

## EFFECTS OF FOAM ADDITIVE ON THE DUCTILITY OF CEMENTED PASTE BACKFILL

D. Sweet, CDC NIOSH, Spokane, WA  
T. Emery, CDC NIOSH, Spokane, WA  
B. Seymour, CDC NIOSH, Spokane, WA  
J. Bourgeois, CDC NIOSH, Spokane, WA  
J. Feiler, Aerix Industries, Golden, CO  
M. Gomez, Aerix Industries, Allentown, PA

### ABSTRACT

For traditional underhand cut-and-fill mining operations, it can be challenging to design a suitable cemented paste backfill (CPB) mix that can meet the necessary strength requirements and yet maintain its ductility. In deep underground metal mines, the CPB must achieve a high enough strength to be competent under high stress conditions while also remaining ductile enough to withstand high strain from squeezing ground as underhand mining continues under backfilled stopes. To eliminate ground falls that result in injuries and fatalities, researchers from the Spokane Mining Research Division (SMRD) of the National Institute for Occupational Safety and Health (NIOSH) have partnered with Aerix Industries, a producer of concrete additives, to study the effects of foaming agents on the strength and ductility of CPB. This laboratory study examines the impact of various amounts of foam additive on the strength and ductility of CPB mix designs, using binder and tailings provided by Hecla Limited from the Lucky Friday Mine.

### INTRODUCTION

#### Background

One of the methods that is effectively used to provide ground support in underground metal mines is to backfill mined-out openings with a cemented waste product, usually either mill tailings or waste rock. Backfill mining methods are particularly useful for difficult mining conditions, and they 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 lead/zinc/silver ore (Blake and Hedley, 2003; Williams et al., 2007). At the Lucky Friday Mine, the use of cemented mill tailings 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, rockburst-prone ground conditions, thereby greatly improving the safety of underground miners (Peppin et al., 2001; Pakalnis et al., 2005). With this mining method, the mining-induced stresses are transferred to a horizon in the host rock beneath the floor of the stope as mining progresses downward. The mined-out stope is then backfilled with cemented paste backfill (CPB)—a high-density mixture of classified mill tailings, cementitious binder, and water—creating an engineered back beneath which the miners can safely work during the next undercut advance.

Owned and operated by the Hecla Mining Company, the Lucky Friday Mine is located approximately 1 mile (1.6 km) east of Mullan, ID near the Montana border. Completion of the No. 4 Shaft winze (Sturgis et al., 2017) has extended the depth of the mine to just over 9,500 ft (2,900 m) below ground surface, making it the third deepest mine operating in the western hemisphere (Alexander et al., 2018). Narrow, sub-vertical veins of lead/zinc/silver ore are currently being mined from the Gold Hunter deposit at depths of about 7,400 ft (2,300 m). 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 14,000 to 17,500 psi (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). In response to these high horizontal stresses, the stope walls converge during undercut mining and compress the CPB as illustrated conceptually in Figure 1.

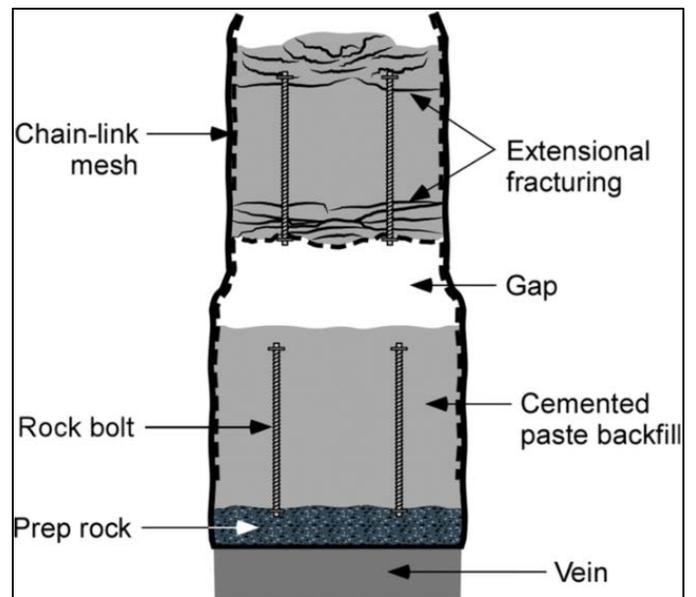


Figure 1. Conceptual vertical cross section illustrating the progression of horizontal closure as backfill is undercut (Raffaldi et al., 2019).

Custom-designed instruments installed in backfilled stopes have shown that during the first undercut mining advance beneath the fill, wall-to-wall closure in a backfill stope typically exceeds the elastic strain limit of the fill. As a result, the horizontal loads applied to the fill usually exceed its intact compressive strength. On average, about 3 inches (7.6 cm) of wall-to-wall closure have been measured in an instrumented stope following each successive undercut advance beneath those instrumented locations. Depending on the span or width of the stope, this represents a strain of about 1.5% to 2.5% with each undercut advance. In comparison, CPB samples usually fail during laboratory UCS testing after about 0.5% to 1.0% strain. In one instrumented stope, over 20 inches (51 cm) of closure was measured through five consecutive undercut advances.

Maximum horizontal fill pressures are typically measured at the midspan of a backfill stope during the first undercut advance. Although horizontal fill pressures have been measured as high as 798 psi (5.50 MPa), they usually average about 435 psi (3 MPa). These horizontal loads can cause crushing and extensional fracturing near the exposed bottom surface of the fill. To protect crews during undercut mining, bolts and chain link mesh are used to retain potential slabs and contain spalling on the underside of the CPB beam. As shown in Figure 1, the

upper surface of the paste fill beam is unconfined and deforms into the gap above.

As underhand mining continues to advance deeper, the cemented backfill is subjected to further horizontal closure with each additional undercut. This closure compresses and eventually compacts the fill until it is completely confined. Even though the cemented backfill fractures and becomes progressively more fragmented through a steady succession of stope closures during underhand mining, the CPB still maintains a long-term horizontal pressure of about 145 to 290 psi (1 to 2 MPa). As a result of this residual strength and confinement, the fill appears to maintain its stability as underhand mining advances deeper. A more thorough discussion of the geology, mining method, backfill, and instrumentation is provided by Raffaldi et al. (2019) and Seymour et al. (2017).

Backfill failures in U.S. mines are usually attributed to inadequate backfill strength, insufficient or inconsistent quality control measures, or larger-than-expected mining spans (Seymour et al., 2013). While backfill failures or collapses do not occur frequently, they can have severe consequences, particularly in underhand cut-and-fill operations where miners are working directly beneath the fill. The safe design of a backfill undercut span requires that the strength of the in-place fill must exceed the strength needed to support the backfill's own self-weight and any additional applied rock mass loads. This design strength is typically determined using analytical equations (Mitchell, 1991), empirical design methods (Pakalnis et al., 2005), and/or numerical modeling. A combination of failure modes—including caving, sliding, flexural, and rotational failure (Mitchell, 1991)—needs to be analyzed, taking into consideration the fill properties, stope geometry, loading conditions, stope closure, ground support, and other factors resulting from backfilling practices such as cold joints and gaps between successive backfill lifts (Pakalnis et al., 2005).

However, these methods primarily rely on the intact strength of the backfill, and they usually do not account for the elastic and post-peak behavior of the paste fill, as it undergoes crushing. A very strong fill is likely to be too brittle to remain stable when stope closures exceed the elastic strain limit of the fill. Instead, a more ductile fill with significant residual strength is needed. The stress-strain response of the backfill needs to be considered over several percent strain to analyze not only the fill's behavior in the elastic range but also to assess its post-peak ductility and residual strength. As a result, improved CPB mix designs are needed to enhance the geomechanical performance and stability of the fill for these conditions.

To address these concerns, NIOSH is conducting research in cooperation with Hecla to determine the effect of binder content, reinforcement, and chemical additives on the ductility of CPB (Emery et al., 2022). One of the chemical additives that is being studied is a foaming agent used for making low-density cellular concrete (LDCC) produced by Aerix Industries in Allentown, PA. NIOSH researchers have conducted an initial series of tests with Aerix to examine the effect of different combinations of binder content and foaming agent content on the engineering properties of CPB. This paper presents the results and findings from these initial tests.

### **Applications for Cellular Concrete**

Cellular concrete is a lightweight cementitious material that is often used for filling void spaces for a broad range of industrial purposes including geotechnical, mining, construction, ready-mix, and manufacturing applications. In its plastic state, cellular concrete is highly flowable and self-leveling. After curing and hardening, it forms a durable, lightweight concrete with insulative properties.

In its most basic form, cellular concrete is comprised of a Portland cement slurry homogeneously mixed with a preformed foam. The preformed foam is made by diluting a foam concentrate with water and passing it through a foam generator along with compressed air, both in the correct proportions, to create a foam with a targeted unit weight that has an appearance very similar to that of shaving cream. As the mixture of dilute solution and compressed air is introduced to the upstream side, the foam generator provides backpressure and shear such that the desired foam is discharged.

The possible mixtures of cellular concrete are nearly infinite because other components having their own characteristics can be added to the mix. For example, Class F or Class C fly ash can be added as a partial replacement to Portland cement to enhance pumping and flow characteristics or to reduce binder costs. Ground granulated blast furnace slag (GGBFS or slag cement) can be added to the Portland cement to reduce the heat of hydration if temperature is a concern. Components typically used in normal-weight or structural concrete can also be used in cellular concrete to enhance its performance, such as fibers to improve tensile strength or accelerators and retarders to adjust its set time.

In general, cellular concrete can be categorized as all-powder mixes (neat-cement mixes) or sanded mixes. Most neat-cement mixes have a wet-cast density ranging from about 20 lbf/ft<sup>3</sup> (320 kg/m<sup>3</sup>) to 60 lbf/ft<sup>3</sup> (961 kg/m<sup>3</sup>). These mixes are generally described as low-density cellular concrete (LDCC), which is defined by the American Concrete Institute as cellular concrete having an oven-dry density of 50 lbf/ft<sup>3</sup> (801 kg/m<sup>3</sup>) or less (ACI 523, 2007). Following the same general guidelines of LDCC, a permeable formulation was developed that is referred to as permeable low-density cellular concrete (PLDCC). Cellular concrete mixes with wet densities above 60 lbf/ft<sup>3</sup> (961 kg/m<sup>3</sup>) usually contain fine aggregates such as sand and are known as sanded mixes.

The largest use of cellular concrete by volume is for geotechnical construction projects. In these applications, cellular concrete is typically used as an engineered backfill to replace traditional compacted soil treatments in poor soil conditions. In many projects, hundreds of thousands of cubic yards of cellular concrete have been placed as backfill behind mechanically stabilized earth (MSE) structures and in the construction of retaining walls and bridge abutments.

LDCC and PLDCC provide many benefits, including faster, more efficient placement, requiring less labor and fewer pieces of equipment; higher lift heights; accelerated construction schedules; no compaction requirements; ability to drain (PLDCC); and the exertion of minimal to zero lateral loads on adjacent structures once the product has hardened. In poor soils, some geotechnical projects may require soil stabilization before construction can occur, such as the replacement of soft soils to provide for a suitable foundation or pavement subbase and the placement of load-reducing fills to mitigate settlement issues. PLDCC is particularly useful in coastal areas where poor soil replacement and load-reducing fills are required in the presence of high groundwater levels.

Other geotechnical-related projects include filling abandoned underground pipelines and filling annular spaces associated with slip-line pipe and the relining of pipe and culvert. Cellular concrete is exceptionally useful in these types of projects because of the material's pumpability and flowability. LDCC or PLDCC can be pumped long distances and placed in an annular space or pipe abandonment from a single access point.

Cellular concrete is also used in several building or construction applications. Lightweight roofs are generally constructed using neat-cement mixes having densities of about 40 to 45 lbf/ft<sup>3</sup> (641 to 721 kg/m<sup>3</sup>). Sanded mixes are often used to pour floor decks to build subfloors or floor underlayment. Besides providing a UL fire rating and an FM rating for roof and floor decks, the preformed foam that is used for these applications also provides beneficial sound and temperature insulation. Although cellular concrete is not designed to provide structural support, systems have been developed for constructing prefabricated and poured-in-place wall panels that are lightweight, insulating, and load reducing.

Cellular concrete is used in a variety of manufacturing applications. It is used to fill the annular space in a double-walled safe to enhance its fire rating for the storage of valuable items and documents. It is used to manufacture lightweight blocks for building construction and lightweight, soundproofing, removable floor deck panels that can be moved and adjusted to accommodate rearranged office or building spaces. In the manufacture of double-walled truss pipe for sewer applications, cellular concrete is used to fill the trussed

annular space and produce a stiffened pipe with enhanced compressive strength.

#### **Mining-specific Applications**

One of the first mining-related applications of cellular concrete occurred in the late 1980s with a Wyoming Abandoned Mine Lands (AML) demonstration to fill a subsidence void that opened in a street overlying an abandoned coal mine in the city of Rock Springs. A foamed neat-cement mix was used to fill a pit that was about 15 ft (4.5 m) in diameter and 8-ft (2.4-m) deep. Unfortunately, after partially filling the hole, the cellular concrete flowed through an opening below the subsidence pile, and much of the material disappeared into the mine. After two truckloads of cellular concrete, the demonstration was stopped because the amount of material required to fill the void was unknown.

Later in the 1990s, sanded cellular concrete mixes were used in experimental projects conducted by the Office of Surface Mining Reclamation and Enforcement (OSMRE), the U.S. Bureau of Mines, AML departments in Colorado and Utah, and the Southern Ute Indian Tribe, among others, in an attempt to extinguish fires that were burning in abandoned coal mines and coal seams. For these projects, boreholes were typically drilled into the fire zone and cased. Cellular concrete mixtures were then pumped into the boreholes until grout rejection was achieved. The overall objectives of these projects were to fill the void areas, cut off the oxygen supply, and encapsulate the fuel to provide cooling. Because of the high temperatures, normal cement and fly ash grout would typically set up or seize rather quickly in the borehole casing. Foamed concrete mixtures were resistant to the high heat and would continue to flow through the boreholes and fill the underground voids. However, because some of these fires had been burning for decades, the results of these projects were mixed, depending on the intensity and layout of the fires. Usually, the fires were mitigated for a few years, and then, they would intensify again.

In 1997, cellular concrete was successfully used to backfill a series of in-panel entries in front of an advancing longwall at the Foidel Creek Mine, an underground coal mine located about 20 miles (32 km) southwest of Steamboat Springs, Colorado. Longwall equipment was being used to mine a low-sulfur, high-quality bituminous coal seam 8.5- to 10-ft thick at a depth of about 1300 ft (396 m). Because of the large size of the 8-Right panel (815-ft (248-m) wide and 18,000-ft (5,468-m) long), three parallel entries about 20-ft (6.1-m) wide were driven across the middle of the panel to provide access for the development of gateroad entries and escapeways for underground miners. To eliminate the need for a longwall face change and prevent the collapse of these entries during longwall mining, the three cross-panel entries were backfilled with a cellular concrete mix consisting of fly ash, 10% cement, and a foaming agent. Bulkheads were constructed across the tailgate and headgate end of each entry to contain the fill. The cellular concrete was batched on the surface and pumped to a 3-inch (7.6-cm) cased borehole, where the material traveled by gravity 1,200 ft (366-m) vertically into the mine and another 3,000 ft (914 m) laterally to the discharge area. A total of 23,000 yd<sup>3</sup> (17,585 m<sup>3</sup>) of cellular concrete was used to completely fill the three entries. Approximately a month after the filling was complete, the longwall successfully mined through the backfilled entries. Instruments installed in the cross-panel entry pillars, backfill, longwall panel, and adjacent headgate entry by NIOSH researchers indicated that as the longwall advanced through the backfilled entries, most of the mining-induced load was supported by the cross-panel entry pillars. The backfill provided stability for the roof and floor of the in-panel entries and confined the entry pillars significantly improving their load-carrying capacity (Seymour et al., 1998).

Today, Aerix engineered-foam technologies and cellular concrete are being used in an increasing number of mining-related applications. Cellular concrete is still used as ground support for the construction of longwall recovery rooms, and it is also used for several other applications, including as annular fill behind shaft and tunnel liners and over arch sets, as yielding supports in coal mines, as lightweight blocks for mine ventilation stoppings, as backfill for subsidence mitigation in abandoned and active mines, and as backfill for cut-and-fill mining methods.

Foam, by itself without any cementitious binders, can be used as a transport mechanism for granular solids, such as sand. When sand is blended with foam in a homogeneous mixture, the foam holds the sand in suspension creating a flowable material. Depending on the site conditions, this material can then be pumped into place or placed by gravity methods to backfill underground structures and voids. After the material is placed and motion stops, the foam dissipates without binders, and the material self-compacts under its own weight and the pressure of additional backfill. This foam methodology provides a cost-effective alternative to traditional grouting or hydraulic backfilling methods because it avoids the added expense of costly binders such as cement or fly ash and uses about 95% less water. This technology was first used in Colorado Springs, Colorado to backfill an abandoned coal mine entry underlying residential housing. Since then, it has been used by government as well as private entities to backfill underground mine voids and structures in Nevada, Wyoming, New Mexico, and North Dakota, where a recent project by the North Dakota Public Service Commission's AML program received a national award from OSMRE for demonstrating a cost-effective method for backfilling coal mine voids.

#### **TEST SETUP**

##### **Cellular Concrete Standards**

The following three ASTM standards specify the production and testing of cellular concrete and the foams that are used to make it: ASTM C869 (2016), "Standard Specification for Foaming Agents Used in Making Preformed Foam for Cellular Concrete;" ASTM C796 (2019), "Standard Test Method for Foaming Agents for Use in Producing Cellular Concrete Using Preformed Foam;" and ASTM C495 (2019), "Standard Test Method for Compressive Strength of Lightweight Insulating Concrete." ASTM C869 focuses on testing the performance of the actual foam used to make cellular concrete. On most projects, the contractor/installer must provide documentation from the manufacturer that the intended foam meets the requirements of this overriding standard. ASTM C796 furnishes a test method for measuring the performance of a foam chemical in the laboratory, and ASTM C495 specifies the correct procedures for determining the compressive strength of cellular concrete made with preformed foam, including the sampling, curing, preparation, and testing of samples.

##### **Batching and UCS Testing at Aerix Laboratory**

The objective of adding foam to a CPB mix is to create a more porous backfill material that responds in a more elastic or ductile manner with greater strain capacity during loading. As shown by earlier tests (Emery et al., 2022), reducing the paste fill's UCS typically produces a corresponding decrease in the Young's modulus of the material. If foamed CPB behaves as anticipated with increased porosity, it could mitigate brittle fracturing by providing a greater strain tolerance and a more plastic stress-strain response after reaching peak strength, thereby improving the stability of the in-place fill and enhancing the safety of underhand mining.

The cemented paste plant at the Lucky Friday Mine produces CPB consisting of dried, classified mill tailings, a pre-mixed binder composed of a blend of 75% slag cement and 25% Portland cement, and water, all of which is mixed to a consistency of about 72% solids. CPB mix designs depend on the intended location for the product underground and the required percentage of binder in the mix. In general, a 10% binder mix is used at intersections of the stope workings with slot drifts from the access ramps (intersection mix), and an 8% binder mix is used in the production stopes (stope mix). Because the Lucky Friday Mine has historical experience and substantial testing information with these mixes, the 8% and 10% binder mixes were used as the base mixes for this study.

Aerix agreed to perform initial batching and testing to identify the properties of a range of potential mix designs. Following the initial batching and testing, Aerix batched additional samples from selected mixes and shipped them to the NIOSH Spokane Research Laboratory (SRL) in Spokane, Washington for advanced testing to determine the stress-strain relationships of the various mixes. Tailings and binder for batching the samples were provided by the Lucky Friday Mine along with batch recipes for the 8% and 10% binder mixes.

An objective of the initial testing was to batch and conduct UCS tests with the base mixes to provide a comparison with similar data obtained through NIOSH testing and to obtain a starting density for the base mixes. A further objective was to add foam at varying percentages to each of the base mixes and thereby, acquire an understanding of how much foam could be added to the mix and still meet the necessary strength requirements. A minimum UCS of 200 psi (1.4 MPa) at 7 days was established for this study, and this limit was used to guide any adjustments to the mix designs as the work proceeded. The base mix strengths and densities were used for comparison to the foamed-paste mixes to provide a target density for the foam addition and to calculate the actual percentage of foam added.

The UCS of a cellular concrete mix is directly related to its density. As a result, the addition of foam not only lowers the density of a mix but also its resultant UCS. Based on experience, the following six mix designs were selected for initial batching and testing: 1) 8% binder base mix – no foam, 2) 8% binder base mix – 5% foam, 3) 8% binder base mix – 10% foam, 4) 10% binder base mix – no foam, 5) 10% binder base mix – 20% foam, and 6) 10% binder base mix – 30% foam. Each mix design was tested at 7, 14 and 28 days of curing. Three test cylinders were tested at each age for a total of 9 cylinders for each batch or mix design. Nominal 3x6-inch (75x150-mm) cylinder molds were used to cast the samples.

The equipment used to batch cellular concrete can vary widely, especially between the laboratory and the field. Particularly with neat-cement mixes, the type of batching equipment can affect the resultant strength of the material, depending on the shear applied to the ingredients and the efficiency with which they are mixed. For this study, the equipment used for batching the samples consisted of a Collomix high-efficiency hand-held paddle mixer, an 8-gallon (30.3 L) plastic tub to mix the ingredients, and a laboratory-scale Aerix foam generator.

All 6 mix designs were batched on the same day, with the two base mixes batched first to acquire baseline densities. Because the base mix recipes for the Lucky Friday Mine consisted of component quantities per cubic yard, the quantities for the mix constituents had to be scaled down to laboratory amounts that would fit in the mixing bucket and fill the nine cylinders. A sample was collected to determine the specific moisture content of the tailings, and this value was used to adjust the amount of water that was added as part of the total ingredients. The calculated ingredient quantities were then weighed, placed in a mixing bucket, and blended with a paddle mixer. After mixing for about 1.5 minutes, a sample was collected in a container of known volume and weighed to determine the starting densities of the base mixes.

Foam is introduced to a cellular concrete base mix in one of two ways. The first is a simple batch-mix method where the base mix is contained in a mixer or container. The foam is then directly injected into the mixer and then blended. The targeted density is reached by timing the foam into the mixer at a known rate or by taking successive density measurements. The second method is called inline injection where the base mix is pumped, and the foam is injected directly into the pumped-grout stream. Inline injection provides a more efficient, continuous grouting method with a higher production capability. For this study, the foam for the CPB samples was introduced by the batch-mix method.

The amount of foam that is added to a mix to achieve a targeted percentage of foam is determined by a comparison to the starting density of the base mix. For example, if the starting density of the 10% binder intersection mix is 134.3 lbf/ft<sup>3</sup> (2,151 kg/m<sup>3</sup>) and a 20% foam addition is desired, then the targeted density of the mix after adding foam would be 134.3 lbf/ft<sup>3</sup> divided by 1.2 or 111.9 lbf/ft<sup>3</sup> (1,792 kg/m<sup>3</sup>). This method is not completely accurate because each addition of foam adds an incremental weight to the calculation, but it is close. The various foam additions for each batch were determined by this method.

After each mix was batched, the required number of cylinders were molded in 3x6-inch (75x150-mm) PVC cylinders and capped. The cylinders were marked with pertinent information including mix

number, cast date, binder content, and foam content. The cylinders were then placed in a large plastic tub with a lid and a rack to keep the cylinders off the bottom of the tub. A steel container with a small tank heater provided high humidity and a warm temperature to simulate conditions in the mine. Conditions in the tub were monitored by means of a hygrometer and a thermometer. Typically, the temperature was around 85°F (29°C) to 90°F (32°C), and the humidity ranged from about 80% to about 85%. The Lucky Friday Mine cures their CPB samples at a similar high temperature to more closely represent the curing conditions underground.

UCS tests were conducted with three samples from each mix at 7 days, 14 days, and 28 days of curing. Prior to testing at 7 days and 14 days, the samples were removed from the humidity tub, demolded, and allowed to air-dry for 24 hours. Samples to be tested at 28 days were removed from the humidity tub at 25 days, demolded, and allowed to air dry for 3 days prior to testing in accordance with ASTM C495.

Average 28-day UCS test results are shown in Table 1 below. It is evident that as the foam content increases, the strength of the material decreases. Though, to better understand how the foam additive impacts the backfill ductility, a complete stress-strain curve is needed. From that, Young's Modulus can be determined as well as post-peak behavior.

**Table 1.** Summary of Results for UCS Testing of Foam Mix Designs at Aerix Laboratory.

Mix Design		Average 28-Day UCS <sup>1</sup> (psi)
Binder	Foam	
8%	0%	590
8%	5%	530
8%	10%	380
10%	0%	650
10%	20%	340
10%	30%	220

<sup>1</sup> Unconfined compressive strength after 28 days of curing

**Batching for Advanced UCS Testing by NIOSH**

To obtain the complete stress-strain curve for the selected mix designs, Aerix batched, molded, and cured the samples in their laboratory and then shipped them to the SRL for advanced testing. As in the initial tests, the 8% and 10% binder recipes were used for the base mixes prior to adding foam. Six total mix designs were batched, consisting of 8% binder mix with 5%, 10%, and 20% foam additions and 10% binder mix with 10%, 20%, and 30% foam additions. Four 3x6-inch (75x150-mm) cylinders were molded from each mix. Aerix retained one cylinder for testing at 28 days and shipped three cylinders to NIOSH for 28-day tests. All samples were cured in a humidity tub in the same manner as the cylinders from the initial round of testing. At 19 days of age, the cylinders were removed from the humidity tub, packed in a cooler with bubble wrap to prevent movement, and shipped to SRL for further testing. Upon receipt, NIOSH researchers unpackaged the molds and stored the cylinders in a humidity-controlled curing chamber for the remainder of the curing period.

**Test Preparation at NIOSH Spokane Research Lab**

Per ASTM C495, after 25 days of curing, NIOSH researchers removed the samples from their molds, allowing them to air dry for 3 days in preparation for 28-day UCS tests. The naming convention for the samples was *binder percentage – foam percentage – iteration number* (e.g., 10% binder, 10% foam, second iteration or 10B-10F-02). After curing for 28 days, each of the samples were measured and weighed following ASTM C495 and then sulfur-capped following ASTM C617 (2015), "Standard Test Method for Capping Cylindrical Concrete Specimens."

All UCS testing was conducted on a stiff-framed, servo-controlled electro-hydraulic 200,000-lbf (889,644-N) Tinius Olsen 1000SL test machine, following ASTM C495. A preload of 50 lbf was applied to each sample prior to running the compression test. Depending on the mix design, the loading rate was adjusted to ensure conformance to the standard and ranged from 0.01 in/min (0.25 mm/min) to 0.02 in/min (0.5 mm/min), increasing with the rise in foam content.

**TEST RESULTS**

To better represent the data, one sample was selected to represent all three samples from each of the six mix designs. Representative samples were selected based on the duration of their post-peak behavior captured during the test, as well as conformance to data trends observed during the study. Measurement data for representative samples are shown in Table 2, and test results are recorded in Table 3. The highest average 28-day UCS was 500 psi (3.4 MPa) for the 10% binder and 10% foam representative sample (10B-10F-01) followed by 430 psi (3 MPa) and 390 psi (2.8 MPa) for the 8% binder, 5% foam (8B-5F-01) and 10% binder, 20% foam (10B-20F-02) representative samples, respectively.

**Table 2.** Measurement Data for Representative Samples.

Mix Design		Average Diameter (in)	Average Height (in)	Density (lb/ft <sup>3</sup> )
Binder	Foam			
8%	5%	3.00	5.24	120.0
8%	10%	3.00	5.28	114.5
8%	20%	3.00	5.04	110.0
10%	10%	2.99	5.18	117.5
10%	20%	3.00	5.27	107.5
10%	30%	3.00	5.26	97.5

**Table 3.** Summary of Results for UCS and Young's Modulus Testing of Foam Mix Designs.

Mix Design		Average 28-Day UCS <sup>1</sup> (psi)	Average Young's Modulus <sup>2</sup> (10 <sup>3</sup> psi)
Binder	Foam		
8%	5%	430	200
8%	10%	310	120
8%	20%	260	120
10%	10%	500	170
10%	20%	390	160
10%	30%	230	90

<sup>1</sup> Unconfined compressive strength after 28 days of curing

<sup>2</sup> Calculated using the tangent modulus computed at 50% of UCS for the 28-day samples

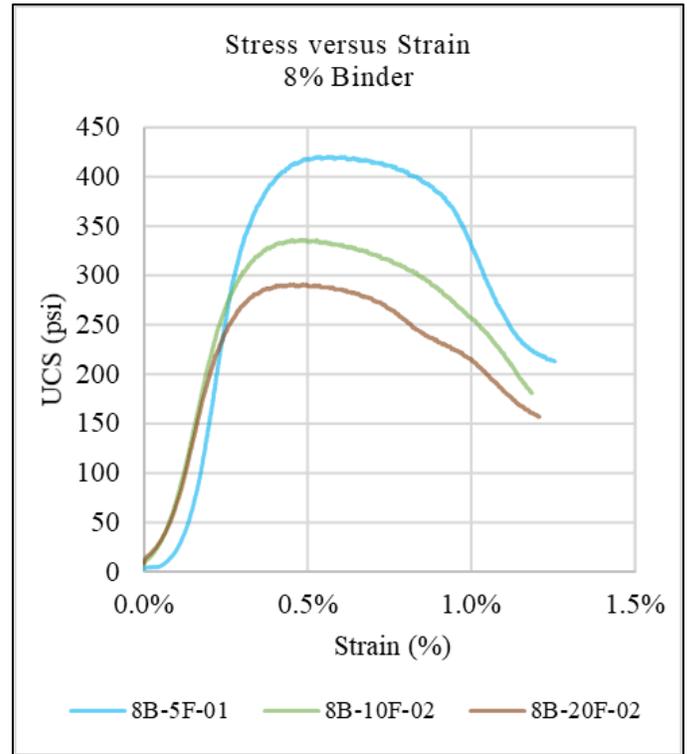
Stress versus strain plots are shown for representative samples from the 8% binder mixes in Figure 2 and the 10% binder mixes in Figure 3. These plots compare the results of representative samples from the same binder mix having different foam contents. In general, the ultimate strength was realized at about 0.5% to 0.75% strain. Each of the mix designs shows a gradual transition from elastic to plastic deformation, with more prolonged and better-defined ductility as the foam content increased.

**OBSERVATIONS**

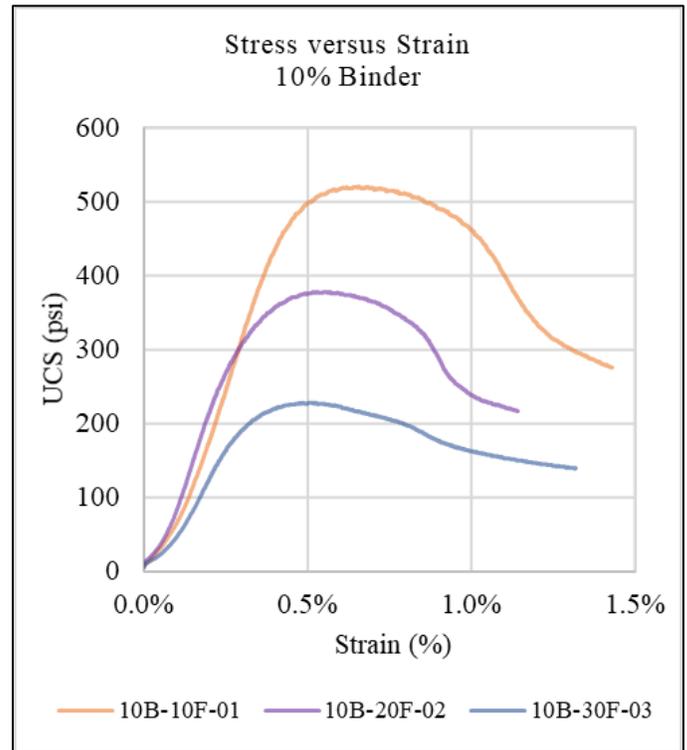
An inspection of the tested specimens revealed that the fracture patterns for the samples coincided with the Type 1 fracture pattern (Figure 4) mentioned in ASTM C39/C39M-21 (2021). This typical fracture pattern is shown in Figure 5 for sample 10B-30F-03 after testing.

The stress versus strain plots shown in Figures 2 and 3 indicate that, in general, as the foam content of the mix increases, the UCS and Young's modulus decrease, regardless of binder content. This trend is also shown in Figure 6, where the stress-strain curve for the standard stope mix is compared with representative curves for the selected foam additive mixes. In an earlier study reported by Emery et al. (2022), NIOSH researchers varied the percentage of binder in traditional CPB mixes to determine the effect of binder content on the elastic and post-peak properties of similar samples. Young's modulus is clearly affected by the foam additive as shown by the shift in the elastic portions of the stress-strain curves and the prolonged post-peak plastic deformations compared to the standard mix curve. All the foam mix designs reached their ultimate UCS much later than the standard mix, demonstrating their higher strain capacity. The CPB foam mix designs with the highest ultimate UCS (10% binder – 10% foam, 8% binder – 5% foam, and 10% binder – 20% foam) all achieved their

ultimate UCS after the standard stope mix was beginning to fail. As compared to the standard stope mix, the foamed backfill curves had much more ductile or "softer" transitions at the yield point during the transition from elastic to plastic deformation.



**Figure 2.** Stress versus strain plot comparing representative samples containing 8% binder and 5%, 10%, and 20% foam contents.



**Figure 3.** Stress versus strain plot comparing representative samples containing 10% binder and 10%, 20%, and 30% foam contents.

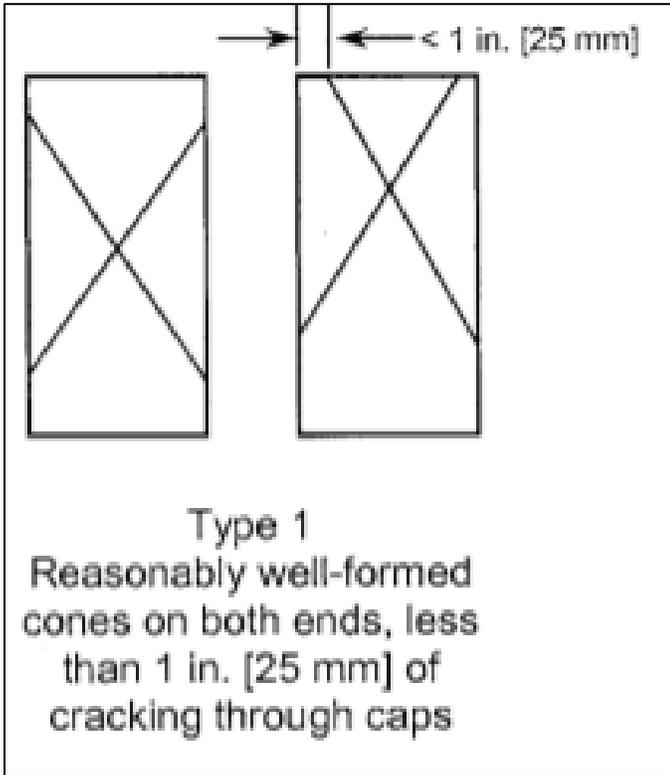


Figure 4. Type 1 fracture pattern defined by ASTM C39/C39M-21, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.



Figure 5. Sample 10B-30F-03 showing a Type 1 fracture pattern as defined by ASTM C39/C39M-21.

A performance summary chart is shown in Figure 7 that compares the ultimate UCS, UCS at 1% strain, and Young's modulus for the average test results of the different foamed backfill mixes. The average UCS at 1% strain is below the 200-psi (1.4-MPa) minimum strength requirement for some of the samples—mix 10B-30F (10% binder, 30% foam) and mix 8B-20F (8% binder, 20% foam). Mix designs 8B-5F (8% binder, 5% foam) and 10B-10F (10% binder, 10% foam) appear to best balance the requirements for low ultimate strength and minimum

strength at post-peak strain. However, further testing under field conditions is needed to confirm these findings.

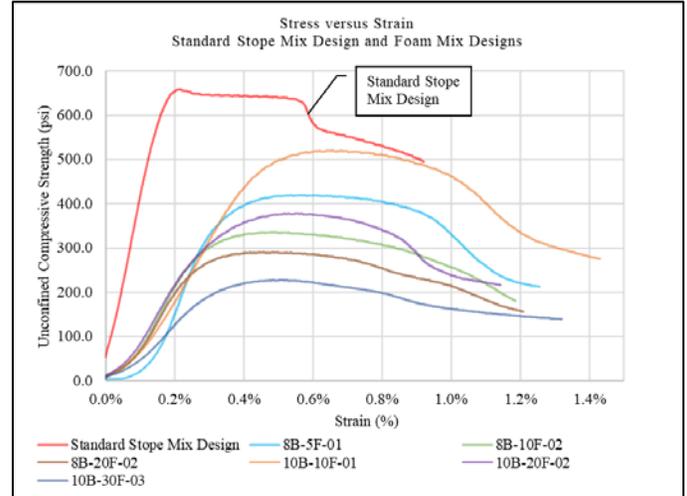


Figure 6. Stress versus strain plot comparing selected foam mix designs with a standard stope mix.

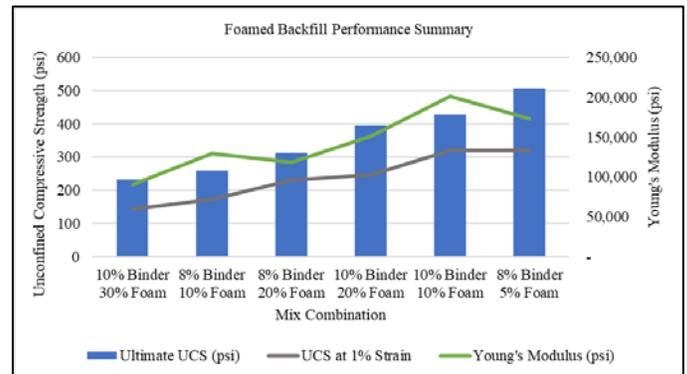


Figure 7. Plot comparing UCS and Young's Modulus from average test results for each foam mix design.

### CONCLUSIONS

This study demonstrates the effects of foam additives on the mechanical behavior of cemented paste backfill (CPB), with a notable decrease in ultimate unconfined compressive strength (UCS) and Young's modulus as the percentage of foam increased. For the 8% binder samples, compared to the 5% foam samples, the 10% foam and 20% foam samples showed a decrease in ultimate UCS of 28% and 40%, respectively, while the average Young's Modulus showed a decrease of 40% and 40%, respectively. Similarly, for the 10% binder samples, compared to the 10% foam samples, the 20% foam and 30% foam samples showed a decrease in ultimate UCS of 22% and 54%, respectively, while the average Young's Modulus showed a decrease of 6% and 47%, respectively. An interesting result from this study is observed regarding the average Young's Modulus for the 8% binder, 10% foam and 20% foam samples. Both showed a 40% decrease compared to the 5% foam samples. This is likely due to an anomalously low value for Young's modulus for sample 8B-10F-03—80,000 psi (551 MPa). Omitting this sample yields an average Young's modulus of 140,000 psi (965 MPa) for the 8% binder, 10% foam samples, which more closely aligns with the other test results.

In summary, these observations are consistent with the overall objective of this case study—developing a more ductile CPB mix to improve the stability of in-place fill during underhand cut-and-fill mining. To verify these lab results and ensure that cellular CPB is a suitable material for backfilling applications in underground mines, additional field tests need to be conducted under actual mining conditions. Nevertheless, the lower density of cellular CPB and its increased

flowability in pumping applications are promising and merit further study for additional mining applications.

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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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