Centers for Disease Control and Prevention
STEPHEN B. THACKER
CDC LIBRARY

Interlibrary Loans and Journal Article Requests

Notice Warning Concerning Copyright Restrictions:

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted materials.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One specified condition is that the photocopy or reproduction is not to be *"used for any purpose other than private study, scholarship, or research."* If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

Upon receipt of this reproduction of the publication you have requested, you understand that the publication may be protected by copyright law. You also understand that you are expected to comply with copyright law and to limit your use to one for private study, scholarship, or research and not to systematically reproduce or in any way make available multiple copies of the publication.

The Stephen B. Thacker CDC Library reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Terms and Conditions for items sent by e-mail:

The contents of the attached document may be protected by copyright law. The CDC copyright policy outlines the responsibilities and guidance related to the reproduction of copyrighted materials at CDC. If the document is protected by copyright law, the following restrictions apply:

- You may print only one paper copy, from which you may not make further copies, except as maybe allowed by law.
- You may not make further electronic copies or convert the file into any other format.
- You may not cut and paste or otherwise alter the text.

ARMA 15-776

Strength and Elastic Properties of Paste Backfill at the Lucky Friday Mine, Mullan, Idaho

Johnson, J.C., Seymour, J.B., Martin, L.A., Stepan, M. and Arkoosh, A.
National Institute for Occupational Safety and Health, Spokane, Washington, U.S.A.
Emery, T.
Hecla Mining Company, Coeur d'Alene, Idaho, U.S.A.

This paper was prepared for presentation at the 49th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 28 June-1 July 2015.

ABSTRACT: At underground mines where cemented backfill is used for ground support, backfill strength properties are an important design consideration, particularly for underhand cut-and-fill mining operations where employees work directly beneath the placed fill. Following a backfill roof fall at a deep underground silver mine, standard tests were conducted to determine the strength and elastic properties of a typical paste backfill composed of cemented mill tailings. Unconfined compression tests and direct and indirect tensile tests were conducted with core samples obtained from paste fill slabs recovered from the roof fall. Test results indicated that the average tensile strengths determined by indirect methods (Brazilian and splitting tensile tests) were about twice the average tensile strength measured by direct tensile tests. To identify cold joints within the backfill, in situ direct tensile tests were also conducted on one of the larger backfill slabs using experimental test equipment. The results of these in situ tests were similar to the direct tensile tests and provided little evidence of additional cold joints within the slab. Elastic properties of the paste backfill were determined through compression tests with strain-gauged core samples. The results of this study are significant because they add to the sparse strength and elastic property data that are available for mine designs utilizing paste backfill.

1. INTRODUCTION

Ground falls are typically the leading cause of fatalities in underground metal mines and a significant source of lost-time injuries [1]. As a result, a well-developed ground support plan needs to be consistently implemented to safely mine under these conditions. In deep underground metal mines, underhand cut-and-fill mining methods are used to mine narrow, steeply dipping veins of ore [2, 3]. In some of these mines, a paste backfill composed of cemented mill tailings is used to support the mined-out stopes or cuts. This cemented backfill forms a massive beam that provides a safe, stable back or roof for the miners who work beneath it on subsequently deeper cuts. The stability of this engineered beam is largely determined by two variables—its thickness and strength. Figure 1 shows computed factors of safety for twelve hypothetical backfill beams using four values of thickness and three values of strength [4]. As indicated by these curves, the thickness of the backfill beam is the primary immediate concern, but the backfill's strength becomes more important as the thickness of the beam increases.

In April 2014, a large backfill roof fall occurred in the 15W stope at the Lucky Friday Mine, a deep underground silver mine operated by the Hecla Mining Company near Mullan, Idaho. This backfill failure was later attributed to a wider than expected stoping span and the presence of flat-lying cold joints in the paste fill. The cold joints are thought to have reduced the effective thickness of the backfill beam allowing thinner sections of the beam to fail, more than likely in bending [4]. Following this event, a study was initiated between the National Institute for Occupational Safety and Health (NIOSH) Spokane Mining Research Division (SMRD) and the Hecla Mining Company to quantify the mechanical properties of the paste backfill.

In underhand cut-and-fill stopes, the in-place backfill usually fails in flexure. Therefore, the tensile strength of the paste fill was of interest, particularly reductions in tensile strength caused by the presence of cold joints within the paste backfill. To address this concern, a shotcrete adhesion test system developed by Seymour, et al. [5, 6] was adapted to perform in situ direct tensile tests with paste backfill. In addition, the compressive strength and elastic properties of the paste fill were also needed for a comparative analysis of mine designs using numerical models. This paper presents the results of these mechanical property tests and describes the equipment and procedures that were used to conduct the in situ direct tension tests.

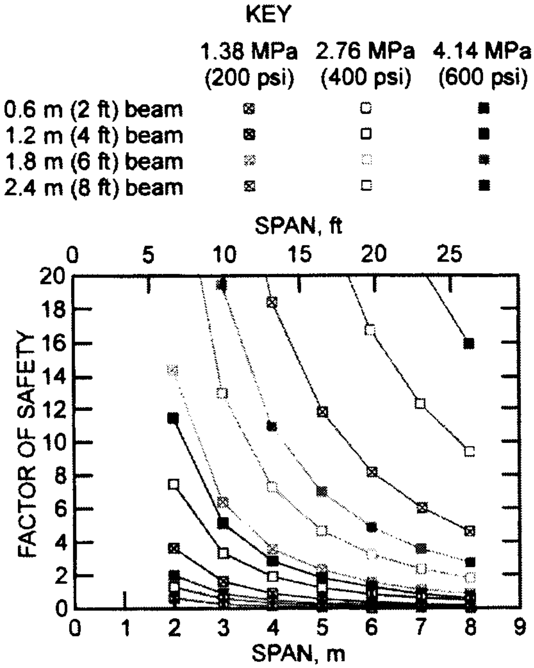

Fig. 1. Factor of safety (flexural failure) versus span length for twelve hypothetical paste backfill beams with varying thicknesses and compressive strengths.

1.1. Mining with Backfill

Figure 2 shows a typical stope that is being prepared for backfilling. The first step is to spread a layer of broken waste rock or muck on the floor about a 0.15 m (0.5 ft) thick. Steel reinforcement bars or rock bolts are placed into this muck on a 1.2 m by 1.2 m (4 ft by 4 ft) square pattern. The bolts are fitted with steel plates and nuts and then wired together. A sturdy wooden fill fence is constructed at the lower elevation of the stope to contain the backfill and allow for the draining of any excess water. This dam is purposely constructed about 2/3 of the height of the stope to restrict the depth of the pour and thus, limit the thickness of the backfill beam to normally about 2.4 m (8 ft). As a result, a void is intentionally created above the upper surface of the backfill beam.

After the paste fill has cured, a subsequent cut is mined in the vein beneath the backfill. As the loose muck falls away or separates from the bottom of the backfill beam, mesh (usually cyclone fencing) is attached to the exposed bolts to further reinforce the bottom surface of the backfill. Additional bolts are installed as needed to support the mesh and reinforce the backfill. The paste fill, bolts, and mesh thus form a massive structural beam that provides a stable mine roof for the miners working beneath it. As the underhand stope is mined further beneath the backfill, the walls of the stope will begin to converge in response to the high ground stresses at these depths. This horizontal closure exerts pressure on the sides of the backfill beam, eventually causing it to fail in tension or flexure on its upper surface. The upper portion of the backfill beam is not reinforced with bolts or mesh, nor is it confined. The void above the backfill beam provides space into which the paste fill can fail. Allowing the backfill to fail on the upper surface of the beam creates a safer environment for the miners who are working directly beneath the reinforced bottom portion of the beam.

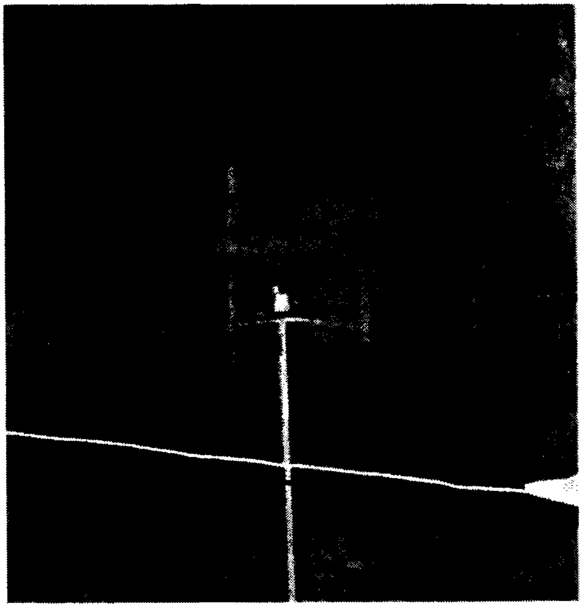

Fig. 2. Preparing a stope for backfill.

The underhand cut-and-fill mining method works well the majority of the time. However, in extreme conditions with long transport distances, high temperatures, and inconsistent placement processes, physical changes can occur in the paste fill that detrimentally affect its intended mechanical properties. Therefore, a suite of laboratory tests were conducted to quantify the strength and elastic properties of the paste backfill.

2. PASTE BACKFILL MECHANICAL TESTS

The material used for the tests was obtained from two slabs that fell from a roof fall in the 15W stope of the mine. These two slabs were placed on shipping pallets and transported to the SMRD laboratory located in Spokane, Washington. The larger slab was covered with plastic and stored in a secured area behind the facility for in situ direct tension tests. The smaller slab was used to acquire material for standard mechanical property tests. This slab was moved indoors where a set of core samples were obtained using a portable stand-mounted electric drill (Hilti model DD 130) equipped with a 8-cm (3-in) diameter diamond core bit (Figure 3). The cores obtained from the small slab are shown in Figure 4. The color of the core indicates oxidation. The original color of the paste backfill is gray appearing at the centers of the cores. The ends of the core (pointed to by the fingers of the hand) are nearest to the surfaces of the slab and are redder in color due to oxidation of the iron in the mill tailings.

Fig. 3. Core drilling of the smaller paste backfill slab.

Fig. 4. Cores obtained from the small paste backfill slab.

2.1. *Brazilian Tensile Strength*

Fourteen Brazilian tests were conducted according to ASTM D 3967 procedures using a Tinius Olsen (12,000 lb) servo-controlled press. Figure 5 shows the test specimens and two of the typical failures. Table 1 lists the results from the Brazilian tensile strength tests. The average Brazilian tensile strength (BTS) was 0.47 MPa (68 psi) with a standard deviation of 0.14 MPa (20 psi) and a coefficient of variation of 30%. The average specific gravity was 2.12 with a standard deviation of 0.02 and a coefficient of variation of 1%.

Fig. 5. Brazilian test specimens and typical failure.

Table 1. Brazilian tensile strengths for paste backfill samples.

No.	Length cm	Diameter cm	Weight gm	Load N	BTS MPa
1	3.57	6.90	275.0	1668	0.43
2	3.56	6.87	282.1	1197	0.31
3	3.59	6.88	280.5	1797	0.46
4	3.59	6.90	283.4	1770	0.46
5	3.58	6.90	283.7	1890	0.49
6	3.58	6.89	280.1	881	0.23
7	3.59	6.87	280.2	1948	0.50
8	3.58	6.90	280.9	1997	0.51
9	3.58	6.90	280.4	2291	0.59
10	3.57	6.90	283.7	2153	0.56
11	3.57	6.88	287.3	3003	0.78
12	3.57	6.87	280.8	1134	0.29
13	3.58	6.88	281.9	1815	0.47
14	3.56	6.87	279.6	1681	0.44

2.2. *Splitting Tensile Strength*

Five splitting tensile strength tests were conducted according to ASTM C 496 procedures using a Reihle (200,000 lb) press. This test is commonly used in concrete construction. The advantage of the splitting tensile strength test is that only one specimen size is needed for both compression and tension testing. A special jig is required to hold the specimen in a horizontal position. Between the specimen and the loading platens are two thin wood strips that deform to the curvature of the specimen and are replaced after each test as shown in Figure 6. A typical failure is shown in Figure 7. The results from the splitting tensile strength tests are listed in Table 2. The average splitting tensile strength (STS) was 0.57 MPa (83 psi) with a standard deviation of 0.10 MPa (15 psi) and a coefficient of variation of 18%. The average specific gravity was 2.10 with a standard deviation of 0.01 and a coefficient of variation of 0.5%.

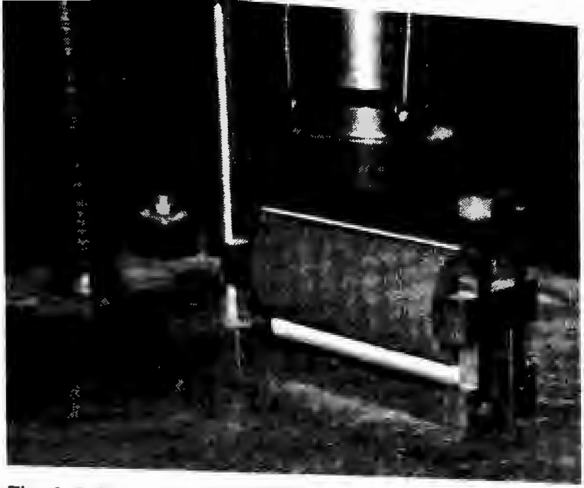

Fig. 6. Splitting tensile strength test.

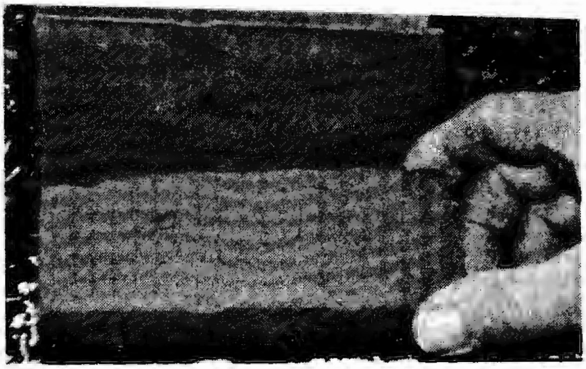

Fig. 7. Typical splitting tensile test failure.

Table 2. Splitting tensile strengths for paste backfill samples.

No.	Length cm	Diameter cm	Weight gm	Load N	STS MPa
1	13.82	6.91	1078.2	7313	0.49
2	13.83	6.90	1094.0	6348	0.42
3	13.83	6.91	1089.7	10,040	0.67
4	13.79	6.91	1095.6	10,307	0.69
5	13.84	6.89	1079.7	8839	0.59

2.3. Direct Tensile Strength

The truest test for tensile strength is obtained by direct tension. Five specimens were tested according to ASTM D 2936, where the specimen was pulled apart. Steel end caps were first epoxied to the ends of each specimen. A chain was attached to the end of each endcap. The chain allows for a straighter pull that minimizes shearing moments applied to the specimen. Attached to the chain was a bolt that was attached to the loading head of the Tinius Olsen press as shown in Figure 8. Usually the specimen did not break horizontally through its center but nearer to one of the endcaps with some shear inclination as shown in Figure 9. Table 3 lists the results from the direct tensile strength tests.

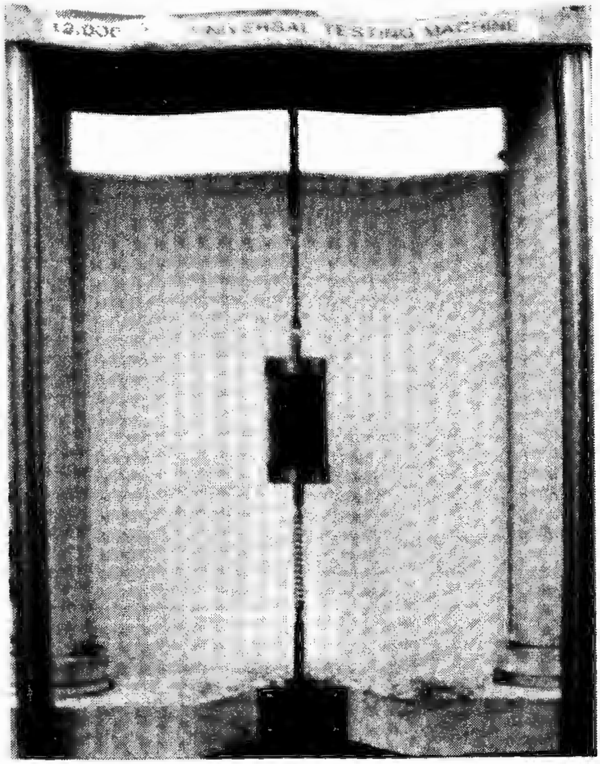

Fig. 8. Direct tensile strength test.

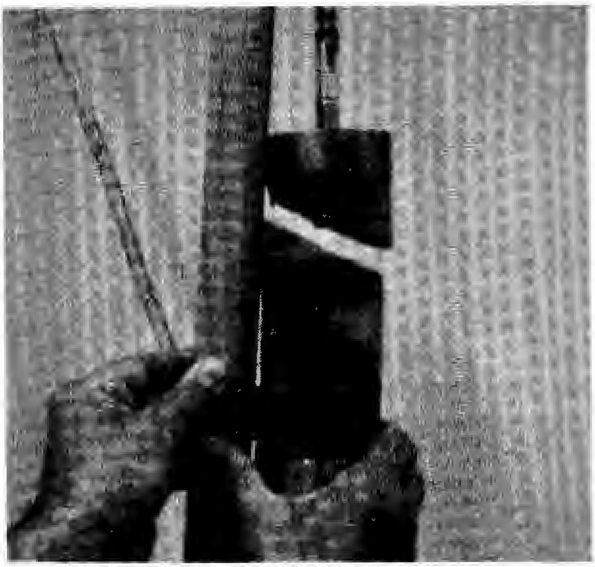

Fig. 9. Typical direct tensile failure.

The average direct tensile strength (DTS) of all five tests is 0.27 MPa (39 psi) with a standard deviation of 0.17 MPa (25 psi) and a coefficient of variation of 64%. Although the sample set is small, these values were recalculated as shown in Table 4. By eliminating both the largest and smallest values in the data range, the coefficient of variation was reduced to 10% while the average direct tensile strength remained very close to its original value.

Table 3. Direct tensile strengths for paste backfill samples.

No.	Length cm	Diameter cm	Weight gm	Load N	DTS MPa
1	13.88	6.91	951.1	13	0.02
2	13.84	6.90	1088.1	360	0.56
3	13.89	6.92	963.6	169	0.26
4	13.84	6.92	1083.2	151	0.23
5	13.84	6.93	1080.4	182	0.28

Table 4. Statistical results for direct tensile strength tests.

No. of Tests Used (Values Dropped)	Average MPa (psi)	Standard Deviation MPa (psi)	Coefficient of Variation
5	0.27 (39)	0.17 (25)	0.64
4 (low)	0.33 (48)	0.15 (22)	0.46
3 (low and high)	0.26 (37)	0.03 (4)	0.10

2.4. In Situ Direct Tensile Strength

A final set of direct tensile tests were performed directly on the larger paste fill slab using an experimental in situ test system that was originally developed for measuring the adhesion strength or bond strength of shotcrete in underground mines [5, 6]. The test involves a number of different drilling steps that produce an attached test core that is then pulled from the host material using a hydraulic ram. The hydraulic pressure at failure is used to compute the tensile failure force and thereby calculate the in situ direct tensile strength of the material. For these tests, the test core is pulled upward against gravity from the larger of the two slabs of paste backfill (Figure 10). This slab is about 1 m (3 ft) long by 1 m (3 ft) wide by 0.6 m (2 ft) high. In this slab, there appears to be a cold joint that lies about 15 cm (0.5 ft) below the top surface of the slab and varies from zero at the surface to a depth of about 30 cm (1 ft).

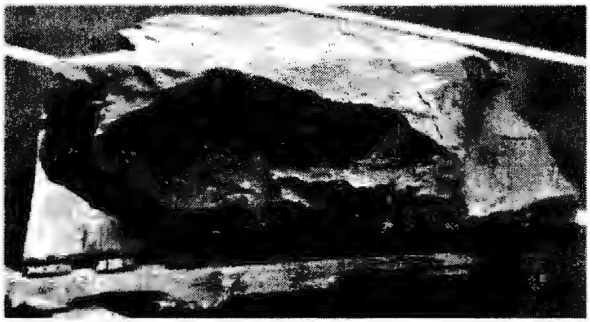

Fig. 10. Larger paste backfill slab on a wood pallet.

Two types of construction bolts, employing either a mechanical or epoxy anchoring system, were used. An electric hand drill was used to install two mechanical anchored bolts that along with wing-nuts secured the drill stand to the slab. The construction drill was attached to the drill stand and a water hose was connected to the drill. A series of drilling steps are then completed using this stand-mounted drill. The first is to drill a pilot hole for an epoxy anchored bolt as shown in Figure 11. This hole has a diameter of 1 cm (7/16 in) and is drilled to a depth of 6 cm (2.375 in). A two part, high strength epoxy is applied into this hole to anchor the spiral shaped pulling bolt into the slab as shown in Figure 12. The pulling bolt is inserted into this hole, and the epoxy is allowed to cure as shown in Figure 13. The epoxy manufacturer's directions specify one hour of cure time at temperatures above 21 degrees C (70 degrees F).

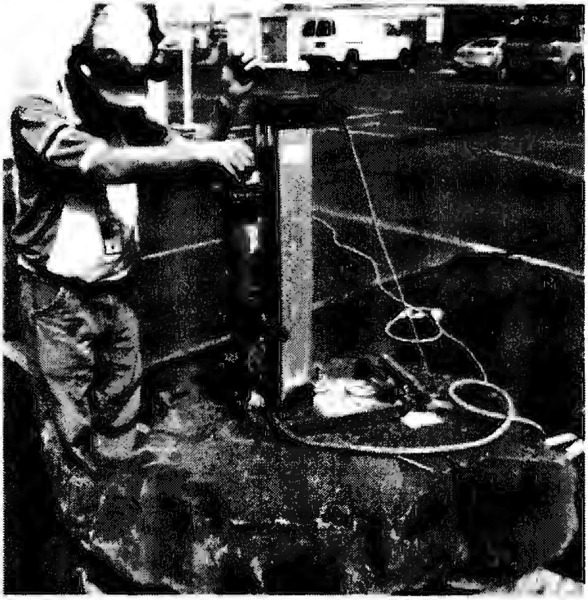

Fig. 11. Drill and stand attached to the backfill slab.

Fig. 12. Pilot hole filled with epoxy prior to insertion of pulling bolt.

Fig. 13. Pulling bolt placed in the epoxy and cured overnight.

However, this curing time proved to be inadequate because in the first four tests, the bolt was pulled out of the slab. The testing procedure was modified to provide more time for the epoxy to cure. This increased curing time was thought to be needed in order to compensate for the high moisture content in the slab. Tests were performed the following day after the epoxy had cured overnight. The next drilling step used a 10-cm (4-in) diameter core bit that was centered on the epoxied bolt as shown in Figure 14. This hole was drilled to a depth of 20 cm (8 in) into the interior of the slab creating the test core. The depth was marked with tape so that the bit would penetrate the joint but not exit the bottom surface of the slab as shown in Figure 15.

Fig. 14. 10 cm (4 in) core bit centered over the pulling bolt.

Fig. 15. The core bit is drilled to the depth of the blue tape.

The final drilling step was completed using a nominal 13-cm (5-in) diameter core bit. This hole was also centered on the pulling bolt, but it was only drilled to the shallow depth of its teeth to produce a kerf around the attached test core as shown in Figure 16. This kerf allowed the pulling fixture to be centered on the pulling bolt and aligned with its axis, thereby minimizing eccentricity during the direction tension test [5].

Fig. 16. Shallow kerf drilled around the test core using a 13cm (5 in) core bit.

A coupling nut is then attached to the pulling bolt, and a long piece of 0.9-cm (3/8-in) diameter all-thread is screwed into the coupling nut. The pulling fixture and hydraulic ram are than carefully inserted over the all-thread as shown in Figure 17.

Fig. 17. Hydraulic ram and pulling fixture being inserted over the all-thread.

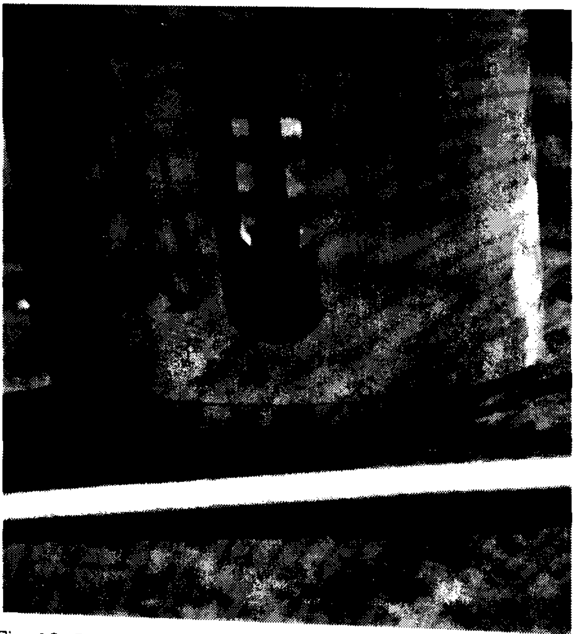

Fig. 18. Seating ring of pulling fixture inserted into kerf.

The seating ring on the pulling fixture is inserted into the kerf as shown in Figure 18. Washers and a speed nut are then attached to the all-thread near the top of the hydraulic ram as shown in Figure 19, and a hydraulic hand-pump, equipped with a pressure gauge, is attached to the hydraulic ram as shown in Figure 20.

Fig. 19. The hydraulic ram pushes upward against a nut attached to the all-thread that is in turn connected to a pulling bolt anchored in the test core.

During these in situ direct tension tests, the test cores generally showed one of the following three types of failure modes: tensile failure, shear failure, or a bolt pull-out failure. Most of the test cores broke in tension at a variety of depths. Figure 21 shows a typical tensile shallow failure. Figure 22 shows a deeper failure in the slab that also includes some shear because the failure surface is inclided about 45 degrees to the core axis. The failure surface can also be identified by inspecting the test hole as shown in Figure 23. A typical bolt pull-out failure is shown in Figure 24. Although the test cores were drilled to purposely intersect an assumed cold joint, only one of the test cores broke near that horizon. Figure 25 shows the longest of specimens being extracted from the slab, and Figure 26 shows that it might match the depth of the inferred cold joint in the slab. Depending on the type and length of failure, a single test hole was sometimes used for multiple tests. A new pilot hole was simply drilled, filled with epoxy, and a new pulling bolt inserted into the hole. In this manner, several tests could be conducted using a single drill set-up. Figure 27 shows the slab near the completion of these in situ direct tension tests.

Fig. 20. Performing an in situ direct tensile strength test.

Fig. 21. Typical shallow tensile failure in the paste backfill.

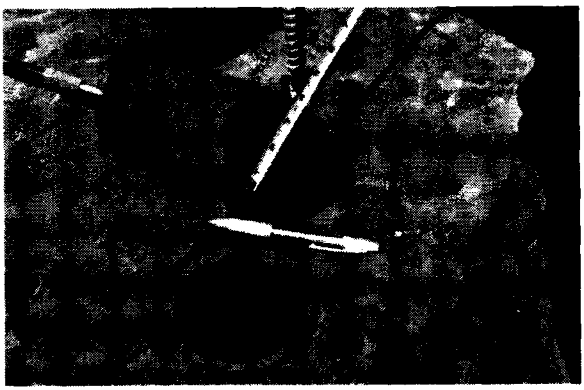

Fig. 22. Typical shear stress failure oriented about 45 degrees to the axis of the test core.

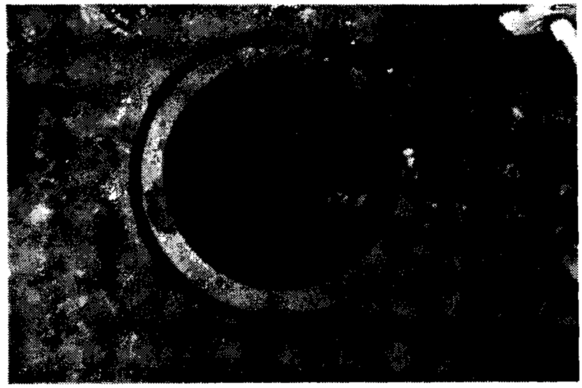

Fig. 23. Shear stress failure shown on the portion of test core remaining in the drill hole.

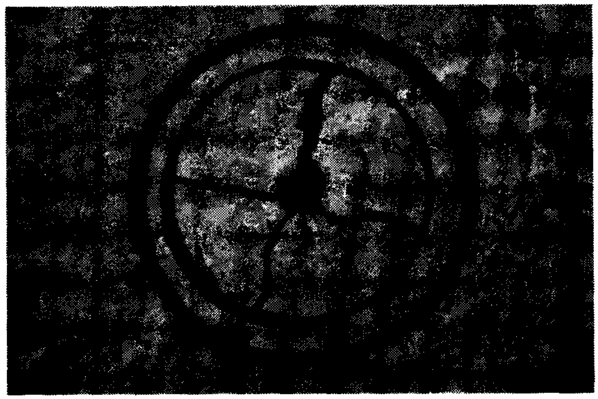

Fig. 24. Typical failure when the epoxy anchored bolt is pulled out of the slab.

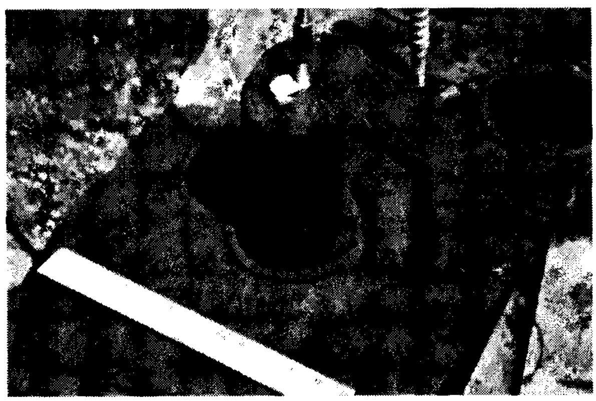

Fig. 25. Removing the longest test core from the backfill slab.

Fig. 26. Failure surface of core appears to match a cold joint.

Fig. 27. Paste backfill slab near the completion of in situ direct tensile testing.

A total of fourteen in situ direct tensile strength tests were conducted on the paste backfill slab. Even though the hydraulic hand pump was operated slowly, most of the tests were completed in about a half minute with the maximum pump pressure at failure automatically recorded on a digital pressure gauge. The maximum hydraulic pressure at failure ranged from 0.33 to 1.74 MPa (48 to 253 psi) with the most common value being about 0.69 MPa (100 psi). The maximum pressure, P was entered in Eq. (1) to compute the maximum tensile force applied to the paste fill core:

$$F = (2.718 * P) - 10.058 \qquad (1)$$

where,

F = The maximum tensile force applied to the core, lbf.

P = The maximum hydraulic pressure applied to the core, psi.

Because each test core was drilled using the same core bit, the cross-sectional area, A of the test core was assumed to be constant and computed using an average core diameter of 9.4 cm (3.70 in). As shown in Eq. (2), the in situ direct tensile strength, T of the paste fill core was computed by dividing the maximum tensile force, F by the cross-sectional area, A of the test core which is equal to 69.4 sq. cm (10.752 sq. in).

$$T = \frac{F}{A} \qquad (2)$$

The in situ direct tensile strength values for the paste fill slab are listed in Table 5. The average in situ direct tensile strength is 0.19 MPa (27 psi) with a standard deviation of 0.12 MPa (17 psi) and a coefficient of variation of 62%. These results are very similar to those obtained from the direct tension tests conducted in the laboratory.

Table 5. In situ direct tensile strengths for paste backfill slab.

No.	Max. Pump Pressure MPa (psi)	Max. Tensile Force N (lbf)	In Situ Direct Tensile Strength MPa (psi)
1	0.48 (70)	801 (180)	0.12 (17)
2	0.68 (99)	1152 (259)	0.17 (25)
3	0.65 (94)	1090 (245)	0.16 (23)
4	0.53 (77)	885 (199)	0.13 (19)
5	0.65 (94)	1090 (245)	0.16 (23)
6	0.34 (50)	560 (126)	0.08 (12)
7	0.34 (49)	547 (123)	0.08 (12)
8	0.65 (94)	1090 (245)	0.16 (23)
9	0.61 (89)	1032 (232)	0.15 (22)
10	1.74 (253)	3016 (678)	0.43 (62)
11	0.33 (48)	534 (120)	0.08 (12)
12	0.77 (111)	1299 (292)	0.19 (28)
13	1.70 (246)	2931 (659)	0.42 (61)
14	1.30 (188)	2229 (501)	0.32 (46)

2.5. *Compressive Strength Tests*

Unconfined compression tests were conducted with cores obtained from the smaller paste backfill slab. These core samples were cut to a length of about 14 cm (5.5 in), approximately twice their diameter. Prior to testing, the ends of the specimens were sulfur-capped because the paste fill material was too delicate for surface grinding. Unconfined compression tests were conducted using the Reihle press. The results of these compression tests are listed in Table 6. The average unconfined compressive strength (UCS) of the five test specimens was 4.15 MPa (602 psi) with a standard deviation of 0.33 MPa (48 psi) and a coefficient of variation of 8%. Figure 28 shows some of the typical shear failures exhibited by the compression test specimens.

Table 6. Unconfined compressive strengths for paste backfill samples.

No.	Length cm	Diameter cm	Weight gm	Load N	UCS MPa
1	13.79	6.93	1091.1	3845	4.54
2	13.78	6.92	1062.7	3155	3.72
3	13.80	6.94	1081.4	3605	4.24
4	13.81	6.93	1064.7	3205	3.79
5	13.82	6.93	1082.5	3766	4.44

Fig. 28. Typical failure for unconfined compression tests.

2.6. *Young's Modulus and Poisson's Ratio*

Before a strain gauge could be attached to a compression specimen, a small amount of epoxy was applied to selected locations on the surface of the specimen and allowed to cure. After the epoxy had cured, these areas were lightly sanded with 320 grit sandpaper, and then the strain gauges were bonded to these areas. This step was necessary for the strain gauges to adhere to the backfill. Figure 29 shows a strain gauged backfill specimen ready for testing. The typical compressive failure mode was in shear as shown in Figure 30.

The five stress-strain plots obtained from these tests are shown in Figure 31. All five tests produced similar results. The backfill does not have a linear relationship between stress and strain to failure. As the stress increased, the modulus of elasticity decreases becoming plastic as it approaches the ultimate compressive strength (UCS). However, the relationship between the horizontal and vertical strain is mostly linear as it approaches failure as shown in Figure 32. The absolute value of the ratio of horizontal to vertical strain near the center portion of the curve gives a constant value of 0.17 for Poisson's ratio.

Fig. 29. Strain gauges applied on top of cured epoxy.

Fig. 30. Typical failure in shear after compression loading.

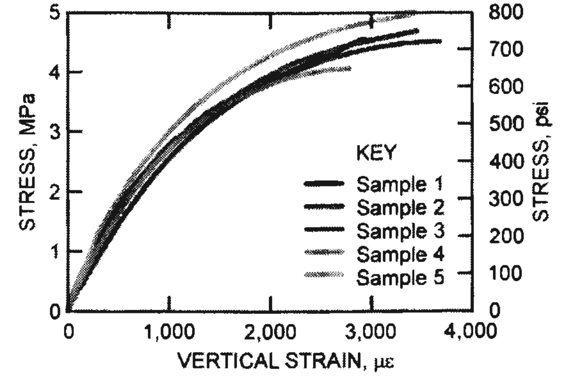

Fig. 31. Vertical stress versus vertical strain of paste backfill.

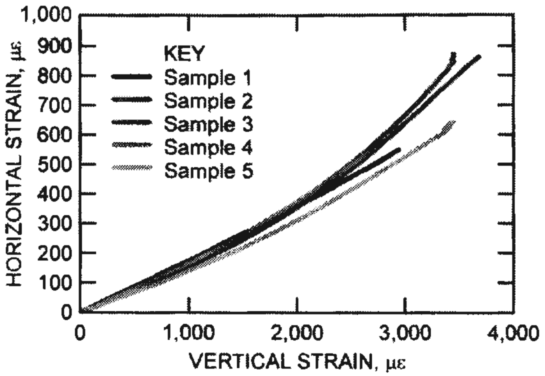

Fig. 32. Paste backfill horizontal versus vertical (axial) strain.

Because the stress-strain diagram of the paste backfill is non-linear it was divided into three segments at 30, 60, and 90 percent of the average UCS. This results in a three piecewise linear approximation to the non-linear curve. The separate plotted results are shown in Figures 33, 34, and 35. Young's modulus from 0-30% of its UCS is 3.59 GPa (0.52 million psi); from 30-60%, it is 2.28 GPa (0.33 million psi); and from 60-90%, it is 1.10 GPa (0.16 million psi).

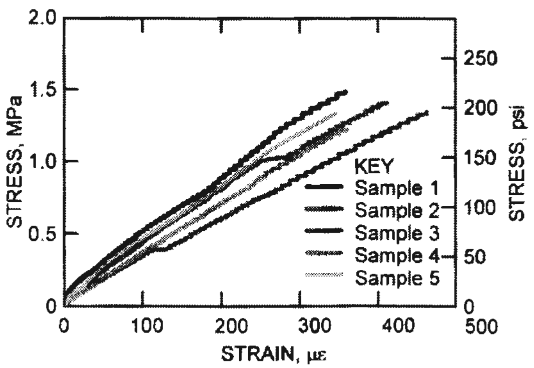

Fig. 33. Paste backfill stress vs. strain from 0 - 30% of UCS.

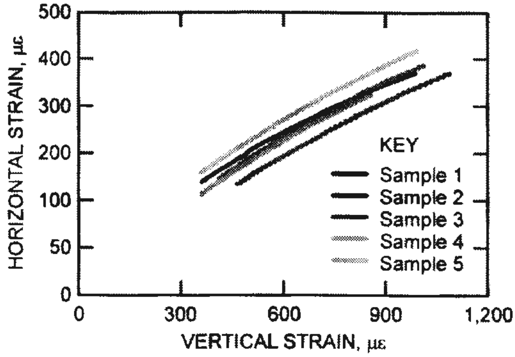

Fig. 34. Paste backfill stress vs. strain from 30 - 60% of UCS.

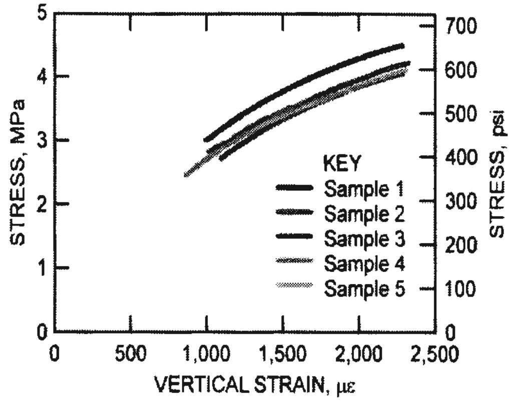

Fig. 35. Paste backfill stress vs. strain from 60 - 90% of UCS.

3. SUMMARY AND CONCLUSIONS

A summary of the results obtained from a suite of tests conducted with paste backfill samples from the Lucky Friday Mine are listed in Table 7. As shown by these results, the tensile strength of paste backfill is highly dependent on the testing method that is used. Although indirect tensile tests are easier to perform than direct tensile tests, the tensile strengths obtained using these indirect test methods can be much larger than those measured by direct tensile test methods. In this study, the average tensile strength of paste backfill, as measured by more accurate but more difficult to perform direct tensile strength tests, was about half the average tensile strength determined through Brazilian tests and splitting tensile tests conducted with similar paste fill samples.

Although an experimental in-situ direct tension test produced an average tensile strength for the paste backfill that was slightly lower, these tensile strength values were similar in magnitude to the results obtained from standard direct tensile tests. This in situ test method appears to be promising, but initial attempts to measure the tensile strength of paste fill across cold joints in a backfill slab were inconclusive. The majority of the test cores from the in situ direct tension tests exhibited failures that occurred in the backfill matrix and not along a predefined weakness plane such as a cold joint.

Table 7. Summary of the paste backfill mechanical properties (the capital letter M in the unit Mpsi means million).

Mechanical Property	Metric Units	Imperial Units
Unconfined Compressive Strength (UCS)	4.15 MPa	602 psi
Young's Modulus (0-30% UCS)	3.59 GPa	0.52 Mpsi
Young's Modulus (30-60% UCS)	2.28 GPa	0.33 Mpsi
Young's Modulus (60-90% UCS)	1.10 GPa	0.16 Mpsi
Poisson's Ratio	0.17	0.17
Specific Gravity	2.10	2.10
Brazilian Tensile Strength	0.47 MPa	68 psi
Splitting Tensile Strength	0.57 MPa	83 psi
Direct Tensile Strength	0.26 MPa	37 psi
In Situ Direct Tensile Strength	0.19 MPa	27 psi

Unconfined compressive strengths for the paste backfill samples exceeded the required design strength and were similar to values reported from previous research studies [7] and for tests recently conducted at the mine site [4]. Additional compression tests conducted with strain gauged samples of paste fill provided values for Young's Modulus and Poisson's Ratio that are seldom reported in the literature.

The unique findings from this study will hopefully provide better information regarding the strength and elastic properties of paste backfill and thus, aid in improving the design of ground support systems for underhand cut-and-fill mining methods, thereby enhancing the safety of underground miners working beneath the fill.

REFERENCES

1. Seymour, J.B., L.A. Martin, C.C. Clark, D.R. Tesarik, and M.A. Stepan. 2013. An analysis of recent MSHA accident data for underground metal mines using backfill. *SME Annual Meeting & Exhibit, Feb. 24-27, 2013, Denver, CO: SME Preprint No. 13-061*, 9 pp.

2. Williams, T.J., T.M. Brady, D.C. Bayer, M.J. Bren, R.T. Pakalnis, J.A. Marjerison, and R.B. Langston. 2007. Underhand cut and fill mining as practiced in three deep hard rock mines in the United States. In *Proceedings of the CIM Conference and Exhibition, Montreal, Quebec, Canada, April 29 - May 2, 2007*, pp. 1-11.

3. Emad, M.Z. 2013. *Dynamic performance of cemented rockfill under blast-induced vibrations.* PhD Dissertation, McGill University, Montreal, Quebec, Canada, Dec. 2013, 207 pp.

4. Emery, T. 2014. Paste fill assessment and revision. Internal Report, Hecla Mining Company, Lucky Friday Mine, Dec. 2014, 25 pp.

5. Seymour, B., L. Martin, C. Clark, M. Stepan, R. Jacksha, R. Pakalnis, M. Roworth, and C. Caceres. 2011. A shotcrete adhesion test system for mining applications. *Society for Mining, Metallurgy, and Exploration 2010 Transactions* 328: 533–541.

6. Martin, L.A, C.C. Clark, J.B. Seymour, and M.A. Stepan. 2015. *Shotcrete design and installation compliance testing: early strength, load capacity, toughness, adhesion strength, and applied quality.* Pittsburgh: US Department of Health & Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, NIOSH Report of Investigations, RI 9697, 108 pp.

7. Williams, T.J., D.K. Denton, M.K. Larson, R.L. Rains, J.B. Seymour, and D.R. Tesarik. 2001. *Geomechanics of reinforced cemented backfill in an underhand stope at the Lucky Friday Mine, Mullan, Idaho.* Pittsburgh: US Department of Health & Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, NIOSH Report of Investigations, RI 9655, July 2001, 18 pp.