rock at ~0.7 m spacing. Rebar are then extended vertically and horizontally, and attached with wire. A wooden frame, installed ~0.3 m into the stope from the rebar, provides a backing onto which a 30–40 cm thickness of shotcrete is applied. In most cases at Cayeli, it is not possible to arch the barricade towards the stope. Such arching would significantly increase the strength of the barricade. Fill barricade construction is shown in Figure 5(b).

In order to measure fill barricade displacement, a steel frame was attached to the perimeter rock. Horizontal struts were positioned between the frame and ~3 cm from the fill barricade surface. Six potentiometers were attached to the struts in order to measure the relative displacement between the barricade and the perimeter rock. In Figure 6(a), the displacement array installed for the second test stope is shown. Figure 6(b) shows a potentiometer in detail. The location of instruments on the fill barricade is indicated in Figure 7.

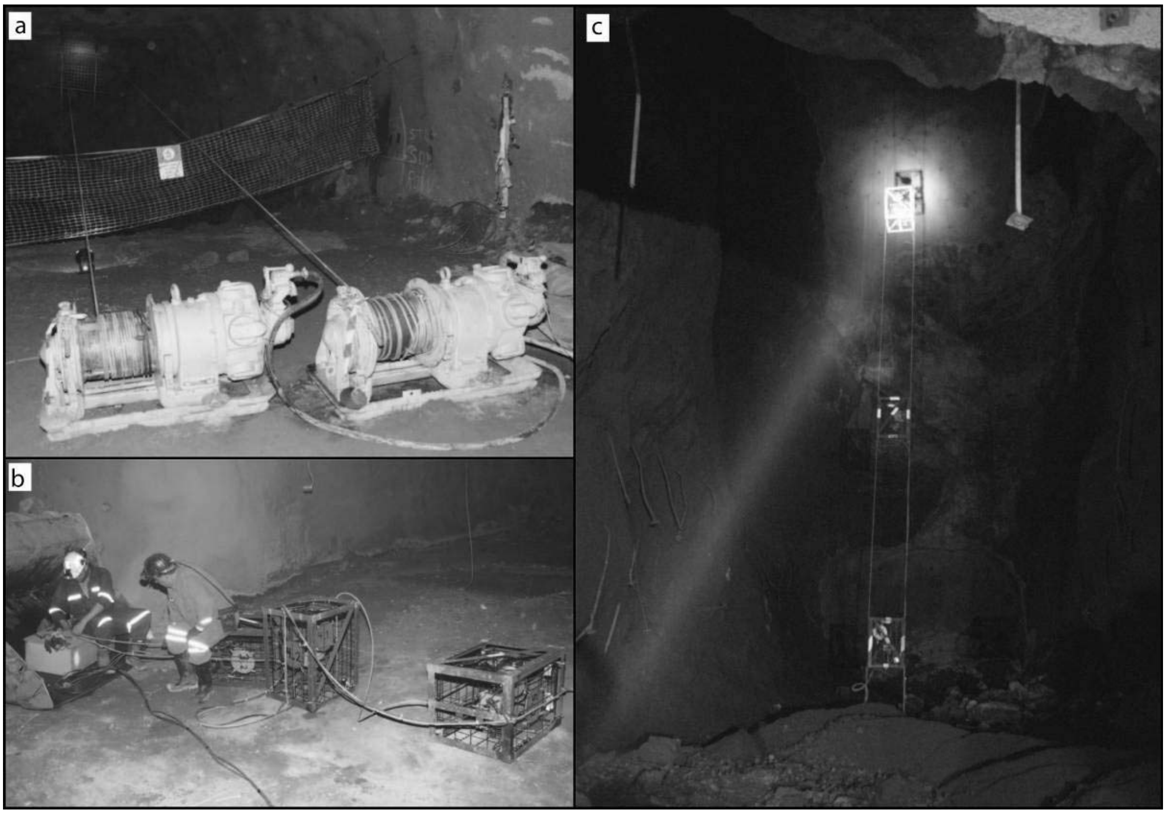

Figure 3 (a) Pulleys, winches and cables installed in overcut; (b) cables were dropped into stope and attached to cages; (c) three cages were then hoisted into the stope with lead wires protected with sand

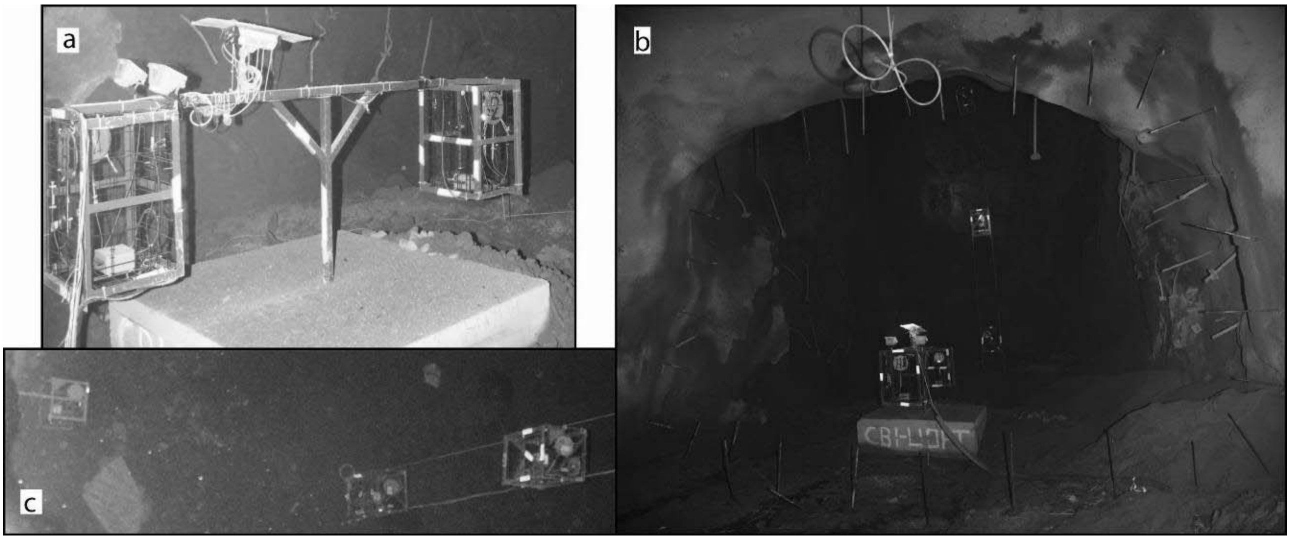

Figure 4 (a) T cages positioned at front of stope; (b) T cages with hanging cages in background (courtesy R. Veenstra); (c) picture taken with camera on remote boom looking down stope. The outermost 'T' cage is visible in the main stope volume (top left), the innermost 'T' cage is hidden under the brow

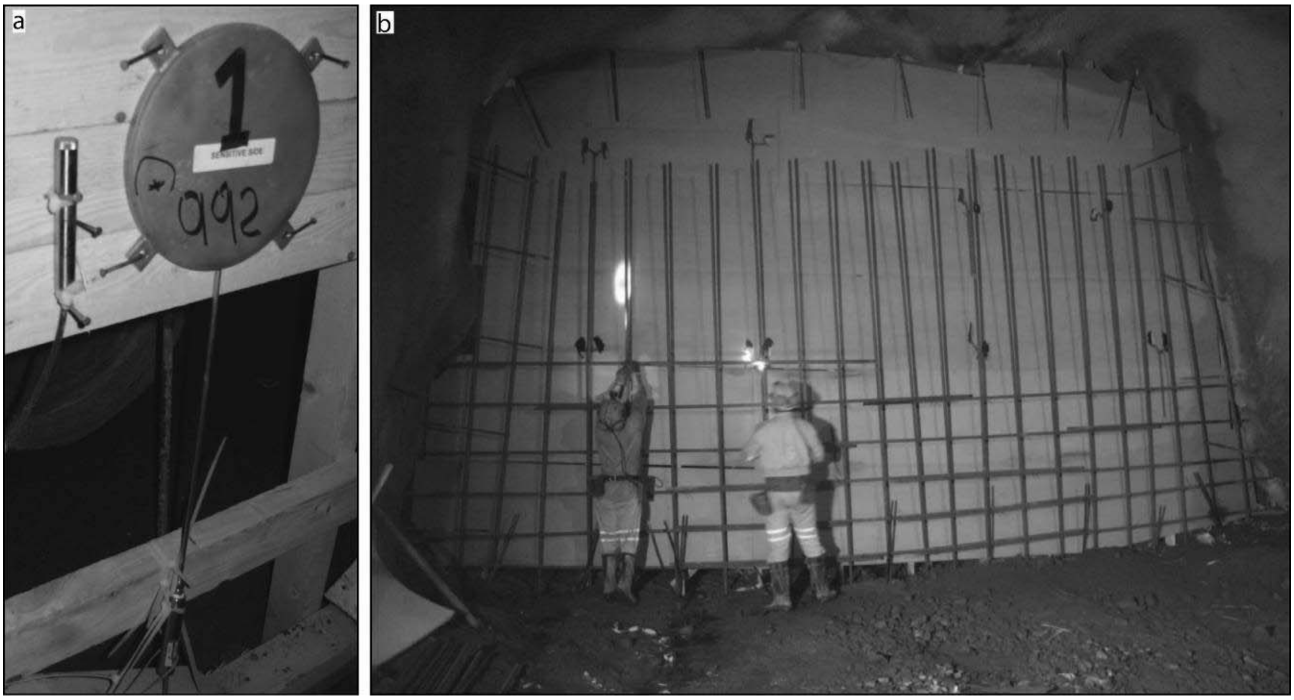

Figure 5 (a) Fill barricade instrumentation; (b) fill barricade construction

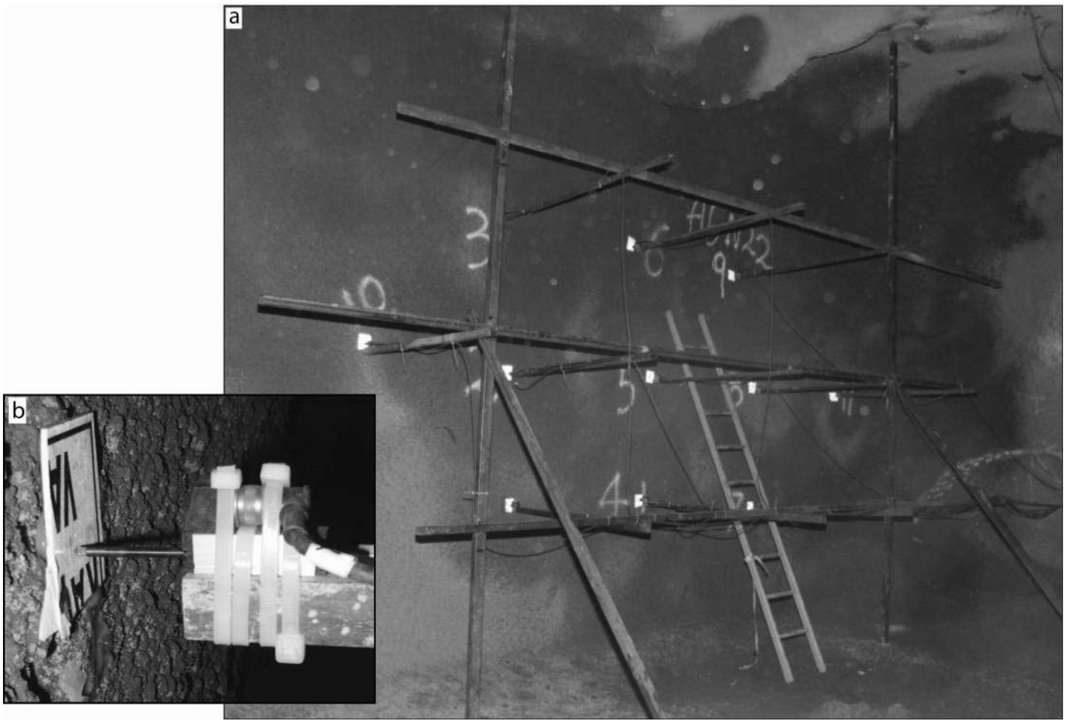

Figure 6 (a) Steel frame with potentiometers mounted; (b) to measure displacement

3 Results

3.1 Barricade deflection and total earth pressures on the fill barricade

Fill barricade displacement is presented with total earth pressures measured on the fill barricade (plotted on the secondary vertical axis), for two day and five day periods in Figure 7. Peak pressures on the barricade are 46, 35 and 55 kPa for the low, mid and top height TEPC respectively. A peak displacement of 8 mm is measured at the centre of the barricade, with 4 mm and 4.5 mm measured at the bottom left, and right potentiometers in the array. Displacements are relatively small for the first 0.25 days, until CPB reaches a certain height on the barricade. Increasing displacement follows, to a time of ~1.25 days, after which barricade displacement is significantly reduced.

Total pressures initially increase at 6.6 kPa/hr, 4.0 kPa/hr, and 3.8 kPa per hour for the 'low', 'mid' and 'high' TEPC. Total pressures plateau for all TEPC on the barricade, with pressures decreasing and subsequently increasing. Figure 8 shows total pressure, water pressure and temperature data for the fill barricade, and for Cages 1–5. Pore water pressures measured at the fill barricade are low in comparison with the equivalent total pressures (19.3, 12.5, and 6.0 kPa for the low, mid and high barricade piezometer locations, respectively). Low pore pressures are probably due to enhanced drainage at the stope boundary, or a relatively small hydraulic column. Similar results were obtained in the previous field studies at Kidd and Williams (Grabinsky et al., 2008; Thompson et al., 2009). A small amount of cracking was observed on the barricade.

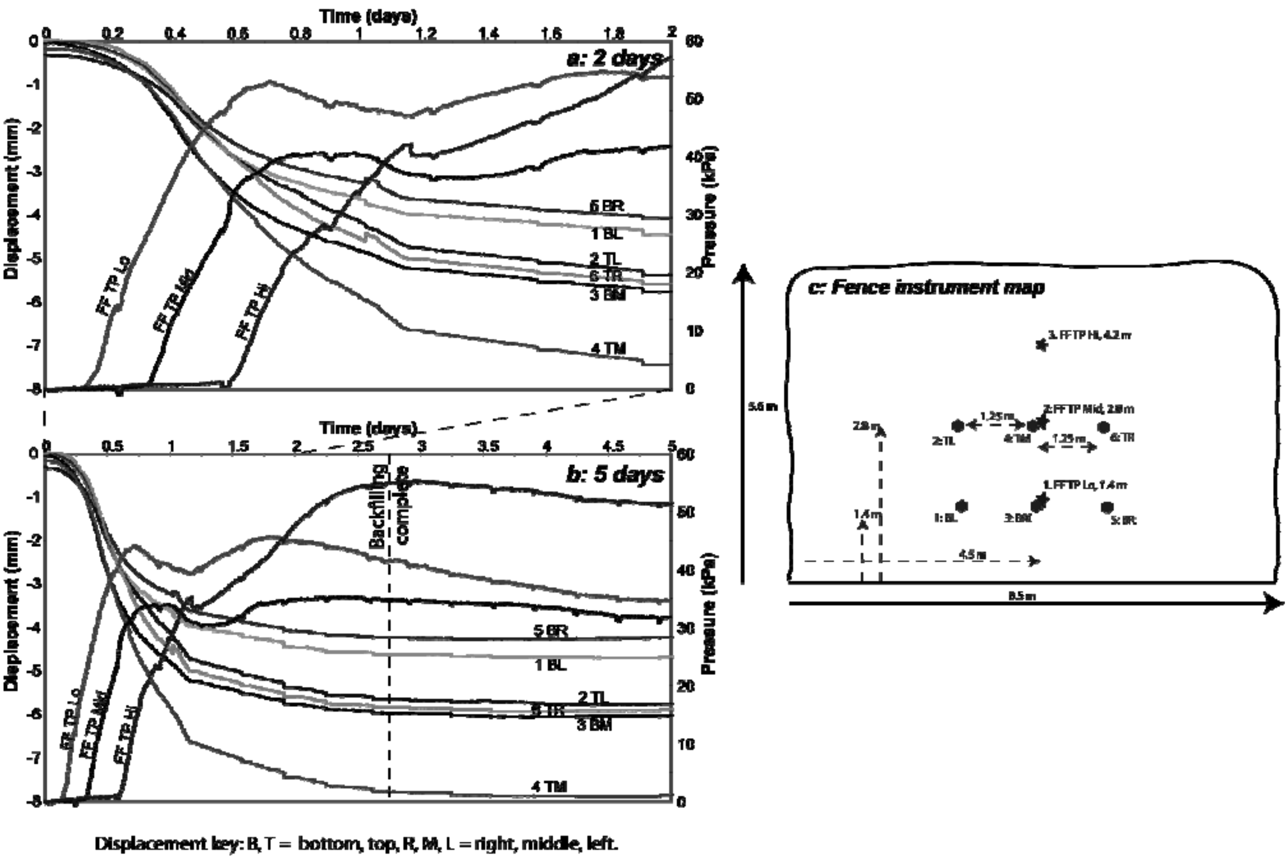

Figure 7 Fill barricade displacement (solid lines) and total earth pressures (dashed lines, scale on the secondary axis) for (a) two days and (b) five days. The positions of displacement transducers (hexagons) and TEPC (stars) are plotted in (c)

3.2 Cage instrument data

Cages 1 to 4 are contained in the 8.5% binder CPB, and Cage 5 is in the 6.5% binder CPB. For all cages, loading is initially hydrostatic, i.e. total pressures are equal in all axes. Cages 1, 3 and 4 remain hydrostatic for between 12.5 and 14 hours, with Cage 2 hydrostatic for 18 hours. Cage 5, in the lower binder content CPB, remains hydrostatic for at least 20 hours, which is the period of remaining paste filling. During the non-hydrostatic loading of Cages 1 to 4, vertical pressures increase under and close to the brow (Cages 1 and 2) at a reduced rate, whereas for cages in the centre of the stope vertical pressures continue at a rate slightly less than (Cage 3) or equivalent (Cage 4) to the hydrostatic loading rate. Although data is limited, one can speculate that the break in slope of vertical pressure at Cage 3 (2.18 days) represents arching of vertical load. Maximum total pressures in the stope are 196 kPa and 194 kPa, measured in the vertical orientation for

Cages 4 and 3 respectively. As shown in Table 1, the maximum pore pressure is experienced for Cage 5 (92.4 kPa), reducing vertically in the stope (Cage 3, 83.2 kPa), and laterally towards the barricade (Cage 1, 46.5 kPa). Also on Table 1, the time to peak pore pressure corresponds with the above pattern, with pore pressure peaking fastest at the stope margins, and increasing with distance laterally into the stope, and then vertically in the stope. The observed pore pressures could be influenced by enhanced drainage at the stope boundaries. Also, limited connectivity of the hydraulic head above the individual piezometers could be a factor.

The volume of the CPB emplaced was 3,262 m^3 and the time required to fill the stope was 69 hours. On average over the 16 m height, the CPB rise rate was 0.23 cm/hr. Local rise rates are plotted in Table 1 calculated using the 'arrival times' of CPB measured at different locations. The CPB is introduced to the stope directly above and about 4 m to the left of Cages 1 and 2. For this reason, higher than expected rise rates of up to 0.59 cm/hr are measured for Cages 1 and 2. The paste is thought to build up and slump, with highly variable rise rates as shown at Kidd Mine (Thompson et al., 2009). This is similar to flows of paste and thickened tailings in surface deposition. Higher in the stope, at Cage 5, the rise rate is equivalent to the mean rise rate based on the stope height and time of filling.

Temperatures are plotted against time in Figure 9 for the high and low fill barricade TEPC locations, and at each cage. Peak temperatures are listed in Table 1. Temperatures increase as the cement hydrates. The highest temperature is measured at Cage 4, followed by Cages 1–3 in the undercut. The fill barricade temperatures are significantly lower than measured at the cages, as consistent with being at the boundary of the heating body. The low cement content about Cage 5 is reflected in its lower temperature gradient.

Table 1 Selected parameters from the 685N20 pour

	Height in Stope (m)	1st Motion (hr)	Av Rise Rate (m)	Peak Pressure (kPa)	Peak Pore Pressure (kPa)	Time to Peak Pore Pressure (hr)	Non-Hydro Loading (hr)
Cage 1	1.8	3.4	0.52	116	47	14.1	12.6
Cage 2	2	3.4	0.59	133	54	15.1	18.6
Cage 3	2.4	6.7	0.36	194	83	27.6	14.3
Cage 4	6.4	25.1	0.26	196	90	31.7	13.9
Cage 5	11.4	48.6	0.23	103	92	20.9*	> 20 *
FF1 TPC	1.4	2.9	0.48	46	19	6.8	n/a
FF2 TPC	2.8	7.7	0.37	35	13	9.1	n/a
FF3 TPC	4.2	14.2	0.30	55	6	47.1	n/a

*end pour

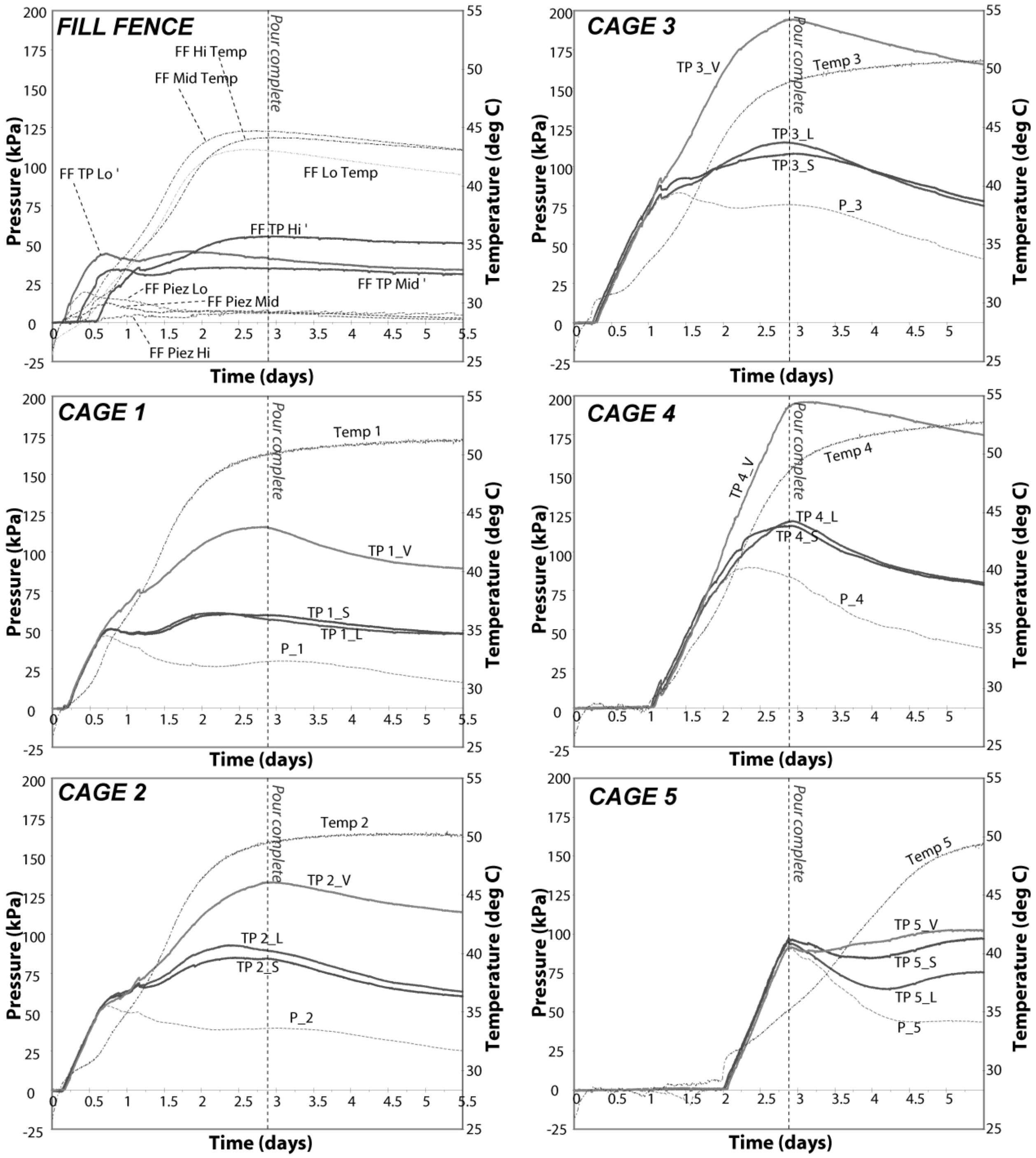

Figure 8 Total earth pressure (TP), pore water pressure (P) and temperature (scale on the secondary axes) measured at the fill barricade, and instrument Cages (1–5). Instrument locations for the fill barricade are shown in Figure 7(c). TEPC measure pressure in vertical (V), and long (L) and short (S) horizontal axes of the stope (Figure 8)

3.3 Long-term pressures

Data was recorded in the test stope until the adjacent stope was mined and access to the cables was lost. The final data are presented in Figure 10, showing total earth pressures, pore pressures and temperature for the instrument cages. For Cages 1–4, pressures decreased from the peak values experienced during backfilling. Pressures on Cage 5 increase slightly on day 16, possibly due to loading of the free surface with waste rock to facilitate later mucking of the stope directly above.

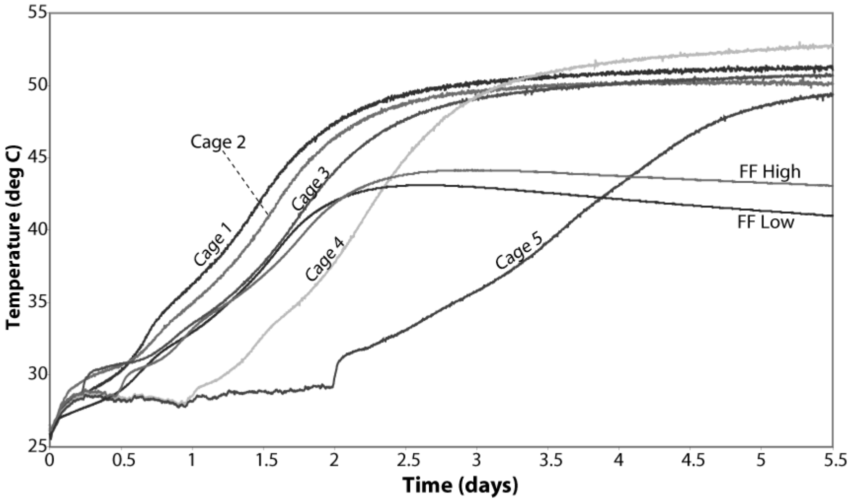

Figure 9 Temperatures plotted for all cages and the high and low barricade locations

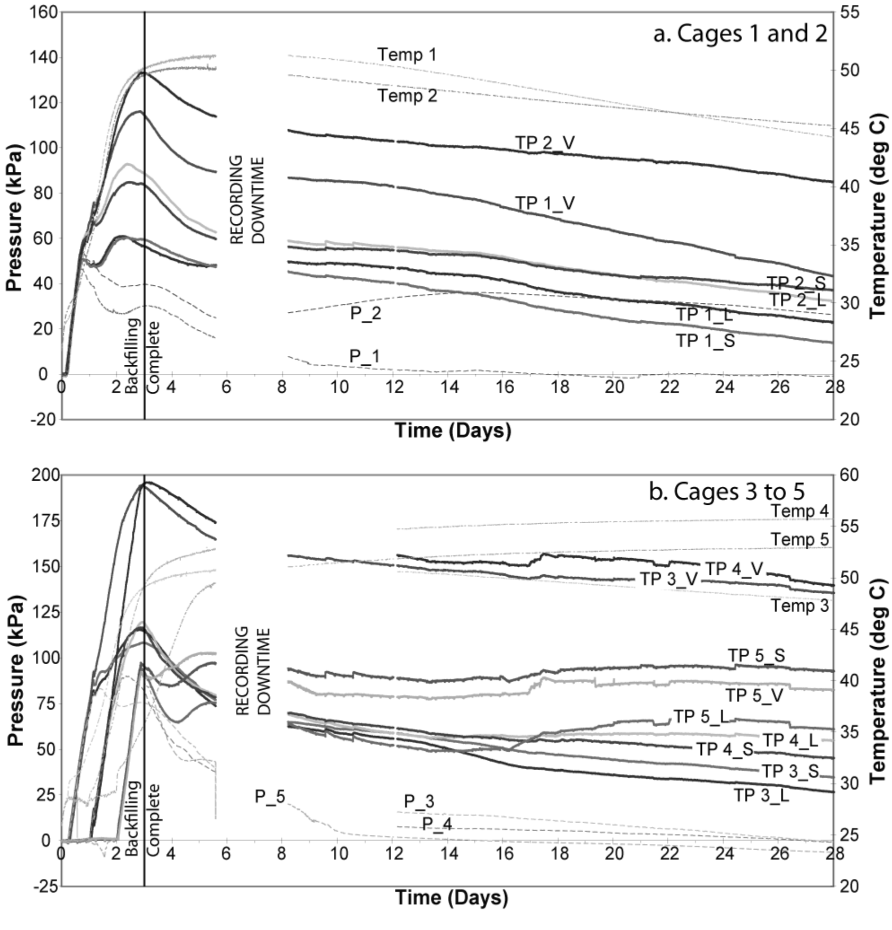

Figure 10 Long-term pressures recorded for Cages 1 and 2 (a) and Cages 3–5 (b)

4 Discussion

4.1 Arching of pressures

In previous fieldwork at Williams and Kidd Mines (Grabinsky et al., 2008; Thompson et al., 2009), total pressures have been demonstrated to decrease from the main stope, with distance into access drifts. Total pressures oriented in the direction of the fill barricade are plotted from the Cayeli test stope in Figure 11, with time starting for each TEPC when CPB 'first arrived' at each location. The horizontal distance from the fill barricade is indicated for each TEPC. At two days, the maximum pressure oriented in the direction of the barricade is 101 kPa. Cages 1 and 2 are separated by 3.5 m, and are approximately equidistant about the stope brow. Horizontal pressure decreases from 90 kPa to 61 kPa over this span. Pressures on the barricade are between 35 kPa and 45 kPa. The ultimate height of CPB above each location is indicated on the figure. The TEPC positioned at 4.2 m on the barricade is not included in this analysis because its elevation is > 1 m higher than the other TEPC considered, and its elevated pressure after two days (54 kPa) is thought due to either: (1) localised loading effects arising from non-uniform stope filling (the delivery of paste was from the overcut, adjacent to Cages 1 and 2, and may have channelled paste toward the fill barricade as the general paste elevation came near the brow of the undercut); or (2) thermal effects, as considered in the following section. This analysis demonstrates that pressures reduce with distance into a drift, but also, the difference between Cages 2 and 3 demonstrates pressures are arched, to a lesser degree, with proximity to the stope walls.

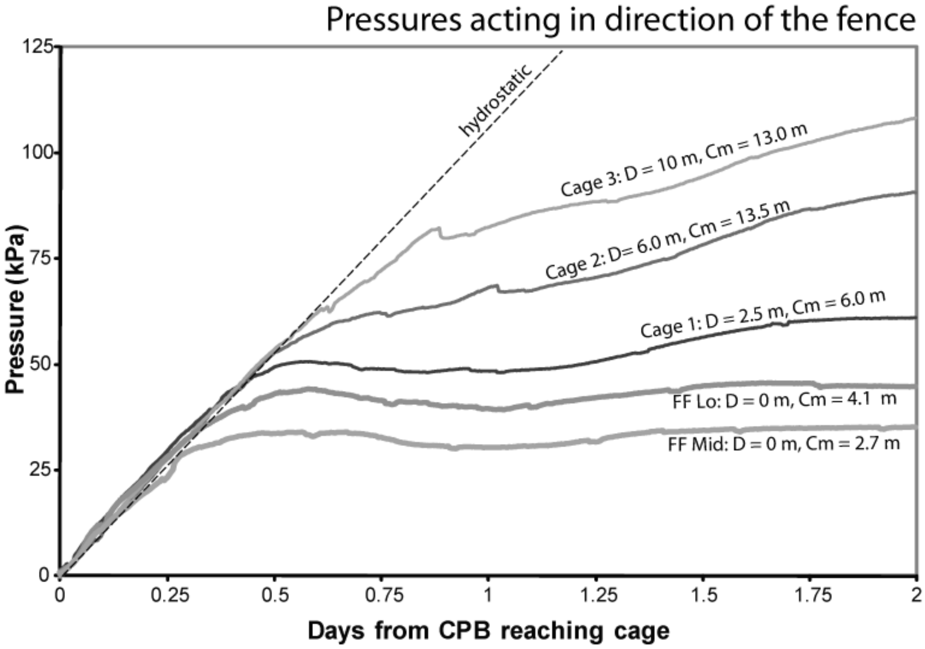

Figure 11 Total earth pressures measured in the long axis of the stope (acting towards the barricade) for Cages 1–3, and fill barricade TEPC at 1.4 m (low) and 2.8 m (mid) height. D is the horizontal distance from the TEPC to the barricade, and Cm is the maximum height of CPB above each TEPC

4.2 Temperature – pressure correlation?

Horizontal total earth pressures measured at Cages 1, 2 (in both the short and long axis of the stope) and the fill barricade exhibit a subtle trend between days 1 and 2.5. Beginning around day one, pressures have either reached a plateau or are decreasing (Figure 8). Subsequently there is an increase and further decrease before the end of the pour at 2.9 days. The relatively rapid pressure gain between days 1.5 and 2 for the above TEPC corresponds with the most rapid temperature gain at these locations. The subsequent reduction in the rate of temperature increase also corresponds with a period of zero, or negative pressure change. Although the data is limited in this case, it is emphasised that a positive correlation has previously been demonstrated at Kidd Mine. In the Kidd fieldwork, pressures were found to increase at rates of up to 28 kPa per degree rise in temperature, during extended periods of downtime in backfilling of a long hole stope (Grabinsky and Thompson, 2009). Thermal expansion was postulated as the mechanism for increasing pressures. Total earth pressure and temperature data from the David Bell Mine in Northern Ontario also indicate a trend of increasing pressure with temperature following the cessation of backfilling of a cut and fill stope. Further work in both the field and laboratory is required to better understand this phenomenon, but as an initial interpretation, increasing temperatures could explain the TEPC data in the undercut observed after 1 day.

4.3 Implications for the Cayeli Mine

We have presented pressure and displacement data for a fill barricade and pressure and temperature data at multiple locations within a stope at the Cayeli Mine. The stope was continuously filled. Its volume was equivalent to a CPB rise rate averaging 23 cm/hr, and backfill was from the non-clastic tailings stream. Maximum pressures measured on the barricade were 55 kPa, which falls within the acceptable standard for barricade pressure currently employed at the mine. Maximum measured barricade displacement was 8 mm, in the centre of the barricade. Ultimately, we have demonstrated that under certain, limited circumstances (i.e. non clastic tails, low rise rate, high binder content), stopes can be continuously poured at Cayeli. It would be desirable to conduct further tests to verify if these low pressures were repeatable. Indeed, the ideal situation at Cayeli would be for barricade pressures to be monitored on a routine basis, with fill barricade pressure (and possibly displacement) data networked to surface. This would enable each stope to be poured to a prescribed pressure limit, with decisions made in real time by engineers and paste technicians. Stringent quality control (QC) for barricade construction is important in identifying potentially problematic barricades.

5 Summary and recommendations

A comprehensive in situ backfilling monitoring program has been completed at the Cayeli Mine. The installation procedure developed during the previous Kidd Mine fieldwork was adapted, and the installation procedure was completely successful. All instruments survived the potentially damaging installation process. Therefore, similar procedures could be followed in other fieldwork situations.

The instruments installed have provided extremely useful data throughout the stope. The TEPC, piezometers, and potentiometers are recommended for further CPB fieldwork. Similarly, their method of installation, either within dog cages (with excess metal removed to allow the easy flow of CPB) or directly attached to fill barricades can be applied in other studies.

It has been shown that the highest total earth pressures induced during backfilling are found, as expected, in the bottom third of the stope, in the vertical orientation. Initially, for the high binder CPB, pressures increased hydrostatically for between 12 and 18 hours. Pressures are reduced close to stope boundaries, and more significantly, under the draw point brow, apparently decreasing with distance into a drift. This suggests the presence of a brow, and the amount a fill barricade is offset from a stope is influential in determining the magnitude of pressures experienced.

It is emphasised that within the same ore body at Cayeli, differences in geochemistry may change the cement hydration rate, and so barricade pressures could differ significantly. That tailing specific recommendations are required at this one site highlights the dangers of applying these field results to other sites without site specific in situ measurements. However, the results presented herein are significant in terms of highlighting areas of potential interest for other operations. Without knowledge of pressures experienced by fill barricades, and their loading capacity, it is difficult to design an efficient backfilling standard procedure. Using the methods summarised here, we provide a framework from which other, site-specific field investigations can be conducted.

Technology exists to enable the routine instrumentation of fill barricades, with pressure (and possibly displacement) data networked to surface, and available in real time. Combined with a better understanding of barricade capacity and stringent barricade construction QC, such data could be used to manage backfilling on a stope by stope basis, with backfilling halted when pressures reached a specific threshold. This would represent a significant improvement for most paste backfilling operations, and would potentially enable improvements in stope cycle time through more efficient pouring strategies, and improved safety through better hazard awareness.

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