

EFFECT OF BINDER CONTENT ON THE DUCTILITY OF CEMENTED HYDRAULIC BACKFILL

T. M. Emery, CDC NIOSH, Spokane, WA
B. Seymour, CDC NIOSH, Spokane, WA
D. J. Sweet, CDC NIOSH, Spokane, WA
J. P. Bourgeois, CDC NIOSH, Spokane, WA
W. Johnson, Hecla Ltd., Mullan, ID
M. Armatys, Hecla Ltd., Coeur d'Alene, ID

ABSTRACT

The Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health (NIOSH) has partnered with a narrow vein, hard rock underground mine to research the effects of the binder content on the elasticity and post-peak ductility of cemented hydraulic backfill (CHB). This is part of a larger study to enhance the long-term integrity of ground support in underground mines. As mining advances deeper and stresses increase, CHB mix designs will benefit if they can be modified to handle higher levels of strain which are induced by an increased stope closure, typically affected by a reduction in stope width and increased mining depth, or through dynamic loading resulting from a local seismic event. This portion of the research examined the impact of reductions in binder and their impact on Young's modulus, peak strength, and post-peak ductility.

INTRODUCTION

Background

Cemented backfills have been used in mining as far back as the 1930s in North America when slag was used to cement hydraulic fill. Then, in the 1970s the paste distribution network was greatly improved, allowing to efficiently pump backfills underground (Singh and Hedley, 1980) which led to innovative mining methods like the underhand mining methods at the Lucky Friday mine by 1988 (Stone, 2014). Now in 2021, mining methods and equipment are much different, and mining operations are being conducted at much greater depths. In the United States alone, Hecla's Lucky Friday mine, Rio Tinto's Resolution Copper mine, and Freeport-McMoRan's Henderson mine have developed down to depths of approximately 9,000 ft, 7,000 ft, and 4,000 ft, respectively, beneath the surface.

To improve the health and safety of working conditions in mines, NIOSH has initiated research to improve the long-term stability of ground support in underground mines. One of the specific aims of this research was to investigate the factors that affect the performance and properties of backfill systems to find long-term stability solutions in this ever-challenging industry. Due to the inherent nature of mining at increasingly greater depths along with the increasingly higher ground stresses, improvements in backfill technology are needed. Enhancing the ductility of CHB, while conserving adequate strength, would improve the strain performance of this material and enable it to maintain its structural integrity and stability over a wider range of mining conditions.

Case Study

A cooperative study was initiated at the Lucky Friday mine (Idaho, US), operated by Hecla Limited, to determine the effect of binder content on the Young's modulus (elasticity) and the post-peak ductility response of CHB. In addition to our long-lasting collaboration, the mine's high in-situ stress environment, extensive backfill practice and the ease to ship material from site to laboratory made it an ideal partnership for such testing.

In civil engineering codes, there are established relationships between the compressive strength and elasticity of concrete (Zhou et al., 2015). Generally, for normal strength concrete, the elastic modulus increases as the compressive strength increases (Zhang, 2011). Although this relationship may also apply to lower strength materials, very few actual case studies have examined this relationship for cemented backfills or low-strength materials such as CHB. To complicate this issue, paste and hydraulic backfills utilize "dirty" materials that can have vast differences in geochemical or physical properties (Thompson et al., 2012). Therefore, comparisons with conventional concrete may not be appropriate for backfill, depending on the conditions at the mine site.

Backfill design can be particularly complicated in high stress ground conditions. The fill must be strong enough to provide stable support for the miners working beneath it and yet ductile enough to withstand the energy from dynamic loading or large deformations caused by rib closure. These sorts of requirements are increasingly becoming part of the standard design for mine backfill (Wickens and Wilson, 2021). At the Lucky Friday mine, which utilizes an underhand-mining method, production stopes experience, on average, about 3 inches (7.6 mm) of in stope wall-to-wall closure per undercut advance, independent of stope width (Raffaldi et al., 2019). This consistent rate of closure provides a unique setting for potentially evaluating the performance of the backfill mixtures under different strain conditions. Considering a constant backfill pour, stope width directly affects the backfill strain response where the narrowest stope section presents the highest strain value along the cut. In this situation, strain is a function of stope width and closure as shown below in Equation 1.

$$\epsilon = \frac{\delta}{L} \tag{1}$$

Where:

- ϵ = strain in backfill
- δ = stope closure
- L = stope width

As the material gets loaded by an external force, the strain responds linearly to the subjected stresses until (or close to) the material reaches its peak strength. Backfill elasticity is normally derived from the linear portion of the stress-strain curve under compression, before yielding has occurred, and stays reasonably consistent with Hooke's law (Roylance, 2001). This property measures the resistance to elastic deformation, relating the Young's modulus to the materials stiffness. Typically, stiffer backfill present a higher peak strength at a lower strain value. The Young's modulus (E) is calculated using Equation 2.

$$E = \sigma/\epsilon \tag{2}$$

Where:

- σ = stress within backfill
- E = Young's modulus of backfill
- ϵ = strain in backfill

Furthermore, ductility is used to describe the deformation that occurs in the plastic region of the stress-strain curve after permanent yielding begins to occur (i.e., plastic strain). Yielding generally begins to occur at the peak strength in concrete, and the same assumption is usually acceptable for backfill mixes (Jafari et al., 2020).

LABORATORY TESTING

Materials

The materials used in this study, a blended binder and mill tailings, were provided the Lucky Friday mine. Classified tailings, having a moisture content of approximately 12.5%, were collected at the mine’s backfill tailings storage facility. The binder, a blended cementitious mixture (75% Type 100 Ground Granulated Blast Furnace Slag, 25% Type 1L Portland Cement) was shipped from Lafarge North America to the NIOSH Spokane Research Laboratory. Tap water was used for batching, whereas the mine used clear water from the mines water system.

Mix Design and Batching

This research study was separated into multiple phases, in which several variations and combinations of CHB mix designs were batched (Table 1). The standard stope mix design, used at the mine, was utilized as the starting point for varying the binder content.

Table 1. CHB study mix designs.

Basic Mix Parameters	Mix A	Mix B	Mix C
% Cementous Dry Wt.	9%	8%	6%
Pulp Density	75%	75%	76%
Water-to-Cement Ratio	3.55	4.32	5.52

Using the specific gravity of the material and the basic components of the mix, a mix design was then computed based on volumetrics or the absolute volume method as in ACI 211.1 (Chen 2000). It should be noted that only the volumetric calculations from the ACI 211.1 method were used to define the mix constituents. This mix design was then used to adjust the percent binder content for the additional mixes. Having a precise mix design made it simple to adjust for smaller batch sizes, different binder contents, and various moisture contents of the tailings.

The first mixes were batched at the Spokane Research Laboratory in Spokane, WA. As shown in Figure 1, the mixes were batched in a 10 cubic foot rotary mixer, with a maximum batch size of 3 cubic feet. The first batch was prepared to yield 3 cubic feet of material, but this proved to be difficult to mix with such a fluid mixture. The remaining batches were batched at 2 cubic feet. A sample of the tailings were dried beforehand to determine the initial moisture content, so that the mix design could be adjusted to maintain the correct water-cement (w/c) ratio. The drum was “battered” as outlined in the ASTM C192 and mixed for a minimum of 2 minutes.



Figure 1. Pouring CHB samples at SMRD laboratory.

NIOSH wanted to maintain the same workability, or flowability, as the mine prescribed to ensure the mix was as true to field conditions as possible. Due to variations in the particle size distribution (PSD) or geologic makeup of the tailings, there can be slight variations from day to day in the workability of a mix. In general industry, it is often customary for a batch plant to hold back a few gallons of water to give the flexibility to add water to obtain the optimum workability. To account for this variability, a small amount of tap water was held back when batching. As shown in Figure 2, the spread test mentioned in ASTM D6103-17 for testing cemented low strength mixtures (CLSM) was used to determine the workability for this type of material.



Figure 2. Spread test during batching.

CLSM is defined as “materials that have a higher strength than soil but less than 8,400 kPa (1,200 psi).” Before the samples were cast, a spread test of 12.5 ± 1 inches in diameter had to be obtained. If not, additional water was weighed and added to the mix. The mix design was then adjusted accordingly.

Laboratory Tests

Standard tests were conducted to determine the unconfined compressive strength (UCS), Brazilian splitting tensile strength (STS), and flexural beam strength (FBS) of the CHB batches. Table 2 lists the number and general type of tests performed for each associated mix design. For the UCS tests, five samples were tested for each curing age with a total of 20 samples tested per mix type. ASTM D4832 Note 2 recommends “In the initial stage of CLSM usage, preparation of three cylinders is recommended to obtain reliable compressive strength data for each test age.” This higher sample count was assumed for two reasons: 1) to ensure that the variability in the material preparation is reduced, to capture the most reliable elastic and strength properties. 2) it was based on the authors experience with the constituent material, when working with Johnson et. al., 2015.

Due to the lack of direct standards for mine backfill, an array of standards was relied upon. The study found that the ASTM standards for CLSM (ASTM D5971, D6023, D6103, D4832) provided excellent guidance for sampling, casting, preparation, and UCS testing of hydraulic backfill.

Table 2. Mix ID with corresponding number/type of tests.

Mix ID	UCS 3-Day	UCS 7-Day	UCS 14-Day	UCS 28-Day	3-Point Beam	Brazilian Tensile
A	5	5	5	5	0	8
B	5	5	5	5	3	8
C	5	5	5	5	0	4

Standard methods for general concrete such as C78/C78M-21 were followed for flexural beam testing. In previous backfill research (Johnson et al., 2015), ASTM D3967-16 was adapted from tests with rock core to measure the indirect tensile strength of backfill. Additional ASTM standards were referenced and relied upon to ensure repeatability, applicability, and scientific quality of the test.

Curing and Sample Preparation

To allow for comparison of past research, reconciliation with mine samples, and future research, standard 4x8-in cylinders were chosen for all testing. Samples were cast according to ASTM D4832-16, another standard for testing CLSM mixes such as CHB (Figure 3).



Figure 3. Casting the CHB samples in 4x8-in cylinders.

After casting, the samples were then cured in both approved ASTM C31/C31M-19a methods. Two sets of samples (Mix ID A & Mix ID B) were cured in climate-controlled curing boxes, and the third batch (Mix ID C) was cured in a water bath. All the cylinders had watertight caps that remained in place during curing. The water bath was maintained at the same temperature as the curing boxes. It was equipped with a water heater and a circulator to ensure consistent temperature throughout the tank. The only deviation from the ASTM method was the curing temperature for the 4x8-in cylinders. Due to the deep geothermal heat radiated by the host rock at the Lucky Friday mine, backfilled stopes cure under high ambient heat. To replicate this environment, the CHB samples were cured at 90°F for this investigation. The cure temperature couldn't be ignored, otherwise the early strength data obtained from NIOSH testing would be much lower at early curing ages than the in-situ mine backfill samples (due to accelerated hydration). This early-age strength is particularly important for determining when miners can re-enter underneath the engineered backfill. Because there was not enough room in the curing boxes and water tank to accommodate the 3-point flexural beam molds, they were instead cured in a fog room at 68°F. Since the beams were to be tested at 28 days only, the early strength gain from the accelerated curing would not impact the test results.

On the day of testing, samples were removed from their molds, and their tops were cut with a diamond saw to ensure end parallelism and smoothness. The ends of the samples were then sulfur capped according to ASTM C617/C617M and tested on the same day. Prior to testing, NIOSH researchers measured the weight and dimensions of the samples to facilitate density calculations and height corrections as needed.

TEST RESULTS

Unconfined Compressive Strength Testing

To develop a strength age curve, UCS testing was performed at 3, 7, 14, and 28 days; these results are shown in Table 3 and include the coefficient of variation (CV).

Table 3. Average UCS testing results.

Mix ID	3-Day UCS (psi) & CV	7-Day UCS (psi) & CV	14-Day UCS (psi) & COV	28-Day UCS (psi) & COV
A	66 25.9%	416 9.1%	590 2.7%	651 1.5%
B	37 10.7%	289 9.3%	478 3.5%	537 2.0%
C	24 5.6%	177 2.2%	312 1.7%	312 1.8%

Sample measurements average 4.00 inches in diameter and 7.17 inches in height, with an average density of 138.8 lbf/ft³. Due to the loss in height from consolidation during the initial stages of curing, strength reduction factors from ASTM C39 were applied and varied from a maximum factor of 0.988 to the lowest correction factor of 0.972. Though a higher coefficient of variation occurred at early maturity, the test results were consistent with the 14-day UCS testing. By the 28-day tests, the coefficient of variation was below 2% for all three mix designs. This resulted in a spread of less than 25 psi between all samples in each mix design. The coefficient of variation for the sample density was also very low at 0.63% for all curing ages combined during testing, indicating consistent procedures were followed for casting and preparing the samples.

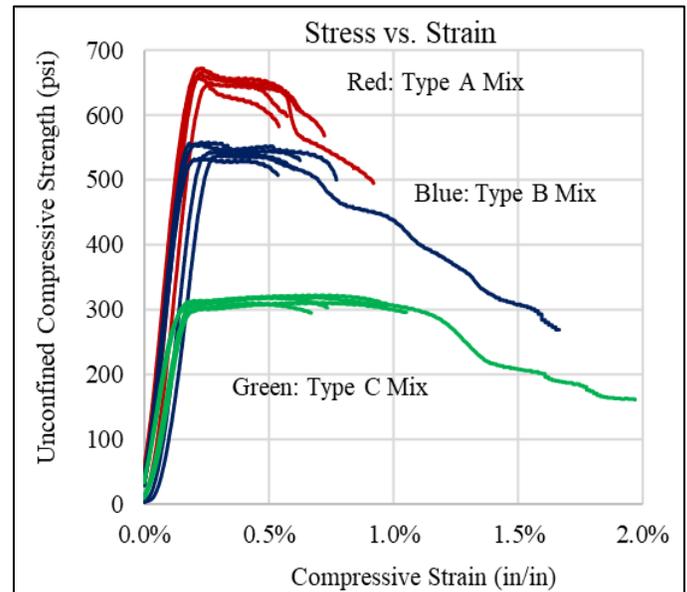


Figure 4. Stress versus strain curves for 28-day UCS tests.

All samples were loaded at a constant strain rate that would yield failure after approximately 2 to 3 minutes. The strain rate was different for different curing ages or binder contents due to the strength of the sample and varied for the study from 0.015 inch/minute to 0.025 inch/minute. The failure patterns were consistent with Type 1 (~well-formed cones on both ends) and Type 2 (a single ~well-formed cone with vertical cracks running through to the other cap) typical fracture patterns as outlined in ASTM C39/C39M-21. Stress-strain curves for 28-day testing are shown in Figure 4, and a comparison of the adjusted UCS versus curing age is plotted in Figure 5. For each mix design that was tested at 28 days, one sample was randomly selected for a longer test duration to better define the post-peak characteristics of the mix.

The post-peak response of the mix design appeared to be dependent on the binder content when all other variables were held

constant. It is quite evident in figure 4 that as the binder was reduced the post-peak ductility greatly increased.

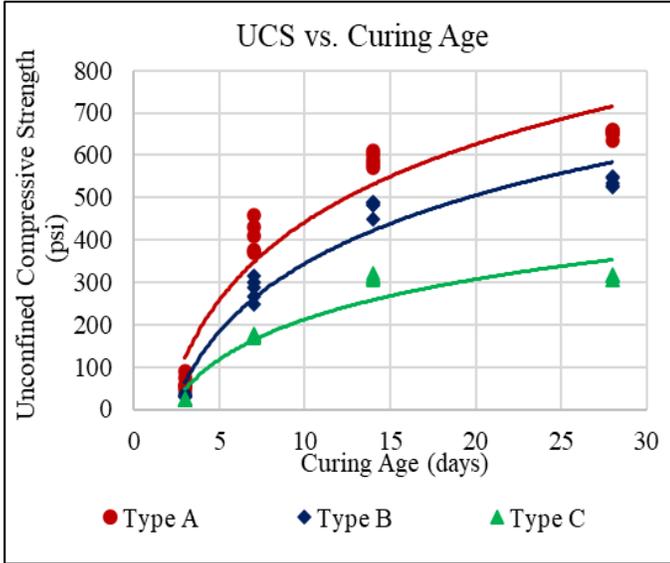


Figure 5. Strength age curve, per mix design.

Brazilian Tensile Testing

ASTM D3967-16 and ASTM C496/C496M-17 were followed for all STS tests after a cure time of 28 days. The samples were loaded at a strain rate between 0.01 and 0.02 inches/minute was used during testing of all samples. Averaged STS results according to mix ID are shown in Table 4. The average 28-day STS values for the mixes are about 10% to 12% of the corresponding average 28-day UCS values listed in Table 2 for these mixes. These results agree with previous research by Johnson et al. (2015) that yielded a Brazilian tensile strength of 68 psi with an average UCS of 602 psi.

Table 4. Average 28-day STS according to mix ID.

Mix ID	Avg 28-Day STS (psi)
A	67
B	57
C	38

3-Point Flexural Beam Tests

Flexural beam tests were conducted with three beams cast from mix design B. ASTM C78/C78M-21 was followed for the flexural beam testing after a cure time of 28 days. Sample measurements for all three molds include an average width of 5.50 inches at the fracture, an average depth of 5.90 inches at fracture, and a span length of 17.6 inches. Each test according to load (lbf) versus net deflection (in) is shown in Figure 6. Maximum applied load at failure and calculated modulus of rupture (MOR) for each individual test are listed in Table 5. Additionally, the MOR can also be used to determine the indirect tensile strength based on the Weibull distribution (Jones and Ashby, 2019; Nguyen et al., 2019) for comparison to the Brazilian tensile testing. In this case, the average 28-day STS and average tensile strength calculated from the Weibull distribution were both 57 psi. Future studies should be conducted to compare STS with tensile strength calculated from the material's MOR from flexural beam tests.

Elastic Modulus Calculations

The Elastic modulus was calculated from the slope of a 28-day sample's stress-strain curve using the tangent method adapted from ASTM D7012-14 at 50% of the ultimate UCS. The reasoning behind these decisions is that the method described in ASTM C469/C469M-14, which is the standard for the determination of Young's Modulus of concrete, was not appropriate for backfill for multiple reasons. First, the initial compression of voids in the beginning of the test is not linear as explained by Unal and Cakmakci (2000). Second, if the method were followed as prescribed, an initial strain value of 0.000050 in/in would yield a strain down near the bottom 1% of the maximum applied load.

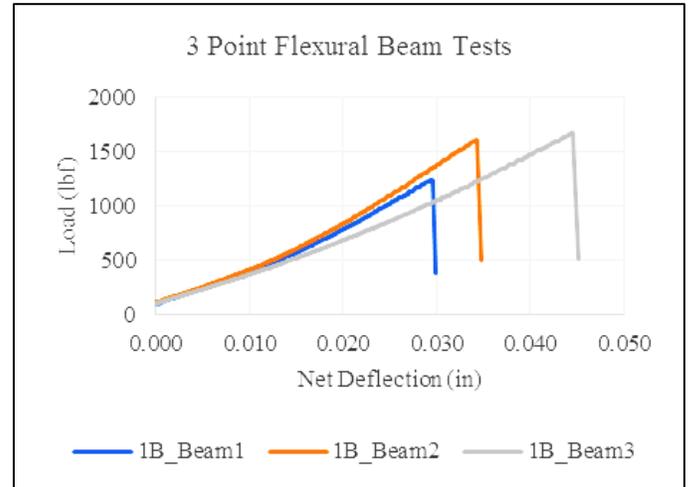


Figure 6. Flexural beam tests load vs. net deflection, mix design B.

Table 5. Flexural beam test results and tensile strength correlation from Weibull distribution.

Test ID	Max Applied Load (lbf)	MOR (psi)	Tensile Strength (psi)
Mix B-Beam 1	1244	115	47
Mix B-Beam 2	1612	150	61
Mix B-Beam 3	1678	156	63
Average	1511	140	57

The decision for basing the calculations off the 50% UCS value also came from research by Johnson et al. (2015) who looked at a range of 30% to 60% UCS as the most linear portion of the stress-strain curve and from Unal & Cakmakci (2000) which assumed the 20% to 50% UCS range. In this case, the stress-strain curves showed the best linearity at approximately 50% of the peak ultimate strength. For sensitivity, four different calculations were performed for Young's modulus to compare the results.

The tangent method and linear regression were found to be the most consistent calculated results. The secant method was highly variable depending on the amount of initial pore consolidation that occurred at the beginning of the sample, and as mentioned the ASTM 469 method was not applicable due to the low strain values. The average Young's Modulus values are summarized in Table 6, and a plot of the Young's modulus versus UCS is provided in Figure 7.

Table 6. Average Young's modulus versus UCS

Mix ID	Binder Content (%)	Average 28-Day UCS (psi)	Average Young's Modulus @ 50% UCS (10 ³ psi)
A	9	651	385 (0%)
B	8	537	325 (16%)
C	6	312	229 (41%)

Similar results were previously reported for in-situ backfill from the same mine for the same range of % ultimate UCS (Johnson et al., 2015). However, in that study, strain gauges were attached to the samples, whereas in this study, platen-to-platen deformation measurements were taken to determine the strain.

Verification of results using standard industry equations for concrete is not possible due to the difference between CHB and general concrete. Many other methods have been researched, but they are usually not practical for development of backfill in mine settings. The following were investigated to see if they could be modified for this mix design for future use.

Using the standard equation for estimating Young's modulus of concrete from the ACI 318, structural code (Equation 3) yields a

Young's modulus that is 3 to 4 times greater than testing results. This disparity is not unreasonable due to the high use of supplementary cementitious materials (SCM), extremely high water-cement ratio, and the exclusive use of tailings for aggregate in this backfill mix.

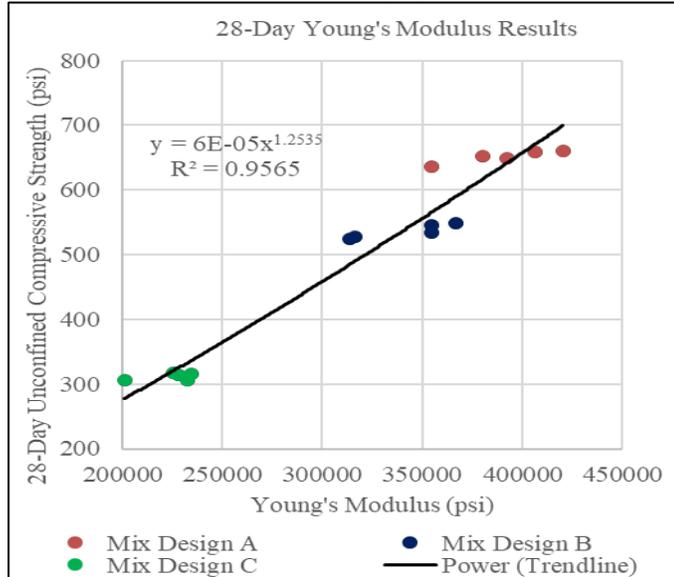


Figure 7. 28-day Young's modulus results.

However, if Equation 3 is modified by changing only the coefficient, the approximation from Equation 4 fits the laboratory testing results quite well for all mix designs as shown in Table 7.

$$E = 33(w^{1.5})\sqrt{f'_c} \quad (3)$$

$$E = 9(w^{1.5})\sqrt{f'_c} \quad (4)$$

Where:

w = unit weight of material

f'_c = ultimate compressive strength at 28 days

Table 7. Predicted Young's Modulus versus laboratory test results

Mix ID	Average Density (lb/ft ³)	Average 28-day UCS (psi)	Young's Modulus as per Modified ACI 318-07 Equation (psi)	Laboratory Results of Young's Modulus (psi)
A	139.1	660	379,368	390,939
B	139.5	537	343,470	341,349
C	139.1	312	260,685	224,405

The same is true in predicting the expected 28-day UCS based on the 7-day UCS results (Equation 5). With a slight change to the coefficient in the formula proposed by Slater (1926), the results fit reasonably well with this dataset as shown in Table 8. As previously stated, these are over-simplified formulas, but they seem to reasonably predict the expected range for these properties as the backfill matures. Further research is warranted to develop more refined methods.

$$UCS_{28} = UCS_7 + 13\sqrt{UCS_7} \quad (5)$$

Table 8. Predicted 28-day UCS versus actual 28-day UCS.

Mix ID	Laboratory 7-Day UCS Test (psi)	Predicted 28-Day UCS from 7-day UCS (psi)	Actual 28-Day UCS (psi)
A	408	671	660
B	289	510	537
C	177	350	312

FIELD TRIAL

Trial Location and Conditions

Following the successful laboratory tests, Hecla decided to field test a reduced binder content mix in a trial location at the Lucky Friday

mine (Figure 8). The selected site was a narrow vein intermediate stope on the 6000 level of the mine (Armatys, 2021).



Figure 8. Underground test pour result showing the exposed sill-mat (in the back) for the mix design B at the Lucky Friday.

The stope was one of the narrowest stopes in the mine at the time. The mining method utilized in this stope was underhand cut-&-fill mined through standard drill-and-blast processes. The Type B mix was chosen for its reduced elastic modulus while keeping the peak strength above the mine's factor of safety for exposed sill-mat stability. This mix potentially adds increased strain capacity in the paste due to a 16% reduction of the elastic modulus (when compared to mix design A). With the stope being extremely narrow (<10'), this would impose the highest level of strain in the event of closure due to mining-induced stresses or seismic activity.

Mining occurred under the fill 28 days after the backfill was placed. As shown in Figure 8, the exposed paste beam showed no superficial failures or significant mesh bagging along the cut. The exposed sill-mat was consistent throughout the cut. Miners reported no issues when mining under the backfill and had positive comments. The only comment encountered was the fill was "pluggy" when drilled for installing split sets. This jargon referred to the backfill being softer and plugging up the jacklegs that were used for installation. At no point were there any reports of weaker or bad ground.

DISCUSSION AND CONCLUSIONS

Observations and future work

Varying only the binder content produced the following changes in the strain capacity, strength, and ductility of the CHB samples:

- The binder content is proportional to the resulting elastic modulus in backfill. When compared to the base mix design A, the Young's modulus of the backfill mixes decreased in both mix design B and C by 16% and 41%, respectively, due to a reduction in binder content of 1.7% and 4.5%, respectively.
- The peak strength is proportional to the resulting elastic modulus in backfill. Therefore, the Young's modulus decreased with decreasing peak strength,
- The post-peak ductility improved as the peak strength decreased. As the peak strength decreased, post peak residual strength of the CHB appeared to flatten out (i.e., maintain load-carrying capacity). In the case of mix design C, the ultimate strength was not at the inflection point of the

curve but towards the end of the “post-peak” curve, demonstrating some signs of strain-hardening.

- The 28-day compressive strength did not increase appreciably beyond the 14-day compressive strength. It was beyond the scope of this study to investigate why this occurred, but a mathematical relationship was derived to forecast 28 day compressive strengths based on the 7 day results (see equation 5).
- The low coefficient of variation for these test results demonstrates the importance of QA/QC controls during batching, sample preparation, and testing processes.

Future work will include additional testing of additives and reinforcements (including fibers) that may aid in enhancing the ductility of backfills.

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DISCLAIMER

The findings and conclusions in this paper are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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