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Cemented Paste Backfill Geomechanics at a Narrow-Vein Underhand Cut-and-Fill Mine

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Abstract

Underhand cut-and-fill mining has allowed for the safe extraction of ore in many mines operating in weak rock or highly stressed, rockburst-prone ground conditions. However, the design of safe backfill undercuts is typically based on historical experience at mine operations and on the strength requirements derived from analytical beam equations. In situ measurements in backfill are not commonplace, largely due to challenges associated with instrumenting harsh mining environments. In deep, narrow-vein mines, large deformations and induced stresses fracture the cemented fill, often damaging the instruments and preventing long-term measurements. Hecla Mining Company and the Spokane Mining Research Division of the National Institute for Occupational Safety and Health (NIOSH) have worked collaboratively for several years to better quantify the geomechanics of cemented paste backfill (CPB), thereby improving safety in underhand stopes. A significant focus of this work has been an extensive in situ backfill instrumentation program to monitor long-term stope closure and induced backfill stress. Rugged and durable custom-designed closure meters were developed, allowing measurements to be taken for up to five successive undercuts and measuring closures of more than 50 cm and horizontal fill pressures up to 5.5 MPa. These large stope closures require the stress–strain response of the fill to be considered in design, rather than to rely solely on traditional methods of backfill span design based on intact fill strength. Furthermore, long-term instrument response shows a change in behavior after 13–14% strain, indicating a transition from shear yielding of the intact, cemented material to compaction of the porosity between sand grains, typical of uncemented sand fills. This strain-hardening behavior is important for mine design purposes, particularly for the use of numerical models to simulate regional rock support and stress redistribution. These quantitative measurements help justify long-standing assumptions regarding the role of backfill in ground support and will be useful for other mines operating under similar conditions.

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Keywords

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1 Introduction

Backfill mining methods have enabled the safe extraction of ore in many mines operating in weak rock or rockburst-prone ground conditions. In the Coeur d'Alene mining district of Northern Idaho, cut-and-fill mining methods have historically been used to mine narrow, steeply dipping veins of silver–lead–zinc ore (Blake and Hedley 2003; Williams et al. 2007). Prior to 1986, overhand cut-and-fill mining methods were predominantly used in the district, and highly stressed sill pillars often failed catastrophically as mining progressed upward from level to level (Peppin et al. 2001). To eliminate the formation of these shrinking and thus increasingly stressed sill pillars, an underhand cut-and-fill mining method referred to as the LFUL or Lucky Friday underhand longwall was developed by the Hecla Mining Company in conjunction with the US Bureau of Mines and the University of Idaho (Werner 1990, Brackebusch 1994). With this method, the mining-induced stresses were transferred to a horizon in the host rock beneath the floor of the stope as mining progressed downward, instead of to a diminishing sill pillar. The mined-out stope was then backfilled with cemented mill tailings, creating an engineered back beneath which the miners could safely work on the next undercut advance (Peppin et al. 2001; Williams et al. 2007). At the Lucky Friday Mine, use of cemented paste backfill (CPB)—a high-density mixture of water, classified mill tailings, and cement—in conjunction with mechanized underhand cut-and-fill mining methods has reduced the number of injuries and fatalities caused by mining in deep, high-stress ground conditions, greatly improving the safety of underground miners (Peppin et al. 2001; Pakalnis et al. 2005).

Although the use of backfill in mines has a sound safety record, implementation of a backfilling program is not without risk, requiring technical oversight, particularly in underhand cut-and-fill mines where employees work directly beneath cemented backfill. However, backfill practices at many such mines are still largely based on practical mining experience. One reason for this is that instrumenting cemented backfill in underground mines is often challenging due to large deformations and high stresses which fracture the cemented fill, damaging instruments and preventing long-term measurements.

Hecla Mining Company and the Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health (NIOSH) are working collaboratively to develop a more quantitative understanding of CPB mechanics, thereby improving safety in underhand stopes. This paper discusses underhand cut-and-fill mining with CPB, as currently practiced at the Lucky Friday Mine, and provides the results of a unique instrumentation program, in which stope closures exceeding 50 cm and resulting horizontal backfill stresses up to 5.5 MPa were successfully measured in the cured cemented backfill using rugged, custom-designed closure meters.

1.1 Lucky Friday Mine

The Lucky Friday Mine, owned and operated by Hecla Mining Company since 1958, is located approximately 1.6 km east of Mullan, ID (Fig. 1). Lucky Friday is the oldest and deepest currently operating mine in northern Idaho's Coeur d'Alene mining district. Utilizing underhand cut-and-fill stoping to mine narrow, sub-vertical veins of lead–zinc–silver ore at depths currently around 2300 m below ground surface, the mine produces an average 725 t/day. Recent completion of a new 1140-m winze, the No. 4 Shaft (Sturgis et al. 2017), has extended the mine to just over 2900 m below ground surface, making it the third deepest operating mine in the western hemisphere (Alexander et al. 2018).

1.2 Geology and Stress Conditions

The Lucky Friday Vein was historically the principal ore-bearing structure at the mine until production began in 1997 from several mineralized veins in the Gold Hunter property located about 1500 m northwest of the original Lucky Friday workings. The upper Gold Hunter deposit is hosted in the Wallace formation of the Precambrian Belt Series and transitions into the St. Regis formation below the 5900 level (about 1800 m below the shaft collar). The Wallace formation lithology consists of weak, highly foliated argillite, argillite alternating with silt caps, and siltite. The argillites of the transitional St. Regis formation below the 5900 level have increasing silt and quartzite content with depth.

The Gold Hunter deposit lies between two west–northwest trending faults, which are separated horizontally by about 457 m, and consists of a system of several definable veins striking west–northwest and dipping 80° to 90° south, parallel to foliation. Production is primarily from the 30 vein—a composite of closely spaced veins and veinlets averaging more than 1.2 m wide. A schematic of the current extent of mining in the 30 vein is shown in Fig. 2. The actual depth of cover is roughly 270 m greater than the depth below collar.

Depending on the rock type and bedding orientation, average unconfined compressive strength (UCS) values for the argillite host rock and vein rock range from about 97 to 122 MPa (Seymour et al. 2016). The major in situ stress is horizontal and oriented northwest with a magnitude about 1.5 times the vertical stress (Whyatt et al. 1995). As a result, the stress magnitude is comparable with deep, South African gold operations (Alexander et al. 2018).

2 Underhand Cut-and-Fill Mining

To mine the Gold Hunter deposit, a series of slot drifts are driven perpendicular to the ore body from access ramps on the footwall (north) side of the vein. An undercut stope is mined horizontally in the vein for a distance of about 180–200 m on either side of the slot drift. Five successive underhand cut-and-fill stopes are typically mined from each slot drift as illustrated in Fig. 3.

2.1 Stope Preparation

After an undercut stope is excavated and supported, a layer of broken rock or "prep muck" with a thickness of 0.4–0.6 m is spread on the floor of the stope. No. 7 DYWIDAG® bolts, 1.8 m in length, are driven vertically into the loose muck on roughly a 1.2 × 1.2 m^2 pattern to retain potential slabs that may form as the fill is compressed by wall closure. The bolts are fitted with steel plates and nuts and wired together as shown in Fig. 4.

2.2 Backfilling

Classified mill tailings are mixed with 8–10% binder (25% cement and 75% finely ground, granulated blast furnace slag) at a surface batch plant and gravity-delivered in a paste-like consistency to the stope via an underground pipeline distribution system. To contain the paste backfill during placement, a wooden fill fence is constructed across the width of the stope, limiting the lateral extent of the backfill pour to about 46 m and restricting the height of the pour. The process creates a backfill beam, having a vertical thickness of about 3 m, and leaves a void or gap, approximately 0.3 m in height, between the upper surface of the backfill pour and the bottom surface of the previously filled cut (Fig. 5).

2.3 Undercutting

After the east and west stopes on either side of the slot drift have been backfilled, the paste is allowed to cure and gain sufficient strength. A subsequent undercut stope is then mined in the vein beneath the newly formed backfill beam (Fig. 6). Loose muck that was placed on the floor of the previous cut protects the fill during blasting and falls away from the back as the heading is advanced. To support the CPB back, chain link mesh is installed overhead using the exposed DYWIDAG® bolts and additional friction bolts as needed. Additional rock bolts and mesh are installed to support the stope walls. The CPB, bolts, and mesh thus form a stable back under which mine personnel can safely work (Fig. 7).

3 Backfill Stability Considerations

Safe design of undercut spans requires that engineers ensure the emplaced backfill strength exceeds the strength required to support self-weight and rock mass loads. Required strength is typically determined by a combination of analytical formulae (Mitchell 1991), empirical design (Pakalnis et al. 2005), and numerical modeling. The CPB mix (water content, binder content, tailings gradation, and additives) must achieve desired workability and flow characteristics for distribution and placement but also meet design strength requirements after curing. Due to the grain size of paste (minus 300 μm), laboratory test results on 4-in-diameter test cylinders are typically considered indicative of in-place strength.

Backfill failures in US mines are usually attributed to inadequate backfill strength, insufficient or inconsistent quality control measures, or larger-than-expected mining spans (Seymour et al. 2013). A combination of failure modes—including (1) caving, (2) sliding, (3) flexural, and (4) rotational failure (Mitchell 1991)—must be analyzed during span design, taking into consideration the fill properties, stope geometry, loading conditions, stope closure, support, and other factors resulting from filling practices such as cold joints and gaps between successive lifts (Pakalnis et al. 2005). In the absence of rotational instability and closure stresses, flexural stability has been found to be the most critical failure mechanism (Pakalnis et al. 2005; Stone 1993). The sections that follow discuss the importance of factors influencing CPB stability at the Lucky Friday Mine.

3.1 Backfill Mix Design and Strength

The CPB mix designs used for underhand stopes are provided in Table 1. Paste fill typically contains at least 15% by weight of particles less than 20 microns (Brackebusch 1994; Henderson et al. 2005). The results of a sieve analysis performed on tailings from the mine are provided in Table 2.

Based on past practices, Hecla requires the CPB in their underhand stopes to have a 28-day UCS of about 2.75 MPa. However, unpublished results indicate that the average UCS of CPB samples collected at the batch plant is typically around 3.4 MPa or higher, and that higher in-place strengths are also measured from CPB samples collected through underground coring. These results are also supported by additional tests with CPB samples obtained by coring large backfill slabs brought to the surface (Johnson et al. 2015). Brazilian and splitting tensile strength tests with CPB samples have shown that the indirect tensile strength of the paste fill is normally about 10% of its UCS (Johnson et al. 2015). In addition, the in-place density of the CPB is about 2050 kg/m^3 with a porosity ranging from 35% to 40%.

As explained by Stone et al. (2019), there are currently no established standards for preparing and testing cemented backfill samples. As a result, standards for other materials such as concrete or rock core are loosely adapted for use with CPB, a much softer material. The CPB sample preparation methods and testing procedures, which were used for the unconfined compression and indirect tensile tests mentioned above, roughly followed guidelines developed for concrete or rock core by the American Society of Testing and Materials (ASTM) and the American Concrete Institute (ACI).

3.2 Rotational, Sliding, and Caving Stability

Rotational failure is not kinematically possible in vertical or near-vertical stopes and therefore does not need to be considered at the Lucky Friday Mine. Sliding failure is kinematically possible but has never occurred at the mine. Considering the Mitchell equation for sliding stability (Eq. 1) demonstrates why this is the case.

$$(\sigma_v + d \times \gamma) > 2\left(\frac{\tau_f}{\sin^2(\beta)}\right)\left(\frac{d}{L}\right), \quad (1)$$

where σ_v is the vertical stress from loading above the sill, d is the thickness of the sill, γ is the unit weight of the paste fill, τ_f is the shear strength of fill/rock contact, β is the stope dip angle, and L is the span of the stope.

Assuming rough stope walls, sliding failure would require mobilization of the paste shear strength. Conservatively assuming that the shear strength of the contacts is due only to cohesion and neglecting normal stress yields factors of safety well in excess of 100 for typical stope geometries and backfill UCS as low as 1.37 MPa (tensile strength is assumed to be 10% of UCS). Any horizontal pressure induced on the fill from stope closure would further increase sliding resistance.

Likewise, caving stability—a function of fill tensile strength and span width—is also not of concern. The Mitchell equation that governs the caving stability of the fill is provided by (Eq. 2):

$$L \times \gamma > 8\frac{\sigma_t}{\pi}, \tag{2}$$

where σ_t is the tensile strength of the paste fill.

For typical stope widths of 3–4.5 m, assuming a tensile strength equal to 10% of UCS results in safety factors well in excess of 20, even for a low strength fill of 1.37 MPa.

3.3 Flexural Stability

Flexural stability is of primary concern in slot intersections during the period prior to any significant undercutting of the previous backfilled stope. This is because the slot intersection is typically the widest open span (up to 6 m diagonally), with initially little closure occurring before mining the cut (Fig. 8).

The Mitchell flexural stability equation can be used to calculate factors of safety for paste fill beams (Eq. 3):

$$\left(\frac{L}{d}\right)^2 > \frac{2(\sigma_t + \sigma_c)}{\sigma_v + d \times \gamma}, \tag{3}$$

where σ_c is the horizontal confinement stress.

Figure 9 presents the results of a parametric stability analysis using Eq. 3, assuming self-weight loading of the CPB beam, a tensile strength of 10% UCS, and neglecting the impact of wall closure, which initially tends to confine the fill and improve its flexural stability. Thickness is the primary factor that determines the flexural stability of a backfill beam for these limited mining spans. As a result, the stability is significantly impacted by any factor that tends to reduce the effective thickness of the beam, such as cold-jointing.

3.4 Fill Placement and Quality Control Measures

The quality control of the fill placement process is therefore vitally important for ensuring design strength and preventing cold joint formation. Stacking and surging of the paste fill can occur near the outlet of the paste pipeline while filling the stope, causing the backfill to be deposited in a discontinuous or intermittent manner. This results in horizontal layering and cold jointing within the overall mass of the paste fill pour. Stacking and surging problems were observed at the Lucky Friday Mine as mining progressed beyond the 5900 level (1800 m below shaft collar) and were attributed to premature hydration of the cement binder, resulting from very long pipeline transport distances. As mining depth increases, the temperature in the rock and underground workings also increases. These higher temperatures, in addition to the frictional heating in the long distribution pipelines, may result in acceleration of the cement hydration process, increasing the paste viscosity and thus, degrading workability and flow characteristics. The mine now uses a binder consisting of 25% cement and 75% finely ground, granulated blast furnace slag to prevent stacking and surging. The slag has been effective in retarding the hydration process, allowing the workability of the mix to be maintained throughout a pour.

Control measures, including monitoring and control of the moisture content of the tailings, schedules for calibrating scales and meters in the batch plant, procedures for sampling and testing the strength of the paste, field tests and procedures for validating flow characteristics and detecting cold joints, training and certification of batch plant operators, and instructions for documenting, recording, and reporting backfill-related information, are also critical for maintaining good quality control of the final placed product.

3.5 Closure Stresses

A unique challenge to underhand cut-and-fill mining at Lucky Friday Mine is dealing with horizontal stress induced in the CPB as a result of stope wall closure. During undercutting, the stope walls converge in response to the high horizontal ground stresses and compress the CPB. These horizontal loads cause crushing and extensional fracturing near the fill surface as shown in Fig. 10.

Results of coring have found that these fractures are primarily horizontal and occur typically within 0.3 m or less of the surface of the beam (Fig. 11). While the bolts and chain link mesh contain spalling on the underside of the beam where personnel are working, the upper surface of the paste fill is unconfined and deforms into the gap above (Fig. 12). The closures encountered in the mine typically exceed the elastic limit of the fill. Therefore, a very brittle fill should be avoided, and a more ductile fill with significant residual strength is desired.

As the underhand mining front continues to advance deeper, the cemented backfill is subjected to further horizontal closure with each additional undercut. This closure eventually compresses the fill. After substantial hanging wall-to-footwall closure, the backfill will, in theory, behave as a compacting material and begin to strain-harden, gaining stiffness as it is compacted and its void spaces and fractures are compressed. The number of undercuts required to initiate this strain-hardening process will depend on the porosity of the fill and confinement.

4 Geotechnical Instrumentation

A systematic instrumentation approach was developed using robust and reliable instruments to quantify the stability and geomechanics of the CPB in response to stope closure. The instrument design is based on previous research by Williams et al. (1992) and Williams et al. (2001), but the approach has been significantly revised to improve the operation and longevity of the instruments and to provide reliable measurements of stope closure and fill pressure to the mine staff on a nearly real-time basis. The progression in the design of these instruments is explained in further detail by Seymour et al. (2017).

4.1 Closure Meter Design

Custom-designed closure meters were built to measure hanging wall-to-footwall convergence in the backfilled stopes (Fig. 13). The closure meters are installed in the stope prior to backfilling and encapsulated during the paste pour. The body of the closure meter consists of telescoping sections of steel pipe and tubing attached to steel end plates, which are bolted to the stope walls. Linear position transducers are mounted internally in the closure meter to measure displacement as the stope walls converge. Pressure cells mounted on steel anchor plates measure the horizontal change in stress in the CPB.

Two types of closure meters were fabricated and installed: single-acting closure meters with one position transducer for measuring displacement across the full length of the instrument (hanging wall-to-footwall closure) and double-acting closure meters equipped with a second position transducer that is used for measuring displacement to a center plate located at the mid-span of the instrument (measuring closure from the hanging wall to the mid-span of the stope).

4.2 Transducers

UniMeasure® HX-P510 linear position transducers were chosen to measure stope closure. The position transducer consists of a rotary potentiometer that is encased within an environmentally sealed, waterproof housing. The rotary potentiometer measures a voltage output as a stainless steel wire cable is extended or retracted from the housing. These voltage measurements are in turn converted to displacement units to reflect a change in position of the cable. The selected model has a resolution of ± 0.01% and a measurement range of 63.5 cm.

Backfill horizontal stress is measured using pressure cells mounted directly to the closure meter's steel anchor plates (Fig. 14). Geokon Model 4810 contact pressure cells with a measurement range of 0–7.5 MPa were selected. This type of earth pressure cell is specifically designed to measure soil pressures exerted on a structure.

This instrument consists of two circular stainless steel plates that are welded together around their edges, forming a narrow cavity which is filled with hydraulic oil. A thick back plate protects the instrument and mounts directly to the structure. A thin front plate is welded to the back plate, forming a flexible hinge for increased sensitivity to pressure changes. Pressure applied to the cell induces an equal pressure on the internal hydraulic fluid that is, in turn, sensed by a vibrating wire transducer connected to the cavity between the two plates by high-pressure stainless steel tubing. A measurement of the change in the frequency of the vibrating wire is converted to pressure using a calibrated gage factor supplied by the manufacturer. The pressure cell is also equipped with a thermistor to help account for the influence of changes in temperature on the instrument's readings.

4.3 Cables

Although current data acquisition system (DAS) designs use the mine's leaky feeder radio for data backhaul to the surface, the instruments themselves must still be wired to the dataloggers. Depending on the distance into the stope, and the location of the datalogger station, 60–180 m of trunk line must be connected to the instruments, hung through the stope and slot to the datalogger, and protected to minimize the potential for damage when mining the undercut.

To protect the transducer signal from electrical noise, each pair of lead wires in the instrument cable is wrapped in Mylar tape with an aluminum foil shield. A bare copper wire is routed with each pair of lead wires to drain any induced currents to ground. Direct burial cables with thick polyurethane jackets are used to protect the encased wires. For additional protection, the instrument cables are either: (1) placed in a flexible, plastic split-tube hose and hung from the back to prevent fill encapsulation or (2) run through polyurethane DriscoPipe®, a product used by the mine for CPB distribution, and hung on the rib.

4.4 Data Acquisition

The closure meters and pressure cells are monitored every 2 h by Campbell Scientific dataloggers located at substations in nearby slot drifts. A typical datalogger station consists of the following components: CR1000 datalogger, AVW200 vibrating-wire analyzer, AM16/32B multiplexers, and various communication interfaces, depending on the specific link to the mine's communication system—either a fiber optic cable or a leaky feeder radio. Both of these systems are linked to a computer server at the surface.

The DAS can be accessed remotely, and the instrument data can be viewed on Hecla's corporate intranet website by mine management and NIOSH researchers on an almost real-time basis. This allows the mine staff to use the instrument data for daily operational decisions or safety concerns and for remote monitoring for maintenance and timely repairs.

5. Instrument Placement

To date, closure meters and pressure cells have been installed, prior to backfilling, at 11 monitoring locations in three 30-vein production stopes: the 5550 level (1690 m below shaft collar), 11 stope immediately above the west side of the large sill pillar shown in Fig. 2; the 6350 level (1935 m below shaft collar), 15 stope; and the 6350 level (1935 m below shaft collar), 12 stope located on deeper mining horizons beneath the sill pillar. The 11-stope and 15-stope instruments are the main focus of this paper as the 12-stope instruments were installed recently and are just starting to be undercut.

The 11-stope instruments were installed in September and October of 2014. To avoid interfering with the production crews, the 11-stope instruments were installed after the fifth and final cut had been mined from the slot drift. The 15-stope instruments were installed in March of 2016. Modifications to the instruments and their installation procedures allowed the 15-stope instruments to be installed during the second cut, while production crews were preparing the stope for backfilling. As shown in Figs. 15 and 16, closure meters (CM) and pressure cells (PC) were installed at four separate locations in each stope. Stope width at the measurement sites varied from 2.73 to 4.11 m, but averaged about 3.4 m.

6 Instrument Results

6.1 Stope Closure

Figure 17 shows typical measured closures from one of the monitoring sites. The approximate undercut start times are indicated on the figure by vertical dashed lines. With each undercut mining advance, the full-span closure meters generally measured a consistent increase in stope closure, averaging about 7.6 cm. The half-span closure meter measurements were a fraction of the total closure, but varied from site to site. Most of the stepped increase in closure occurred as underhand mining advanced directly below the locations of the instruments. The specific cause of the signal interruption in the half-span closure measurements shown in Fig. 17 has not been conclusively identified.

In 11 stope, a total of five undercut advances were monitored over a period of about 2 years. Measurements collected from all 11-stope backfill instruments from September 18, 2014 through September 7, 2016 are shown in Table 3, grouped by the monitoring locations noted in Fig. 15. Cuts for which data are not entered indicate that the instruments were not providing reliable measurements at the time of that undercut.

Two instruments (CM 1-L, CM 3-S) stopped working shortly after the first undercut. CM 2-L began providing reliable results again during Cut 4. Moisture intrusion may be the cause of this intermittent behavior. Three instruments (CM 2-S, CM 3-L, CM 4-L) provided continuous readings through all five cuts. Total measured stope closure ranged from 40 to 50 cm during this period.

Measurements recorded from the 15-stope backfill instruments from March 18, 2016 to March 13, 2017 are provided in Table 4, grouped by the monitoring locations shown in Fig. 16. After almost 6 months and three undercut advances, all of the instruments installed in the 15 stope were continuing to function, except CM 5-S and CM 7-S. Five closure meters (CM 5-S, CM 5-L, CM 6-L, CM 7-L, CM 8-L) were able to monitor through Cut 4. Three instruments (CM 5-S, CM 5-L, CM 8-L) were functioning after Cut 5, measuring as much as 33 cm of closure.

6.2 Horizontal Backfill Pressure

Figure 18 shows a typical example of the horizontal backfill pressures measured at one of the closure meter sites. As the first undercut heading is driven beneath the locations of the instruments, the horizontal pressure in the CPB increases rapidly. Loading of the CPB beyond its intact compressive strength occurs shortly thereafter, as depicted by the peaks in the pressure measurements during the first undercut. Average residual pressures of 1–2 MPa indicate, however, that the fill remains stable over several undercuts.

In 11 stope (Table 5), the maximum horizontal pressure measured during the first undercut ranged from 1.59 to 5.40 MPa and averaged about 3 MPa for the ten pressure cells, exceeding the 28-day target strength of 2.75 MPa. Fill pressure varied depending on the monitoring location in the stope and the specific placement of the pressure cells. The largest fill pressures were generally measured at the midspan (center) of the stope rather than at the hanging wall (south) or footwall (north), with a few exceptions.

Cemented paste backfill pressure measurements in 15 stope (Table 6) were similar to those of 11 stope, with maximum horizontal pressure measured during the first undercut ranging from 1.85 to 5.47 MPa and also averaging about 3 MPa for the 12 pressure cells. Design changes for the 15-stope closure meters provided better protection for the instruments and their lead wires, significantly improving the longevity of the instruments, especially the pressure cells.

Similar to a uniaxial or unconfined compression test, the maximum fill pressure appears to occur at the mid-span of the stope. Although the precise type of yielding and its initial location within the stope is unknown, the yield mechanism is likely a combination of tension and shear that is affected by stope geometry, local geology, and the presence of any lower strength zones within the fill.

6.3 Backfill Temperature

While the 11-stope instruments were initially read manually for several months, the 15-stope instruments were monitored continuously with a datalogger before, during, and after the pour. This allowed determination of the effects of stope filling and paste curing on the readings.

Temperature changes can significantly affect pressure cell measurements in cemented backfill (Tesarik et al. 2006). As paste is poured and begins to cure, its temperature rises due to hydration of the curing cement. This increase in temperature causes the pressure cells to give a false indication of initial applied stress increase. Although the instrument is supplied with a temperature correction, this correction is for the vibrating-wire sensor itself, not the pressure cell bladder and contained oil.

The maximum fill temperature recorded during curing averaged about 49 °C ranging from 41 to 57 °C. Figure 19 shows a typical response of a pressure cell before, during, and after a pour. Once the stope is filled and the CPB begins to cure, a rapid increase in temperature is observed, which then levels off. This rise in temperature is accompanied by an apparent rise in pressure of about 0.2 MPa. After the temperature levels off, pressure changes can be attributed solely to stope closure. The temperature effect is negligible for long-term monitoring because the backfill temperature stabilizes, and the in-place CPB is usually subjected to pressures well in excess of the temperature response.

6.4 In Situ Stress–Strain Response

To further interpret the geomechanical response of the CPB to mining, in situ stress versus strain was plotted using the closure and fill pressure measurements. Many 11-stope instruments stopped functioning after the second undercut, making it difficult to construct stress–strain curves for each closure meter. Therefore, stress–strain curves were created for the east and west sides using measurements averaged from the instruments that were still functioning. The results are shown in Fig. 20.

The longevity of the 15-stope instruments allowed the in situ stress–strain behavior of the CPB to be constructed for each of the four 15-stope monitoring sites. Horizontal stress in the paste fill was calculated by averaging the pressure measurements obtained from the three pressure cells at each site, while horizontal strain was computed using the total stope closure data at each site. The 15-stope stress–strain results are shown in Fig. 21.

The 11-stope and 15-stope data show that peak strength occurs between 0.5 and 1% strain, consistent with laboratory testing of the paste fill. For a typical stope width of 3.4 m, this represents only about 2.5 cm of closure.

6.4.1 In Situ Modulus—While the 11-stope instruments were initially read manually on a weekly basis before the DAS could be set up, the 15-stope instruments were connected to the DAS immediately. Therefore, the elastic response of the CPB to undercut mining is clearly indicated by the initial rapid increase in stress with very small strains.

Using the 15-stope data, an average in situ modulus was determined for each of the four closure meter sites by analyzing the slope of the stress–strain response over a stress range of 30–60% of the average peak strength achieved during the first undercut. The resulting values are shown in Table 7.

The average in situ tangent modulus, 3.2 GPa, is comparable to in situ tangent modulus values reported by Williams et al. (2001) for CPB used in the old Lucky Friday Vein workings, which ranged from 0.68 to 5.09 GPa and averaged about 2.41 GPa with an average in situ ultimate strength of 2.8 MPa.

UCS tests were also performed with a series of 10.2-cm-diameter cast CPB cylinders after 28 days of curing. The mix designs for these test cylinders used typical mill tailings from the backfill plant and varied only in binder content and binder blend. A strong relationship was found between their compressive strength and tangent modulus. The in situ results from Table 7 are plotted with the laboratory data in Fig. 22 and show that the in situ properties compare quite well with the laboratory results.

The average in situ modulus value is also comparable to the Young's modulus of 2.28 GPa, which was reported by Johnson et al. (2015) for unconfined compression tests on strain-gauged 7.6-cm-diameter cored cylinders of CPB with an average UCS of 4.1 MPa. Although this testing was performed on CPB of a slightly older mix design, the only significant difference was in binder blend (100% portland cement instead of the cement–slag blend that is currently used), not tailings or binder content. Comparison of the in situ and laboratory strengths and moduli supports the commonly held assumption that CPB properties are not significantly different for design and analysis purposes whether they are determined from laboratory specimens, in situ samples, or in situ measurements.

6.4.2 Long-Term Strain Hardening—During the fifth undercut, the backfill in the 11 stope began a pronounced change in behavior with local strain hardening (a prominent, consistent, positive increase in the slope of the stress–strain curve) occurring between 13 and 14% strain. This response is significant because it occurred at multiple instrument locations separated by as much as 65 m, indicating that the backfill, which had been exhibiting behavior associated with a traditional shear yielding mechanism accompanied by a loss of confinement, transitioned to a compaction-hardening response. This type of stress–strain response is typical of uncemented sand fills (Piper et al. 1993; Gürtunca et al. 1993) and broken materials (Papas and Mark 1993). It is also consistent with descriptions of the fill, as having the air "sucked out" of it, provided by experienced miners who have excavated through decades-old backfilled areas. This strain-hardening response has never been measured at the Lucky Friday Mine and is explained in further detail by Seymour et al. (2017). This CPB response is significant, because it gives an indication of when the fill may start compacting and taking load, which has important implications for regional ground support. The initial stiffness measured for this compaction-hardening response ranges from 41 to 115 MPa.

On the other hand, the 15-stope data show that the strain levels (7–8%) in the backfill after the fifth undercut are generally not yet high enough for compaction hardening to occur. Although no additional mining in the 15 stope has occurred, two functioning pressure cells in 15-stope east are showing a steady increase in loading with time (0.08–0.15 MPa/month). This may indicate that a strain-hardening behavior is occurring more than a year after the fifth undercut was completed. However, the amount of strain cannot be determined because the closure meter's displacement transducers are no longer operational. A sustained pressure increase has not yet been measured by the remaining pressure cells in 15-stope west at this time.

While the slope of the strain–strain curve for CM 7 shows a steady positive increase after about 3% strain, this response is certainly not representative of the other 15-stope closure meter stations (Fig. 21). The response of CM 7 may indicate that the measured strain-hardening behavior is a local phenomenon. However, in contrast, both of the stress-strain curves for the 11-stope instruments show a pronounced change from strain-softening behavior to strain-hardening behavior at similar levels of strain. For these mining conditions, strain-hardening behavior is difficult to measure, because the instruments must continue to function over a long period of time and through several undercut mining advances. As a result, these unique custom-designed instruments have provided unique long-term measurements of stope closure and fill pressure, and the conclusions obtained from an analysis of this instrumentation data have improved our understanding of CPB geomechanics in these conditions.

7 Conclusions

The instrumentation approach developed by NIOSH, in cooperation with the Hecla Mining Company, has been successful in monitoring stope closure and the stability of CPB through multiple undercuts at the Lucky Friday Mine. Stope closures exceeding 50 cm and horizontal backfill pressures of nearly 5.5 MPa were recorded over five undercut advances. This is significant because the large deformations associated with this mining method and the generally harsh environmental conditions have historically posed significant challenges to making such measurements. The information obtained from this study is not only useful for mine design at the Lucky Friday Mine but also helps justify long-standing assumptions regarding the role of backfill in ground support.

The measurements show that hanging wall-to-footwall closures of about 7.6 cm, on average, occur with each successive undercut. Depending on excavation dimensions, this represents a strain of about 1.5–2.5%. Maximum horizontal fill pressures during the initial undercut advance average about 3 MPa. This exceeds the design UCS requirement of 2.75 MPa.

However, a residual strength of 1–2 MPa is maintained over several undercuts, allowing the fill to remain stable even though stope closure exceeds the CPB elastic strain limit. This means that traditional methods of backfill span design, which rely solely on intact fill strength to satisfy limit equilibrium stability equations, are insufficient in deep underhand cut-and-fill mines. A very strong fill is likely to be too brittle to remain stable when stope closures exceed the fill's elastic limit. Therefore, the stress–strain response of the fill, over several percent strain, must be considered.

Both the in situ strength and in situ tangent modulus are comparable to properties derived from laboratory tests on CPB samples. This provides confirmation that CPB properties determined by laboratory-scale tests are representative of in situ properties and can therefore be safely used in mine design.

Significantly, the CPB stress–strain curve shows a marked change in response after roughly 13–14% strain. This indicates that the backfill is transitioning to a compaction-hardening behavior, typical of uncemented sand fills and broken materials, rather than behaving as an intact cemented material failing in shear. Although only the start of this compaction-hardening response was measured, this result is important because it has significant implications for longterm regional rock support and stress redistribution.

To ensure continued safe and productive operation as mining progresses deeper, Hecla is currently revising the mining method used at the Lucky Friday Mine and is transitioning to tele-remote continuous mechanical excavation. Trial operation of a new mechanical excavator, the Hecla Mobile Miner, is planned to begin by early 2020 (Alexander et al. 2018). Backfilling with cemented paste will continue to play a vital geomechanical role in the new underhand method, and the data from this study will provide important quantitative results for future changes in mine design.

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Disclaimer The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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Fig. 1.

Map showing the location of the Lucky Friday Mine in the Northern Idaho Panhandle near the Montana state line

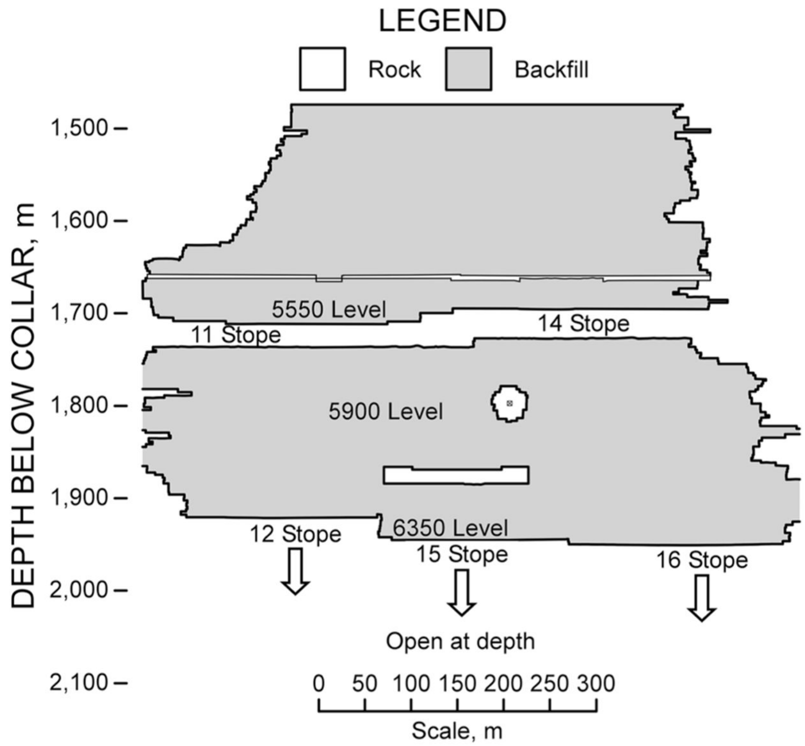

Fig. 2.

Simplified long-section of mining in the 30 vein of the Gold Hunter deposit, view direction is due north, shaft collar elevation is approximately 1035 m above mean sea level (AMSL), actual depth of cover is roughly 270 m greater than depth below shaft collar

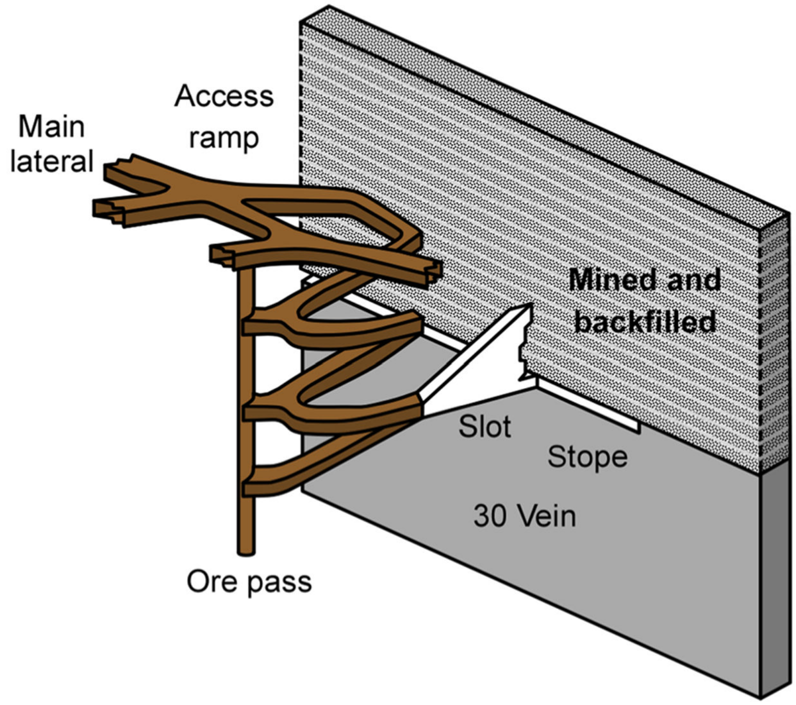

Fig. 3.

Conceptual diagram of the underhand cut-and-fill mining method practice at the Lucky Friday Mine

Fig. 4.
Preparing the 5550 level (1690 m below shaft collar), 11-stope east for backfilling

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Fig. 5.

Photograph in the 6350 level (1935 m below shaft collar), 12-stope east showing fill fence and 0.3-m gap between consecutive backfilled levels

Fig. 6.
Photograph in 6350 level (1935 m below shaft collar), 32 slot showing current cut and remaining fill fences from the two backfilled cuts above

Fig. 7.
Photograph in 6350 level (1935 m below shaft collar), 12-stope east showing reinforced CPB back

Fig. 8.

Photograph in 6350 level (1935 m below shaft collar), 32-slot intersection looking toward 12-stope east and showing difference in span width for intersection and undercut stope

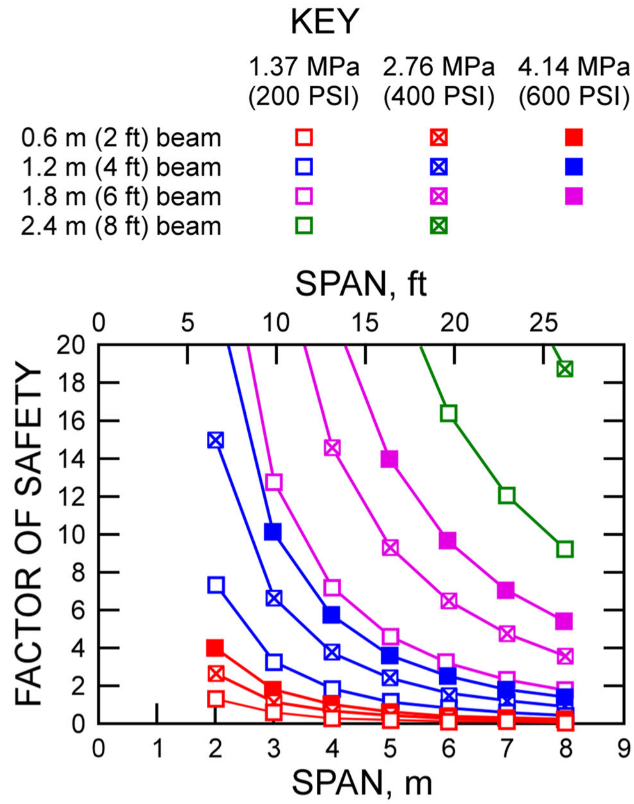

Fig. 9.

Factor of safety for flexural failure versus span width for paste backfill beams with varying thicknesses and compressive strengths

Fig. 10.
Surface extensional fracturing due to horizontal closure in a back composed of CPB

Fig. 11.

Breaks observed in backfill core are primarily due to drilling-related effects with the exception of the fractures at the collar

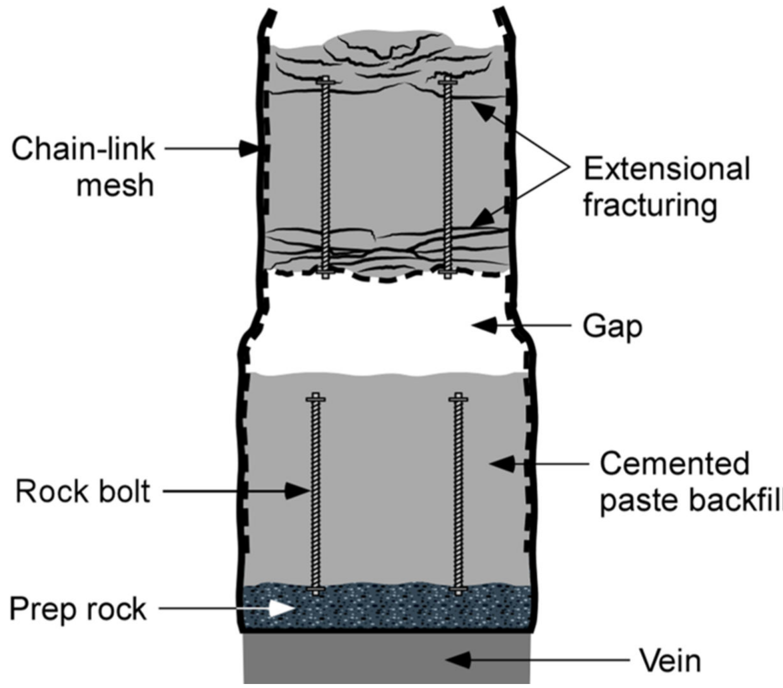

Fig. 12.

Conceptual vertical cross section illustrating the progression of horizontal closure as backfill is undercut

Fig. 13.
Typical backfill instrumentation setup used to monitor stope wall convergence and horizontal fill pressure

Fig. 14.
Contact pressure cell (manufactured by Geokon, Inc.) mounted on a closure meter anchor plate

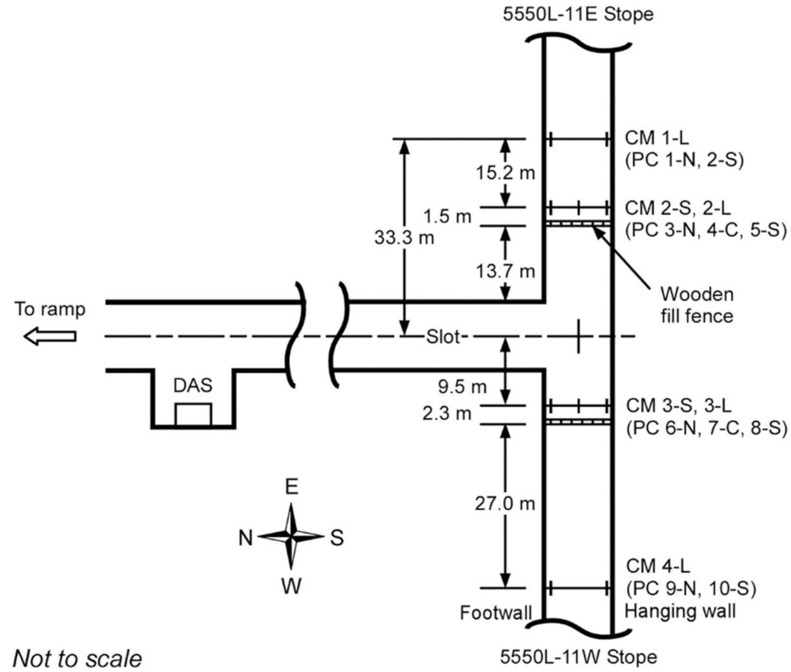

Fig. 15.

Plan view of 5550 level (1690 m below shaft collar), 11-stope backfill instrumentation sites (L denotes a full-span closure meter, and S denotes a half-span closure meter)

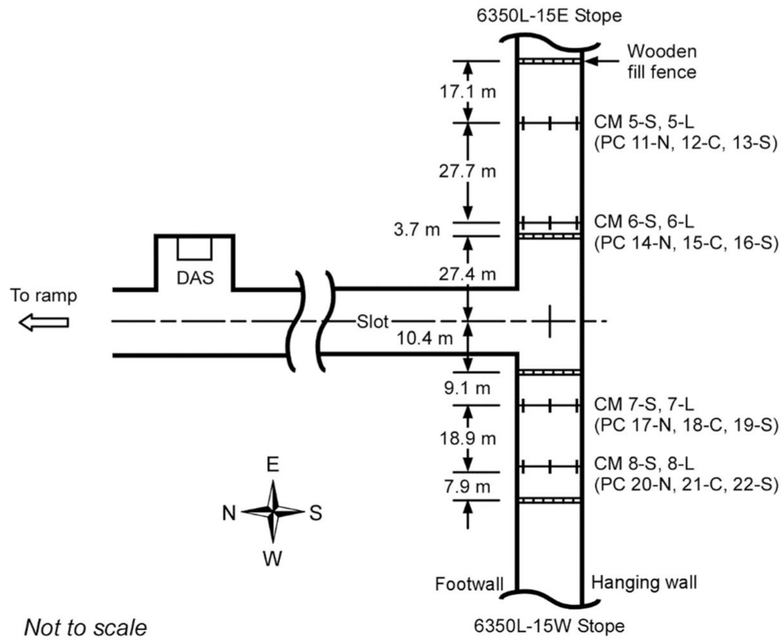

Fig. 16.

Plan view of 6350 level (1935 m below shaft collar), 15-stope backfill instrumentation sites (L denotes a full-span closure meter, and S denotes a half-span closure meter)

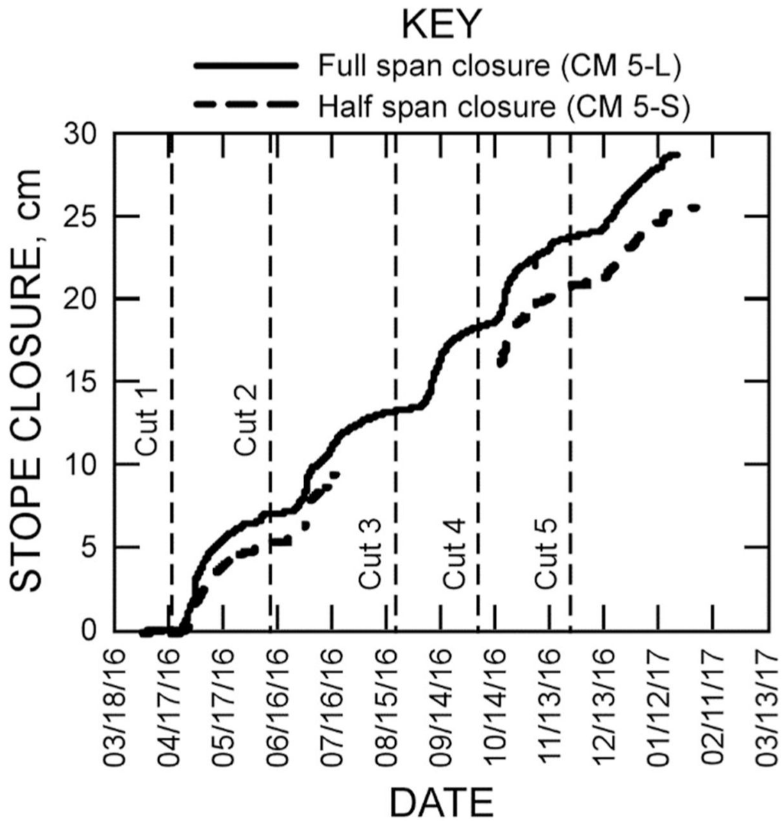

Fig. 17.
Stope closure measurements from CM 5-L and CM 5-S in 6350 level, 15-stope east

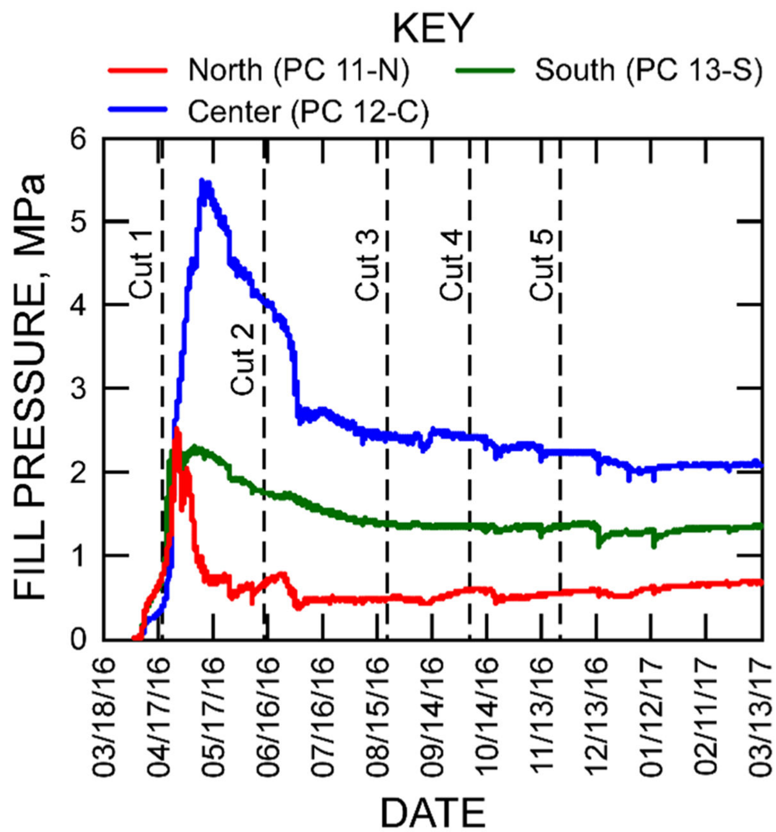

Fig. 18.

Horizontal backfill pressure measurements from CM 5 monitoring site in 6350 level, 15-stope east

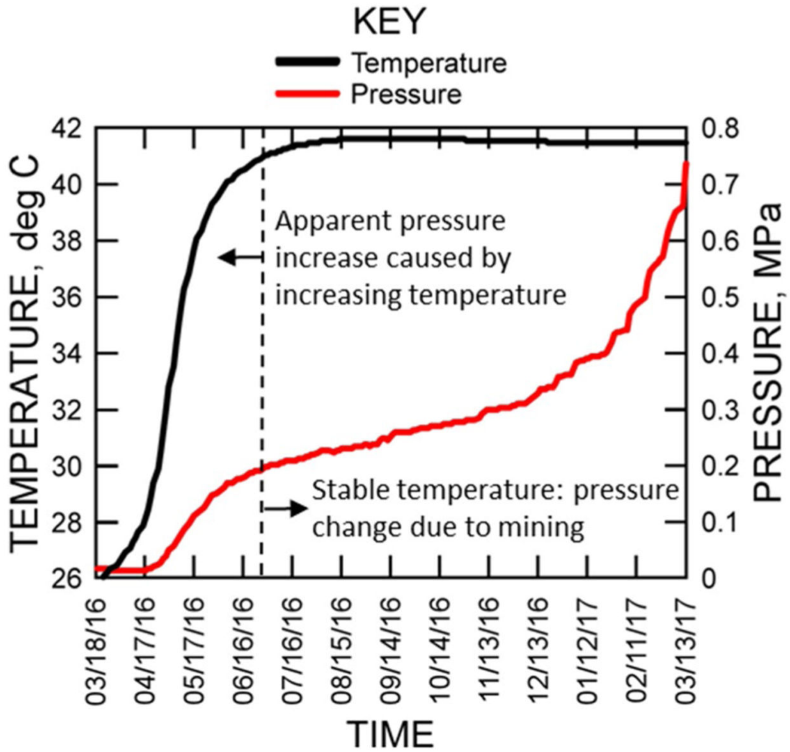

Fig. 19.

Temperature and pressure data from PC 12-C during and after the paste pour

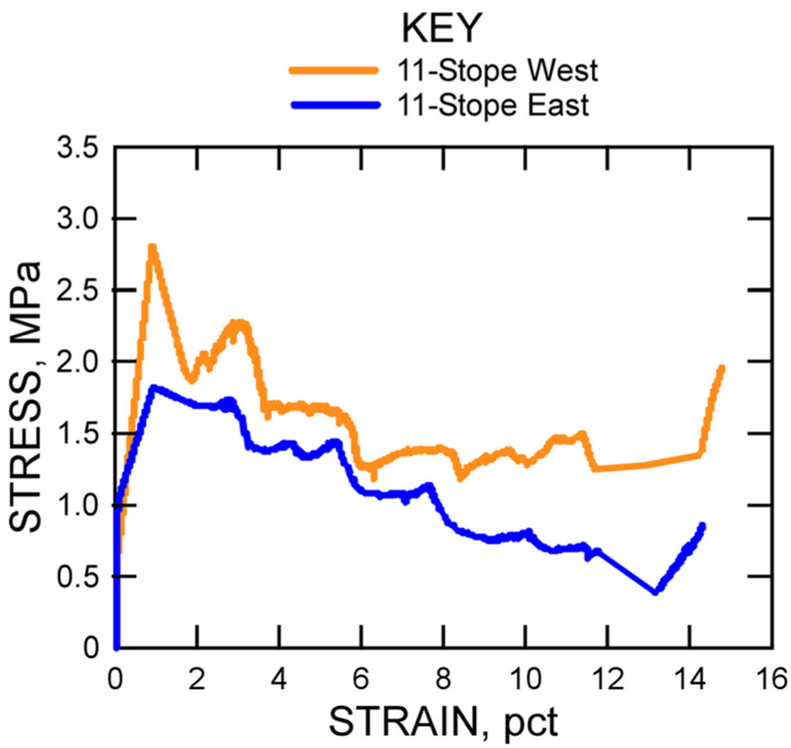

Fig. 20.

In situ backfill stress versus strain, 5550 level (1690 m below shaft collar), 11 stope

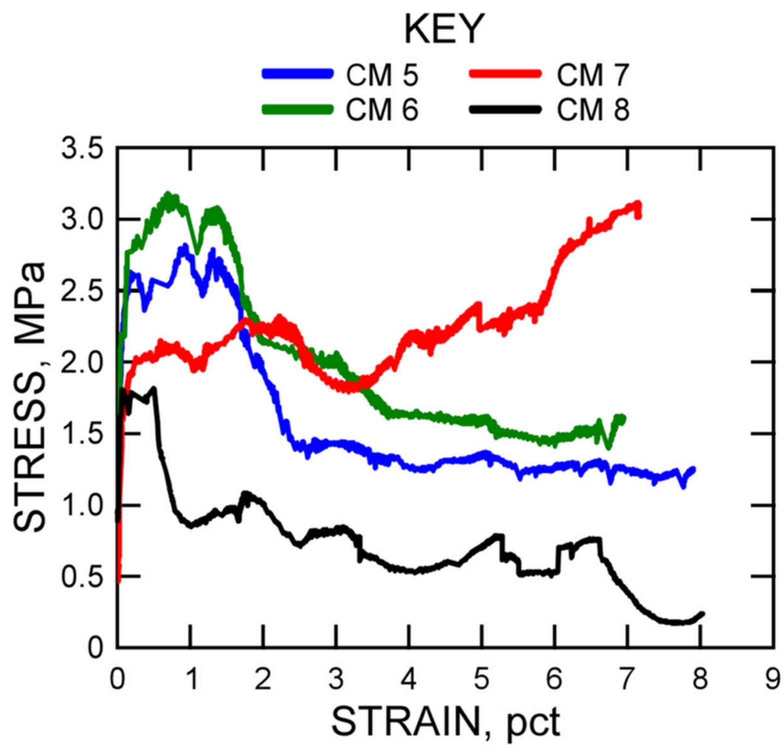

Fig. 21.
In situ backfill stress versus strain, 6350 level (1935 m below shaft collar), 15 stope

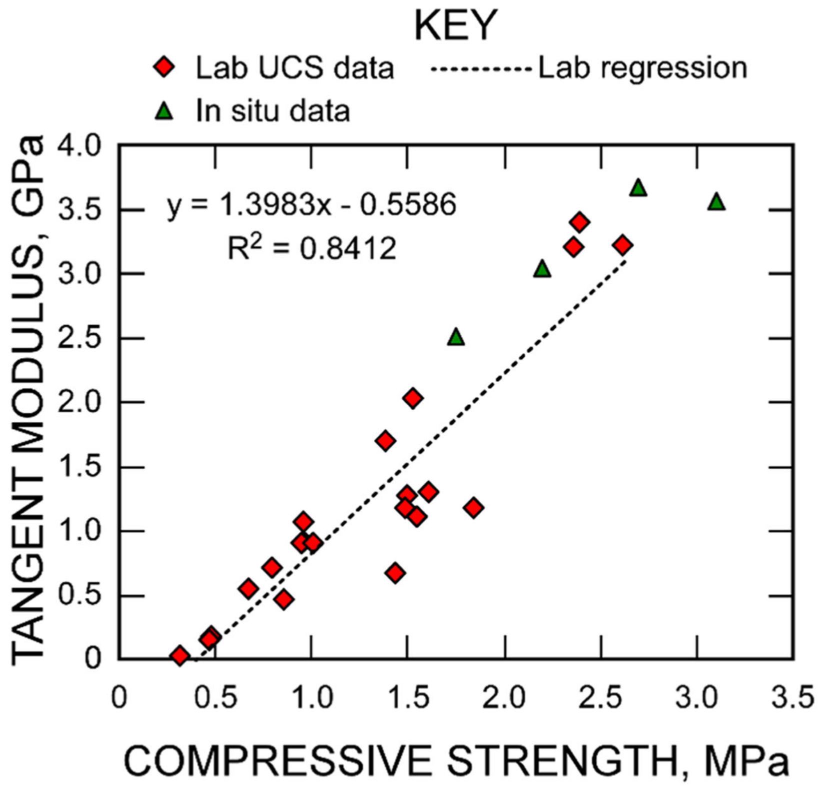

Fig. 22.

Comparison of laboratory and in situ paste backfill compressive strength and tangent moduli

Table 1

Typical cemented paste backfill mix designs used at the Lucky Friday Mine

Mix	Binder content[a] (%)	Water/cement
General stope fill	8	3.3
Intersection fill	10	3.3

[a]25% portland cement, 75% blast furnace slag

Table 2

Typical sieve analysis for classified mill tailings

Mesh size	Nominal sieve opening (μm)	Percent passing (%)
40	425	100.0
50	300	99.9
80	180	96.8
100	150	93.6
140	106	85.7
200	75	71.1
325	45	47.0
400	38	32.5

Table 3

Stope closure measurements from 5550 level, 11-stope closure meters

Sensor	Location	Description	Cut 1 (cm)	Cut 2 (cm)	Cut 3 (cm)	Cut 4 (cm)	Cut 5 (cm)
CM 1-L	East	Full-span closure meter	8.18	–	–	–	–
CM 2-S	East	Half-span closure meter	2.52	10.43	16.25	22.01	42.06
CM 2-L	East	Full-span closure meter	6.62+	–	–	31.58	49.16
CM 3-S	West	Half-span closure meter	3.90	–	–	–	–
CM 3-L	West	Full-span closure meter	6.42	15.07	21.89	29.90	43.36
CM 4-L	West	Full-span closure meter	9.72	16.84	23.67	30.64	40.59

Table 4

Stope closure measurements from 6350 level, 15-stope closure meters

Sensor	Location	Description	Cut 1 (cm)	Cut 2 (cm)	Cut 3 (cm)	Cut 4 (cm)	Cut 5 (cm)
CM 5-S	East	Half-span closure meter	5.47	–	–	21.18	25.57
CM 5-L	East	Full-span closure meter	7.31	13.47	18.63	24.11	28.77
CM 6-S	East	Half-span closure meter	2.94	7.19	10.35+	–	–
CM 6-L	East	Full-span closure meter	6.19	11.90	16.30	22.65	–
CM 7-S	West	Half-span closure meter	2.26	5.38	–	–	–
CM 7-L	West	Full-span closure meter	4.55	10.56	17.77	20.07+	–
CM 8-S	West	Half-span closure meter	1.74	3.91	6.63	–	–
CM 8-L	West	Full-span closure meter	7.21	13.61	22.02	27.77	33.23

Table 5

Horizontal backfill pressure measurements from 5550 level, 11-stope pressure cells

Sensor	Location	Peak (MPa)	Cut 1 (MPa)	Cut 2 (MPa)	Cut 3 (MPa)	Cut 4 (MPa)	Cut 5 (MPa)
PC 1-N	East side, north wall	4.04	2.33	1.56	1.05	0.95	–
PC 2-S	East side, south wall	3.74	3.03	1.84	–	–	–
PC 3-N	East side, north wall	1.78	1.86	1.71	1.71	1.79	3.28
PC 4-C	East side, stope center	3.49	–	–	–	–	–
PC 5-S	East side, south Wall	5.40	–	–	–	–	–
PC 6-N	West side, north wall	2.12	2.15	1.75	1.28	0.64	0.49
PC 7-C	West side, stope center	3.24	–	–	–	–	–
PC 8-S	West side, south wall	2.16	–	–	–	0.92	0.91
PC 9-N	West side, north wall	1.59	1.18	1.81	–	–	–
PC 10-S	West side, south wall	2.07	1.48	1.80	–	–	–

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Table 6

Horizontal backfill pressure measurements from 6350 level, 15-stope pressure cells

Sensor	Location	Peak (MPa)	Cut 1 (MPa)	Cut 2 (MPa)	Cut 3 (MPa)	Cut 4 (MPa)	Cut 5 (MPa)
PC 11-N	East side, north wall	2.54	0.72	0.42	0.56	0.58	0.62
PC 12-C	East side, stope center	5.47	3.74	2.35	2.36	2.21	2.07
PC 13-S	East side, south wall	2.29	1.71	1.36	1.32	1.34	1.28
PC 14-N	East side, north wall	2.31	1.71	1.33	1.34	1.36	–
PC 15-C	East side, stope center	4.29	2.71	1.62	1.44	1.05	–
PC 16-S	East side, south wall	3.04	2.28	1.90	1.98	2.09	–
PC 17-N	West side, north wall	1.62	1.88	2.16	2.59	–	–
PC 18-C	West side, stope center	2.99	2.74	2.55	2.48	3.07	4.02
PC 19-S	West side, south wall	1.97	1.28	1.40	1.48	1.71	2.33
PC 20-N	West side, north wall	1.87	1.11	1.07	0.80	–	–
PC 21-C	West side, stope center	1.96	0.89	0.31	0.63	0.56	0.24
PC 22-S	West side, south wall	1.85	1.12	0.91	0.67	–	–

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Table 7

Measured in situ tangent moduli of CPB in 6350 level, 15 stope

Monitoring location	In situ compressive strength (MPa)	In situ tangent modulus (GPa)
CM 5	2.7	3.7
CM 6	3.1	3.6
CM 7	2.2	3.1
CM 8	1.8	2.5