Determination of Early-Age Ductility of Steel Fiber-Reinforced Shotcrete Lining System at INCO's Stobie Mine

by Jean-François Dufour, J. Denis P. O'Donnell, Sr., and Michael Ballou

The state of technology in shotcrete materials has evolved steadily throughout the world and particularly in North America during the last 20 years. The use of supplementary cementing materials such as silica fume, fly ash and slag, the new generations of chemical admixtures, and the development of various types of fibers (steel and synthetic) significantly enhance the performance of shotcrete for a variety of applications.

These technological advancements have led the international mining industry to become a major user of shotcrete for underground support. Because the potential for instability in underground rock openings is a threat to the safety of miners, the support of permanent openings in underground mining is a critical area of shotcrete application. For over 20 years, mining companies have recognized the value of steel fiber reinforcement in shotcrete. It has been proven that the performance of steel fiber-reinforced shotcrete compares favorably with steel-welded wire mesh reinforced shotcrete in various ground support applications.[1]

The introduction of steel fibers in shotcrete increases its energy absorption or "toughness," increases impact resistance, and provides increased ductility. Ductility is defined as the ability to continue to carry loads after the shotcrete microstructure has cracked. These mechanical properties are considered extremely important parameters with respect to support linings designed for the underground environment.[2] (The effects of addition rate, geometry, and property of fibers are beyond the scope of this article.)

Although the ability of steel fiber-reinforced shotcrete to carry loads in flexure beyond its flexural capacity can be assessed in laboratories using a variety of beam and panel test methods, the understanding of how to relate it to ground support design guidelines for underground mine development is limited and subjective.[3]

Test methods evaluating the load-carrying capacity of steel fiber-reinforced shotcrete (SFRS) performed after 7 and 28 days of curing do not assess the performance at early ages. Design assumptions for early re-entry in underground openings are therefore difficult to make because early-age behavior of shotcrete under stress has not been determined. In northern Ontario, Canada, a current practice in the mining industry is to allow the steel fiber-reinforced shotcrete, applied for primary ground support, to cure for 8 h before allowing miners to work under it. One of the design criteria is to consider the compressive strength of the shotcrete sufficient with a minimum requirement of 4 MPa (600 psi). It is common belief, however, that the mining and tunnelling industries show a large interest in extending this limit to determine how soon miners can safely return to work under shotcrete without steel welded-wire mesh applied for primary ground support.

The primary purpose of this study was to determine and validate, under field conditions, the postcrack behavior and capacity, or the energy absorbing capacity, at early ages of an accelerated SFRS mixture in comparison with an accelerated nonreinforced (plain) shotcrete mixture applied using the dry-mix method. This evaluation would provide design guidelines to help determine when earlier re-entry into mine headings can safely occur. In addition to this test, data on early-age compressive strength is presented to provide corroborative data.

The second objective of this study was to provide an on-site test method that would effectively demonstrate to mine personnel the performance of steel fiber-reinforced shotcrete linings and to increase general understanding of the practice of a safe re-entry to mine openings.

Testing Procedures and Equipment

The tests were performed in-situ, underground at various curing times within the first 24 h of the shotcrete application, as outlined in Table 1. The testing program was conducted at INCO Limited's

Table 1: Compressive strength development, MPa

Curing time (h)	Compressive strength at early age (apparatus moulds) (MPa)	Compressive strength (panels-cores) (MPa)	Curing time (days)
2	3.6 (520 psi)	27 (3920 psi)	1
4	5.1 (740 psi)	32.9 (4770 psi)	2
6	5.5 (800 psi)	37.1 (5380 psi)	3
8	6.6 (960 psi)	49.2 (7130 psi)	7
12	19.3 (2800 psi)	62.3 (9030 psi)	28
24	27 (3920 psi)		

Stobie Mine, on the wall of the 3840 cross-cut on the 3300 level. Two dry-mix shotcrete mixtures were tested. The first was an accelerated plain shotcrete mixture used as a control mixture. The second mixture was an accelerated SFRS mixture. Both shotcrete mixtures were produced at King Packaged Materials' Onaping Falls Facility and delivered to the project site.

To perform such a test program, two 30 tonne (33 ton) capacity pulling frames were used (refer to Fig. 1 and 2[5-7]).

The 254 mm (10 in.) diameter steel plates were mounted to the wall of the drift at a distance of approximately 1.2 m (47 in.) apart. The shotcrete mixtures were then applied over the plates to the desired test thickness (63.5 mm [2.5 in.]). A wooden plug was inserted into the hole in the center of the plate prior to shotcrete application to protect the threads of the nut (Fig. 3). The wood plug was removed soon after initial set of shotcrete.

The test frames were suspended from the existing screen above the test sites. A Dywidag steel rod was then passed through the test frame and threaded into the nut on the plate behind the shotcrete. A hollow cylinder hydraulic ram was used to pull the plates. The GRC testing frame was set up so that the load could be measured directly by a hollow load cell mounted on top of the hydraulic ram. The hydraulic pressure in the line to the ram was also measured for a backup. Displacement of the plates was measured relative to the testing frame.

A total of 12 steel plates were used to conduct the "early-age pullout" tests. To reduce the effect of variables in the testing, two plates were required for each test of the SFRS mixture. The test program was initially designed to conduct testing at 4, 8, 12, and 24 h (a total of eight plates). It was decided on site, however, that one plate would be tested at 2 h. It was therefore agreed to sacrifice one 12 h test. With respect to the control shotcrete mixture (without fibers), four plates were tested at 4, 8, 12, and 24 h at only one plate per test.

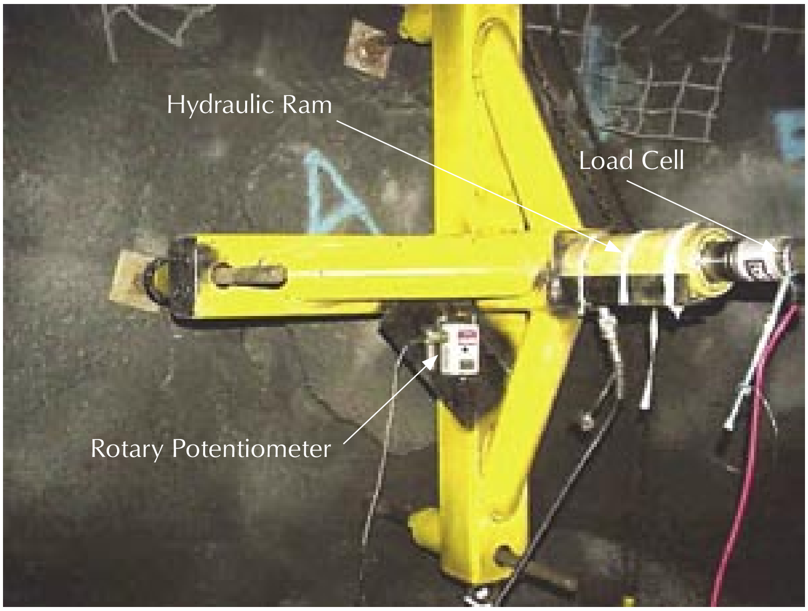


Figure 1: GRC sturdy loading (pulling) frame (modified version).

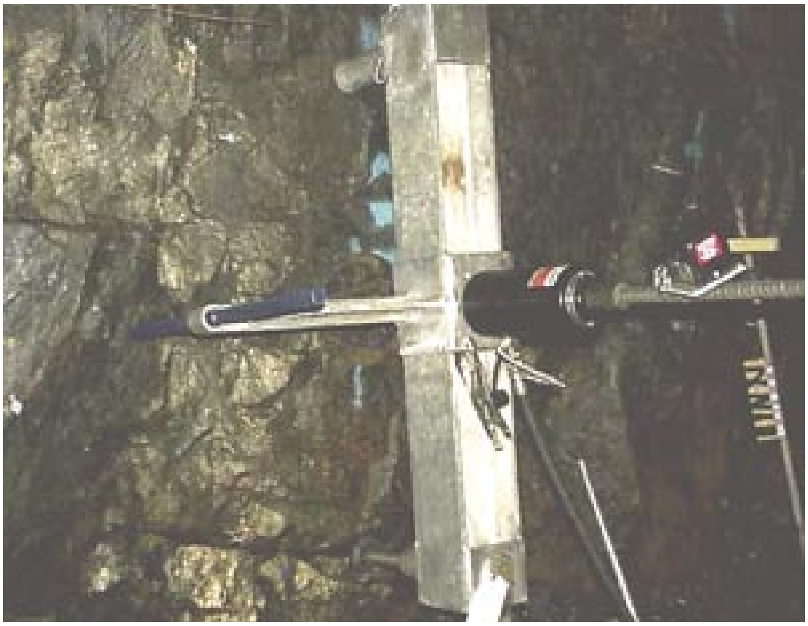
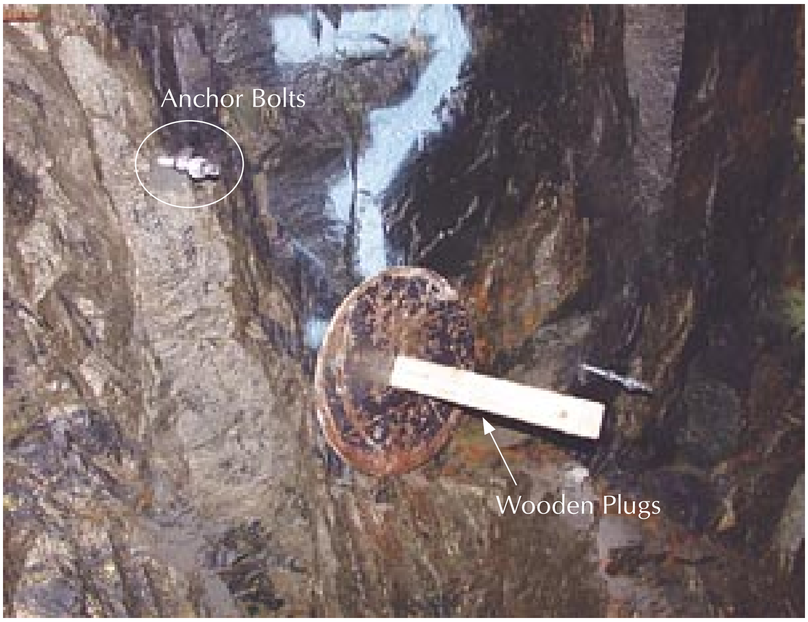


Figure 2: INCO loading (pulling) frame.

Site Description and Conditions

The test site in the 3840 cross-cut on the 1005 m (3300 ft) level of Stobie Mine provided exposures of both ore (sulfides) and rock. The pull plates were installed on the wall below the mesh at approximately 0.9 m (3 ft) above the floor. A



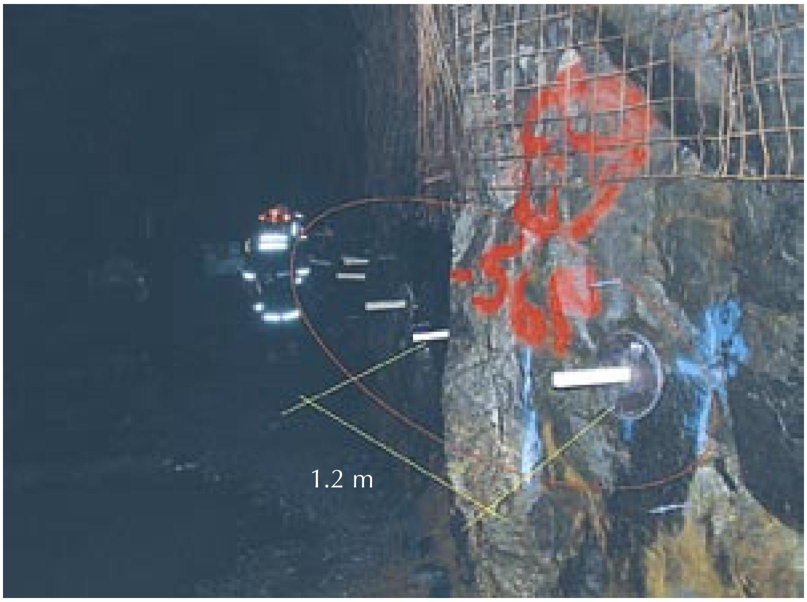


Figure 3: Test site—Layout of steel plates prior to shotcrete operation.

geomechanical assessment of the underground test site was also conducted.

Materials and Properties

The shotcrete mixtures used for this study were standard accelerated and accelerated steel fiber-reinforced mixtures, both containing silica fume as approved for use at INCO. The steel fibers used in this study were also INCO-approved and were hooked-end, Dramix® steel fibers. The fibers were 30 mm (1.2 in.) long (l), and 0.55 mm (0.22 in.) diameter (d) and had an aspect ratio (l/d) of 55. The tensile strength of the fibers was 1150 N/mm^2 (167 ksi). The fibers used in the dry-mix shotcrete came in collated (glued) bundles so that the fibers would mix evenly throughout the shotcrete mixture and not collect together in balls. As the shotcrete traveled through the hose and shotcrete nozzle, the fiber bundles separate into individual fibers. The results showed that the fibers were uniformly distributed throughout the mixture.

The early-age compressive strength development of shotcrete is a critical measurement when shotcrete is used for the support of underground excavations, for construction (shotcrete posts and barricades), and for the rehabilitation of severely damaged mine openings (rock bursts).

Table 1 presents the early-age behavior (f_c' at 2, 4, 6, 8, 12, and 24 h) of the shotcrete mixtures used for this study including also 2-, 3-, 7- and 28-day results.

Early-age compressive strength testing was performed using a direct method derived from an adaptation of the ASTM C 116, "Standard Test Method for Compressive Strength of Concrete Using Portions of Beams Broken in Flexure." Shotcrete was sprayed in sets of beams in standard steel molds that were stripped before testing.[4] Also, cores were extracted from panels that were shot to determine compressive strengths from 24 h to 28 days.

Performance and Observations

The load-deformation curves of the 2 and 4 h tests are presented in Fig. 4. It indicates that the 4 h plain shotcrete did not perform as well as both the 2 and 4 h SFRS panels. The graph also illustrates that a relatively abrupt loss of load-carrying capacity after peak strength occurred with the 4 h plain shotcrete compared with the SFRS. The behavior observed is well illustrated in the cumulative energy graph presented in Fig. 5, showing very little residual load-carrying capacity. It shows the capacity of the fiber mixture at both 2 and 4 h to absorb a considerable amount of energy compared to the mixture without fibers (Plate 4).

At such early age, however, it should be noted that cohesion failure occurred more than adhesion failure for the steel fiber-reinforced mixture. In other words, the failure within the shotcrete was greater than the area failed at the interface rock-surface. The aforementioned assessments are well illustrated in Fig. 6 and 7, which also indicate the mode of failure of both the plain and SFRS mixtures during testing.

For comparison purposes, Fig. 8 shows the load-deformation responses (smaller scale) from 2 to 24 h of curing time, assessing the hardening and the evolution of the load-carrying capacity over time of the shotcrete (plain and steel fiber-reinforced). The curves in red represent the non-reinforced regular shotcrete mixture.

Further Analysis

A sheet of mine screen with 100 x 100 mm (4 x 4 in.) mesh was also placed in front of the failure zones prior to photographing to facilitate the estimation of the area of failure (Fig. 10). The various angles and failure planes made with the shotcrete-rock contacts were also determined along with the thickness of shotcrete applied on each plate.

Using empirical calculating methods, a conservative safety factor can be determined for a 4 h re-entry. Figure 11 demonstrates a safety factor plot for rock wedges with square bases of 2 to 9 m (7 to 30 ft) on a side using the conservative values of 4.5 tonnes/m^2 (4.15 tons/yd^2) and 18 degrees, for thicknesses of 62.5 mm (2.5 in.) and 100 mm (4 in.) of SFRS using a dosage rate of 45 kg/m^3 (76 lb/yd^3) of steel fibers. The graph shows that with a short-term safety factor of 1.3, a thickness of 62.5 mm (2.5 in.) of shotcrete can be expected to support a wedge with a square base of 6 m (20 ft) on a side and bounded by two planes dipping at 60 degrees. Similarly, a thickness of 100 mm (4 in.) of SFRS should support a wedge of similar geometry with 8 m (26 ft) on a side, with a safety factor of 1.3.

Conclusions

This in-situ study of the postcrack capacity or the energy absorbing capacity at early age of accelerated SFRS demonstrated clearly that this test method can be used to:

1. Demonstrate to underground personnel, in a tangible (factual) way, the support pressure that can be developed by accelerated and steel fiber-reinforced dry-mix shotcrete from 2 to 24 h after application;
2. Provide numerical load-deformation on-site data of various shotcrete mixtures from 2 to 24 h after application; and
3. Provide important data to calculate safety factors for accelerated steel fiber-reinforced dry-mix shotcrete that allow 4 h re-entry into mine headings with wedges of various sizes.

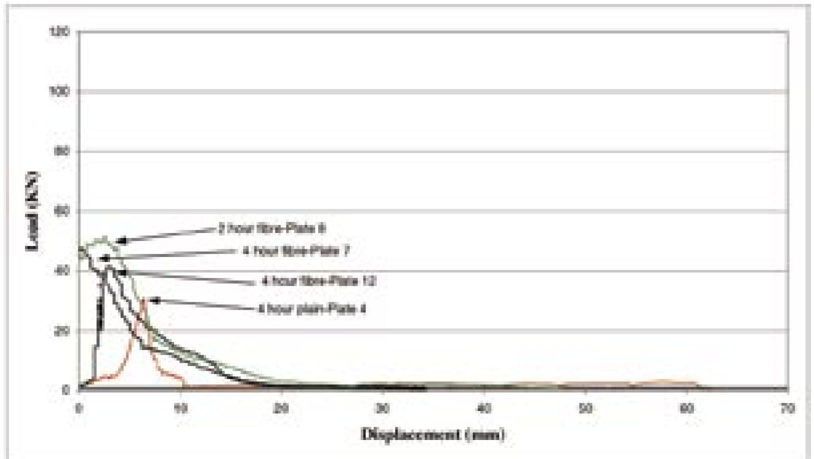


Figure 4: Load-deformation curves at 2 and 4 h of hydration.

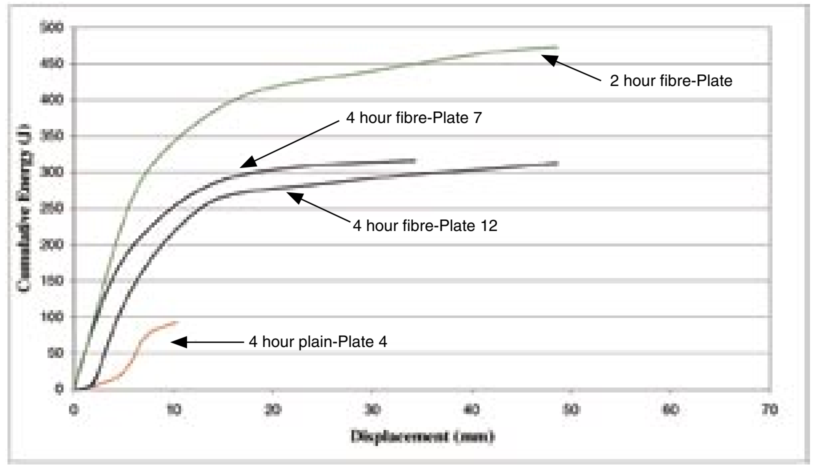


Figure 5: Cumulative energy curves at 2 and 4 h of hydration.

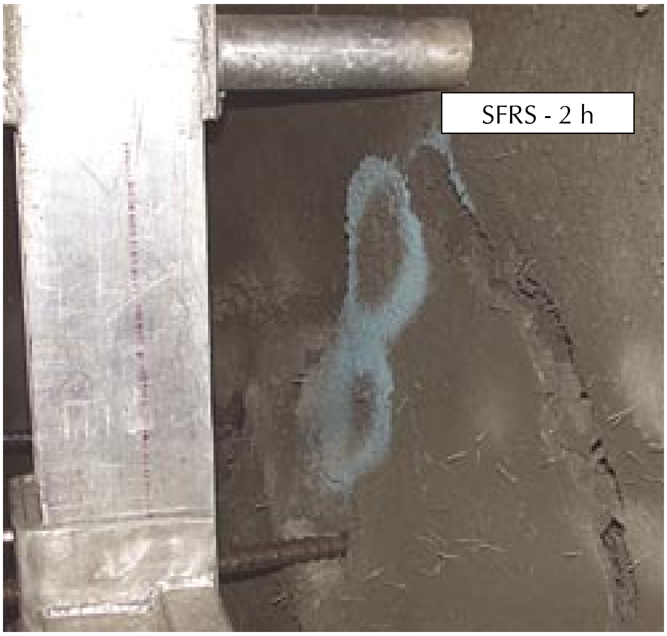


Figure 6: Failure with residual load capacity.

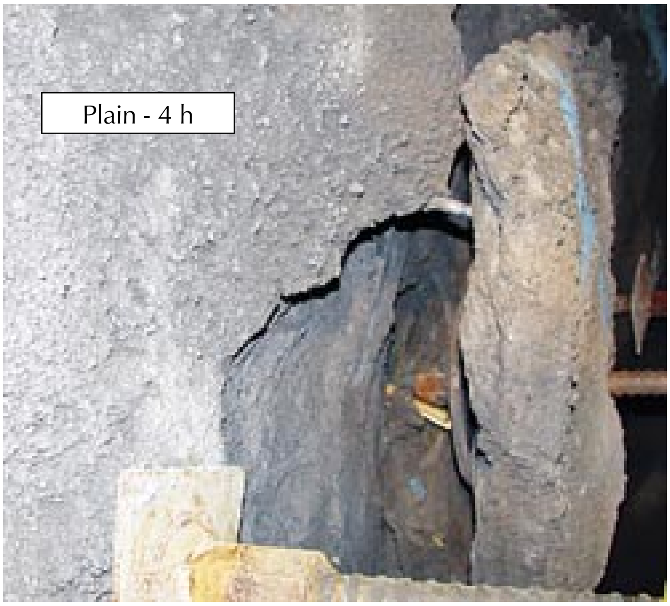


Figure 7: Brittle failure (does not carry load beyond flexural capacity).

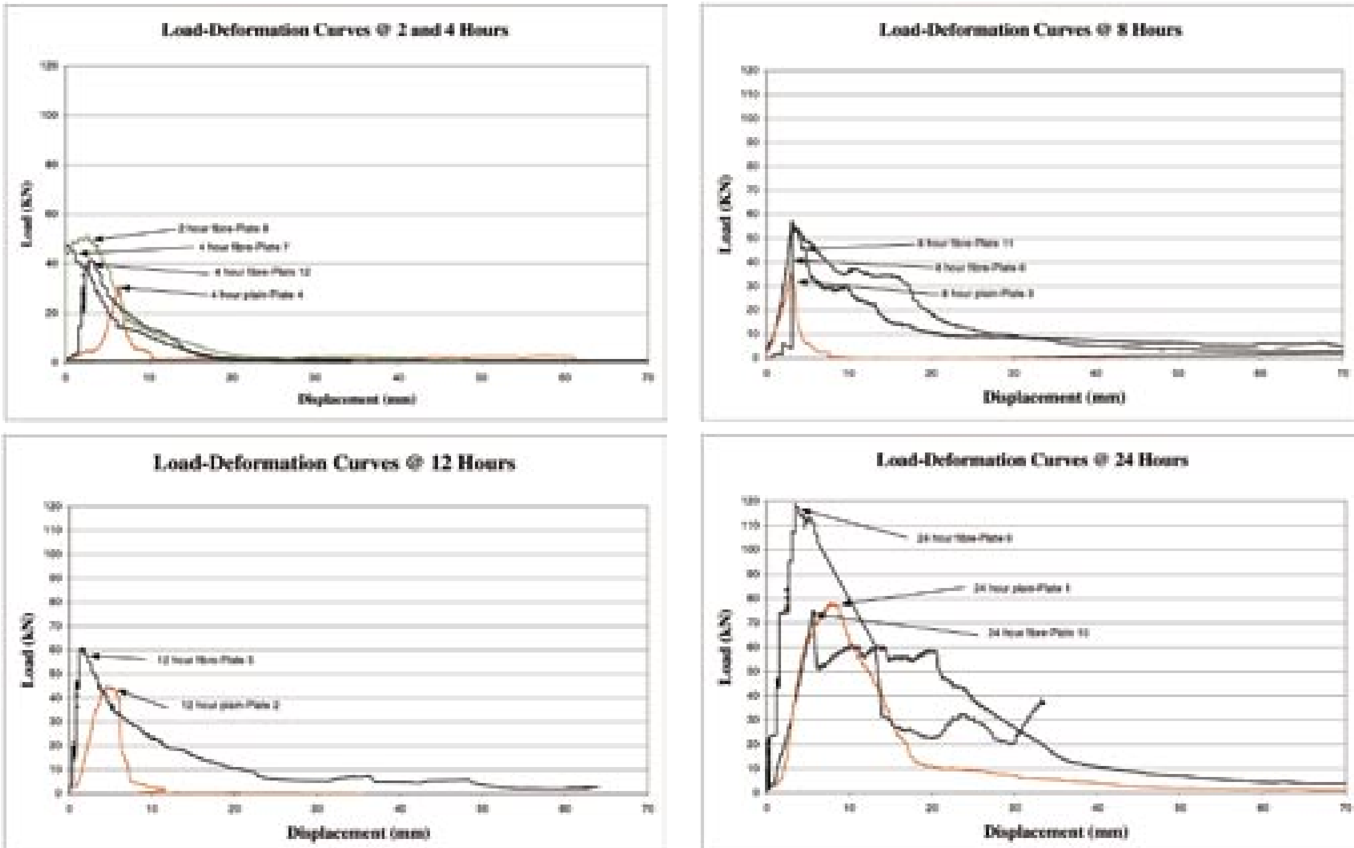


Figure 8: Load-deformation curves—evolution over time within the first 24 h of curing time.

Recommended Further Research

Additional testing should be conducted to increase the database of early strength values developed by this test. Consideration should also be given to performing numerous early strength tests with various thicknesses of shotcrete in an environment with homogeneous rock conditions.

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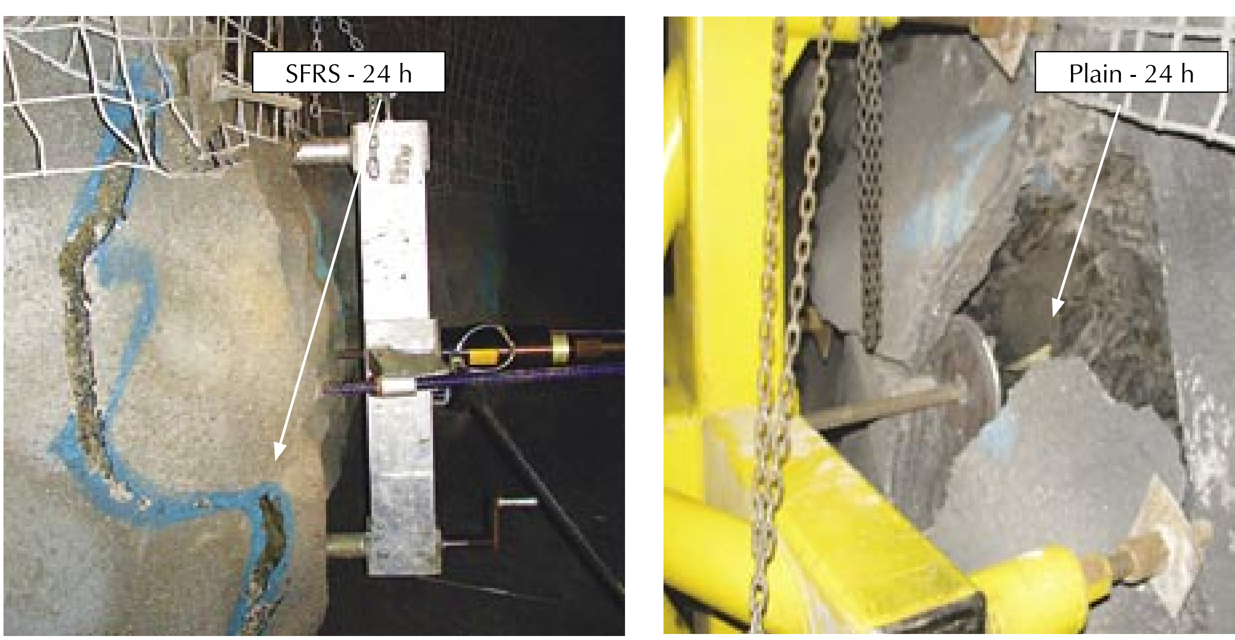

Figure 9: Failure with residual load capacity and without (brittle) at 24 h.

Research Engineers, MIRARCO, King Packaged Materials Co., and the Stobie Mine shotcrete and logistic personnel who all played an important part in this project.

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Figure 10: Surface area of failure.

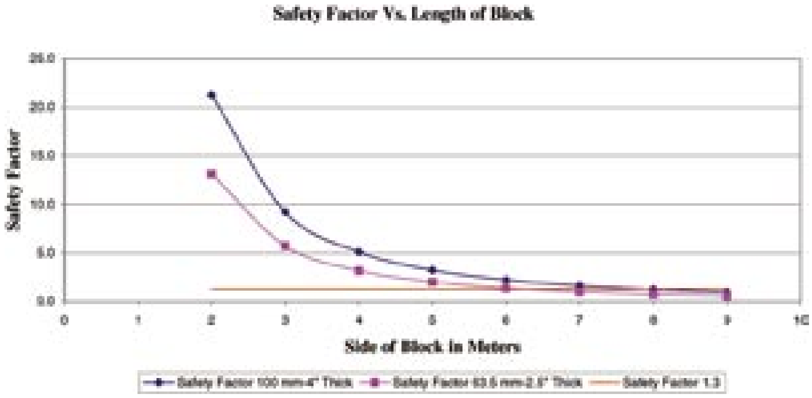
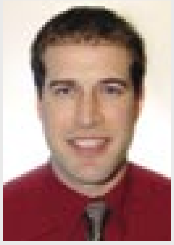


Figure 11: Safety factor plot for wedges with square bases of 2 to 9 m (7 to 30 ft) on a side using values of 4.5 tonnes/m² (4.15 tons/yd²), 18 degrees, and thicknesses of 62.5 and 100 mm (2.5 and 4 in.) of shotcrete.



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