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

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The state technology in shotcrete 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 fibres (steel and synthetic) significantly enhance the performance of shotcrete for a variety of applications.

These technological advancements have lead the international mining industry to become a major user of shotcrete for underground support. Since the potential for instability in underground rock openings is an existing threat to the safety of miners, the support of permanent openings in underground mining is a critical and important area of shotcrete application. For over 20 years, mining companies have recognized the value of steel fibre reinforcement in shotcrete. It has been proven that steel fibre reinforced shotcrete compares favourably with steel welded wire mesh reinforced shotcrete in various ground support applications [1]. At INCO's Stobie Mine in Sudbury (Canada) in 1996, a study was also conducted on field pull testing of shotcrete to evaluate possible replacement of mesh by shotcrete which indicated steel fibre reinforced shotcrete could replace #6 gauge welded wire mesh where only minor displacements were expected (0-10 mm) after the application of shotcrete. Where large ground movements are expected plain and steel fibre reinforced shotcrete as a replacement for mesh may be inappropriate [2].

It has been established that the introduction of steel fibres in shotcrete increases the energy absorption or "toughness", increases impact resistance and provides increased ductility. Ductility is defined as the ability to continue to carry load after the shotcrete microstructure has cracked. These mechanical properties are considered extremely important parameters with respect to support linings designed for the underground environment [3]. (The effects of addition rate, geometry and property of fibres are beyond the scope of this paper.)

Although the ability of steel fibre reinforced shotcrete to carry loads in flexure beyond the flexural capacity can be assessed in laboratories using a variety of beam and panel test methods developed by Europeans, North Americans, Japanese, and recently by Australians, the understanding of how to relate it to ground support design guidelines for underground mine development is limited and subjective [4].

In addition, these test methods evaluating the carrying load capacity of steel fibre reinforced shotcrete performed at 7 and 28 days of curing, do not assess the performance of such shotcrete at an early age because of logistical considerations. Design assumptions for early re-entry in underground openings are therefore difficult to make since early age behaviour of shotcrete under stress has not been determined. In Northern Ontario in Canada, a current practice in the mining industry is to allow the steel fibre reinforced shotcrete, applied for primary ground support to cure for 8 hours before allowing miners to work under it. One of the design criterions is to consider the compressive strength of the shotcrete with a general requirement of approximately 4 MPa. It is common belief however, that the mining and tunnelling industries show a large interest in extending this limit to determine how quickly miners can safely return to work under shotcrete applied for primary ground support, without steel welded wire mesh.

The primary purpose of this study was to determine and validate, under field conditions, the post-crack behavior and capacity, or the energy absorbing capacity at early age of an accelerated steel fiber reinforced shotcrete mix (SFRS) in comparison with an accelerated non-reinforced (plain) shotcrete mix using the dry-mix method. This evaluation would provide design guidelines to help determine early re-entry into mine headings. In addition to this test, data on early age compressive strength is presented in order to provide corroborative data.

The second objective was to provide an “on site” test method that would effectively demonstrate to mine personnel the performance of steel fibre reinforced shotcrete linings and to increase general understanding of the practice of a safe re-entry to mine openings. As indicated earlier, similar tests were carried out underground at the same mine in 1996 [2] however the tests were only performed after the wet-mix applied shotcrete had cured for 28 days. Procedures, properties and performance of this study are presented in the following sections.

Various failure modes were observed and practical mining analysis derived from them is also provided in this paper.

1.0 TESTING PROCEDURES AND EQUIPMENT

This study is an attempt to address the mining industry’s needs and as described above, tests were performed in situ, underground at various curing times within the first 24 hours of the application of the shotcrete, as outlined in Table 1. The testing program was conducted at INCO Limited’s Stobie Mine, on the North wall of 3840 cross-cut on 3300 level. Existing steel welded wire mesh covered the entire wall, so portions of the mesh had to be cut and removed to expose the in situ rock testing area. Two dry-mix shotcrete mixes were tested, the first was an accelerated regular shotcrete mix, which was used as a control mix, and the second was an accelerated steel fibre reinforced shotcrete mix. Both shotcrete mixes were produced at King Packaged Materials’ Onaping Falls Facility and were delivered underground to the testing area.

In order to perform such a test program, the Geomechanics Research Center (GRC) had designed a sturdy, but quite heavy, steel portable loading (pulling) frame and INCO Limited also designed and fabricated, using the same principles as the GRC’s, a light weight aluminium portable pulling frame. The capacity of both devices was 30 tonnes (294.3 KN) and they are presented in Figures 1 and 2.

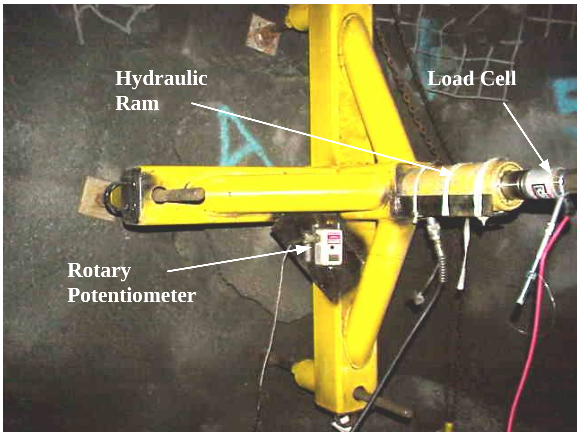

Figure 1: GRC Sturdy Loading (Pulling) Frame (Modified Version)

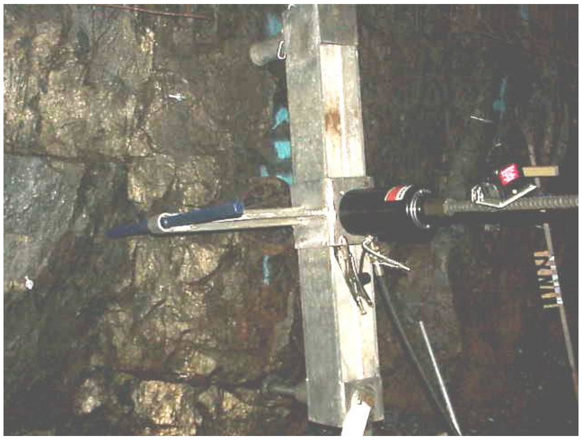

Figure 2: Inco Loading (Pulling) Frame

The testing equipment is described as follows:

- 30 tonne capacity loading (pulling) frame
- 30 tonne, 150 mm hollow cylinder hydraulic ram
- 12 x 254 mm (10”) diameter pull plates, 12.7 mm (1/2”) thick
- 25 tonne load cell
- Rotary potentiometer displacement transducer
- Computer-based data acquisition system
- 25.4 mm (1”) diameter Dywidag threadbar, 2 m (6’) in length to attach to pull plate

Important procedures were carefully followed to ensure the site was adequately prepared for testing. The 254 mm (10”) diameter steel plates (with a Dywidag nut in the center of each plate) were mounted to the wall of the drift at the proposed test locations (holes were pre-located and pre-drilled before the test). A distance of approximately 1.2 m separated the plates from each other. The shotcrete mixes were then applied over the plates to the desired test thickness (63.5 mm, 2.5”). 1.2 x 1.2 m wall panels were thus created, with the plates in the centre of each wall panel. 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. The wood plug was removed soon after initial set of shotcrete. The test frames were moved into position after the shotcrete had been allowed to cure for the appropriate time period.

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 back up. Displacement of the plates was measured relative to the testing frame. It is important to note that the testing frame apparatus was also modified from its previous version (Figure 3, first prototype) in order to increase the rigidity of the frame.

INCO’s test frame system was designed to measure pressure in the hydraulic line. Displacement was measured relative to the opposite wall of the drift. Both testing frames were used to ensure that the tests would be done in the time allowed, and to have a back-up in case one or the other devices broke down, or did not work correctly. Both of the frames worked properly, and provided accurate test results.

A total of twelve steel plates were used to conduct the “early age pull-out” tests. To reduce the effect of variables in the testing, two plates were required for each test for the steel fibre reinforced shotcrete mix. The test program was initially designed to conduct testing at 4, 8, 12 and 24 hours (a total of 8 plates). It was decided however on site, that one plate would be tested at only 2 hours. It was therefore agreed to sacrifice one 12 hour test.

With respect to the control shotcrete mix (without fibres), 4 plates were tested at 4, 8, 12 and 24 hours at only one plate per test.

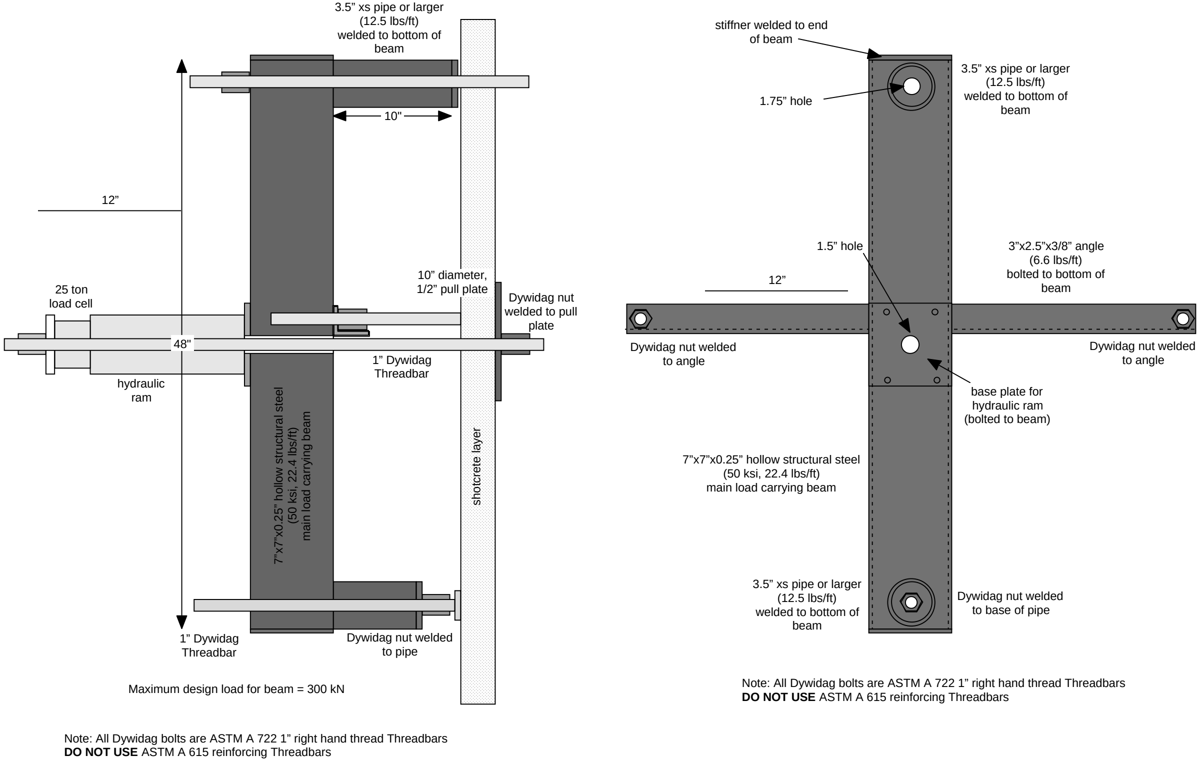

Figure 3: Detailed side and plan view of GRC initial portable loading frame [5]

2.0 SITE DESCRIPTION AND CONDITIONS

The test site in 3840 cross-cut on the 3300 foot (1005 m) level of Stobie Mine was chosen because it provided exposures of both ore (sulphides) and rock. It is considered a standard practice to choose a uniform surface to conduct comparative tests, however given the number of tests planned and the lack of uniform ground in the section of the mine available for testing the opportunity to conduct the tests on both rock with and without sulphides was welcomed. The site chosen was at the hanging wall contact of the ore body. The ore types present were massive sulphides, disseminated sulphides in quartz diorite and stringers of sulphides in the sericite schist of the sheared hanging wall contact. The host rock, quartz diorite, is a strong, brittle, intrusive of good quality, with a rock mass rating (RMR) of 75–82. The sulphides found in this nickel and copper mine are pyrrhotite, chalcopyrite and pentlandite. The hanging wall rocks are sheared and brecciated meta-gabbros and meta-sediments.

As with all excavations at Stobie, 3840 cross-cut was driven with conventional drill and blast methods. Due to the sheared nature of the area and the minimal wall control used by the blasting crew, the wall of the test site can be considered as irregular with blocky ground and moderate to significant blast damage. The footwall portion or entrance of this cross-cut was driven to be used as a top sill and subsequently as a bottom sill for the Vertical Retreat Mining method and is 5.5 m wide and 4.5 m high. The last 10 m of the cross-cut was driven as a site to diamond drill from and is 3.6 m wide by 3.9 m high. Support of the back and the walls to 1.5 m from the floor consists of #6 gauge welded wire mesh and 1.8 m long resin grouted rebars installed on a 1.2 x 0.75 m spacing. The pull plates were installed on the north wall of the excavation below the mesh at about 0.9 m above the floor.

An assessment of the testing site was conducted underground and a description is presented in Table 1. The condition of the rock surface is described for each wall panel where the steel plates are anchored. The type of shotcrete mix and the times at which the in situ load-deflection tests were performed are also available for each steel plate. The steel plates are identified as #1 to #12.

Table 1: Plate identification and site description

Plate Identification (#)	**Shotcrete Mixes**	**Curing Time (Hours)**	**Site Description**
1	Regular	24	Strongly sheared biotite/sericite schist. Foliation 40° to wall. Rough surface.
2	Regular	12	Biotite/sericite schist. Schistosity parallel to rock face. Rough surface
3	Regular	8	Sulphides and rock. Plate on nose. Rough surface.
4	Regular	4	Massive sulphides and rock. Rough surface.
5	Fibre Reinforced	12	Stringer sulphides. Rough surface.
6	Fibre Reinforced	8	Slickensided sulphide and rock. Strong flat joints parallel to wall.
7	Fibre Reinforced	4	Dyke perpendicular to plate intersecting plate location. Rock inclusion above plate, sulphides below plate.
8	Fibre Reinforced	2	Sulphide with rock inclusions. Rough planar surface.
9	Fibre Reinforced	24	Massive to disseminated sulphides. Irregular joints. Very rough surface.
10	Fibre Reinforced	24	Disseminated sulphides. Irregular surface.
11	Fibre Reinforced	8	Disseminated to massive sulphides with occasional rock stringers. Rough blocky surface.
12	Fibre Reinforced	4	Stringer to disseminated sulphides. Irregular rough surface.

3.0 MATERIALS AND PROPERTIES

The shotcrete mixes used for this study were produced and pre-packaged by King Packaged Materials Company in Onaping Falls, Ontario plant in 1000 kg bulk bags and were delivered underground to the testing area. The mixes were King Packaged Materials' standard accelerated and accelerated steel fibre reinforced, both silica fume enhanced mixes approved for use at INCO.

It has been established that early age compressive strength development of shotcrete is an important parameter in the mining industry when it 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).

The following tables present the early age behaviour (f'c at 2, 4, 6, 8, 12 and 24 hours) of the shotcrete mixes used for this study including also 2, 3, 7 and 28 day results.

Table 2: Early Age fc Development (Moulds)

Curing Time (Hours)	**Compressive Strength at Early Age (MPa)**
2	3.6
4	5.1
6	5.5
8	6.6
12	19.3
24	27.0

Table 3: Compressive Strength (Cores)

Curing Time (Days)	**Compressive Strength (MPa)**
1	27.0
2	32.9
3	37.1
7	49.2
28	62.3

Early age compressive strength testing was performed using a direct method derived from an adaptation of the ASTM C116 *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 moulds, which were stripped before testing [6]. Also cores were extracted from panels that were shot to determine compressive strengths from 24 hours to 28 days.

The steel fibres used in this study were hooked-end, cold drawn, Dramix® steel fibres, manufactured by Bekaert Corporation. The fibres were 30 mm (1.2") long (l), and 0.55 mm (0.22") diameter (d). They had an aspect ratio (l/d) of 55. The tensile strength of the fibres was 1,150 N/mm² (167 ksi). The fibres used in the dry mix shotcrete came in collated (glued) bundles so that the fibres would mix evenly though out the shotcrete mix and not collect together in balls. The steel fibres were mixed with the other dry components into bulk bags by King Packaged Materials Company. The glue in the fibres is designed to dissolve and to break apart in the mixing. As the shotcrete traveled through the hose and shotcrete nozzle, the fibres are separated into individual fibres in the finished steel fibre reinforced shotcrete. The end results showed that the fibres performed as planned, allowing proper distribution throughout the mix.

4.0 PERFORMANCE AND OBSERVATIONS

The following section describes the performance of various systems and elaborates on the failure modes (which are summarized in Table 6) and their relationship to the ground conditions (which are summarized in Table 1). Visual estimates were made of the percent mode of each failure type, adhesion (failure at the interface rock-shotcrete), cohesion (failure within the shotcrete) and rock mass failure in which the rock was pulled off the wall.

The difference between the performance of standard shotcrete and steel reinforced was clearly demonstrated by the physical reactions of the mixes during the pulling process. However the reaction of the steel fibre reinforced shotcrete is best understood from the following description of conditions while pulling Plate 10 (24 hour test). At first crack and as the two shotcrete slabs created by a vertical crack over the center of the plate were being pulled from the wall, the load on the unit was still 4 tonnes when the vertical crack was 6 mm (0.25") wide. When the crack was opened 25 mm wide the plate was displaced 75 mm from the wall and the slabs of shotcrete were still holding to the wall. By comparison the standard shotcrete once failed fell to the floor.

Plate 1 (24 hour test) was installed in strongly sheared biotite and sericite schist with a foliation at 40° to the wall (creating a rough surface). The plate was covered with 100 mm of plain shotcrete and pulled at 24 hours after application. This is the only plate that completely failed by pulling the rock off the wall. The peak load was 51.4 KN, which we can assume was less than the cohesion or adhesion strength of the shotcrete at 24 hours.

Plates 2, 3 and 4 were covered with plain shotcrete and were pulled at 12, 8 and 4 hours respectively and the failures were 50, 80 and 60 percent cohesion and 50, 20 and 40 percent adhesion respectively. There is no evidence of a relationship between the time after application and the type of failure. The excavation wall varied from sheared rock to mixtures of rock and ore and this seems to have had an impact on the failure type. Plate 3 was located on a nose or convex area that would have promoted cohesion failure.

Plates 6, 9 and 10 were pulled through steel fibre reinforced shotcrete at 8, 24 and 24 hours respectively and caused 90, 80 and 100 percent adhesion failure principally due to the presence of coated joints which would have reduced adhesion. Plate 10 was affected by both application problems (water pressure variations underground) and extension of the failure zone from plate 9.

4.1 In situ "Load-Deformation" Pull Tests [7]

The test results of the early age field pull tests are presented in Table 4. The geometry of the failure zones at each of the test sites is summarized in Table 5, and Table 6 describes the modes of failure, which were determined visually by the authors.

Table 4: Summary of pull tests

Actual Curing Time (Hours)	**Plate Identification (#)**	**Shotcrete Mixes**	**Peak Load (KN)**	**Displacement at Peak (mm)**	**Energy Dissipation Capacity (J) ******	**Pulling Frames**
2.0	**8**	**Fibre**	**51.4**	**2.7 *****	**472**	**INCO**
4.1	**7**	**Fibre**	**48.1**	**0 *****	**316**	**INCO**
4.6	4	Plain	31.1 *	6.4	93	GRC
4.25	**12**	**Fibre**	**41.7**	**3.1**	**312**	**INCO**
7.9	3	Plain	36.0	3.1	92	GRC
8.0	**6**	**Fibre**	**56.5**	**3.1**	**894**	**INCO**
8.2	**11**	**Fibre**	**57.2**	**3.1**	**790**	**GRC**
12.0	2	Plain	44.9	4.6	197	GRC

12.0	**5**	**Fibre**	**61.0**	**1.5**	**731**	**INCO**
24.3	1	Plane	78.1	7.8	1004	GRC
24.1	**9**	**Fibre**	**119.3**	**3.5**	**1647**	**INCO**
24.6	**10**	**Fibre**	**75.3** **	**5.6**	**1707**	**GRC**

* Load determined from pressure reading
** Disturbed by test on Plate 9
*** Preloading may have contributed to low displacement values at peak
**** Energy absorption capacity cut off at 60 mm of displacement
Note: **Steel Fibre Reinforced Shotcrete**

Table 5: Summary of failure zone geometry

Plate Identification (#)	Failure W (mm)	Failure H (mm)	Failure Area (from pictures) (m^2)	Shotcrete Thickness @ Centre (mm)	Thickness Edge (mm)
1	1118	1194	0.939	101.6	--
2	660	838	0.459	76.2	69.9
3	584	635	0.258	114.3	69.9
4	813	813	0.488	101.6	76.2
5	**762**	**787**	**0.385**	**95.3**	**57.2**
6	**1016**	**813**	**0.568**	**114.3**	**--**
7	**813**	**813**	**0.480**	**76.2**	**76.2**
8	**813**	**1092**	**0.552**	**101.6**	**101.6**
9	**1499**	**991**	**1.373**	**101.6**	**101.6**
10	**1448**	**1067**	**1.404**	**127.0**	**101.6**
11	**1295**	**1295**	**1.146**	**101.6**	**101.6**
12	**914**	**813**	**0.526**	**76.2**	**76.2**

Note: **Steel Fibre Reinforced Shotcrete**

Table 6: Summary of failure observation

Plate Identification (#)	Cohesion failure (%)	Adhesion failure (%)	Rock mass failure (%)	Failure Observation
1			100	Rock was pulled off the wall in very sheared zone.
2	50	50		N/A
3	80	20		N/A
4	60	40		N/A
5	30	70		N/A
6	10	90		Coated joint caused 60% of adhesion failure
7	80	20		Concave failure, vertical joint 90° to wall.
8	90	10		Rock visible in bottom left of failed zone, shotcrete thin in this area. Cracks visible in failed zone shotcrete just above plate location.
9		80	20	Failure at joints and fractures in rock. Shotcrete stayed in one piece and failed at feather edge of the shotcrete panel. Noticeable flexure in INCO pull test frame.
10		100		Application of shotcrete inconsistent (varying water content), problem with shotcrete fibre at pot. Failure on coated joint surface. Some effect of the failure zone from Plate 9 overlapping.
11		40	60	Ore peeled
12	100			N/A

The following figures illustrate the load-deformation responses and the cumulative energy data for all the dry-mix shotcrete panels made with and without fibres. In order to facilitate the comparison, the ordinate and abscissa scales of the graphs remain the same.

Figure 4 presents the load-deformation curves for the 2 and 4 hour tests. As expected, the 4 hour regular shotcrete did not perform as well as both the 2 and 4 hour steel fibre reinforced shotcrete panels. The graph illustrates that a relatively abrupt loss of load carrying capacity after peak strength occurred with the 4 hour regular shotcrete compared to the steel fibre reinforced shotcrete. The behaviour observed is well illustrated in the cumulative energy graph presented in Figure 5 showing very little residual carrying load capacity. It also shows the capacity of the fibre mix at both 2 and 4 hours to absorb a considerable amount of energy compared to the regular mix without fibres (Plate 4).

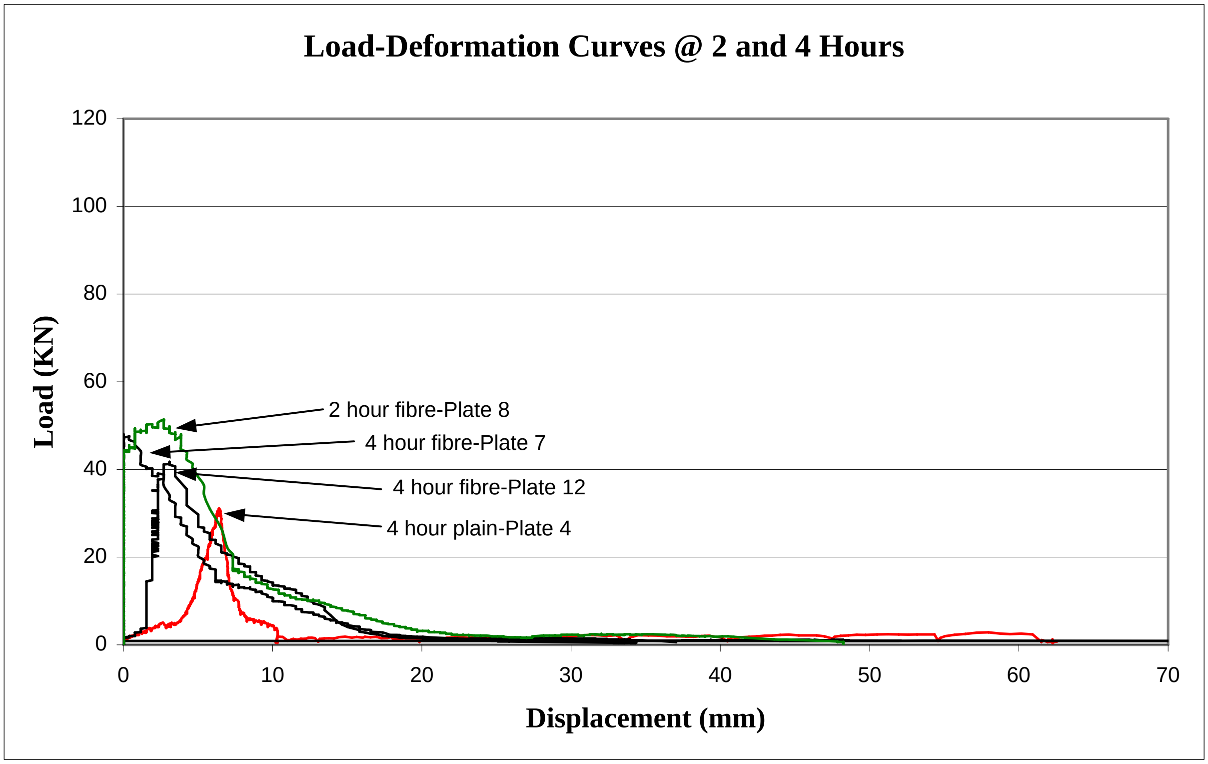

Figure 4: Load-deformation curves @ 2 and 4 hours of hydration

The graph presented in Figure 5 also indicates that the 4 hour tests performed on the steel fibre reinforced shotcrete (Plates 7 and 12) are consistent but exhibit a cumulative energy response lower than the same mix loaded at 2 hours (Plate 8). The measured shotcrete thickness at plate 8 however is approximately 25 mm (1”) thicker than at plates 7 and 12, and as observed in Table 5, the failure area is larger. This could explain the higher load carrying capacity value obtained in the 2 hour test.

At such early age, cohesion failure occurred more than adhesion failure for the steel fibre reinforced mix. In other words, the failure within the shotcrete was greater than the area failed at the interface rock-surface.

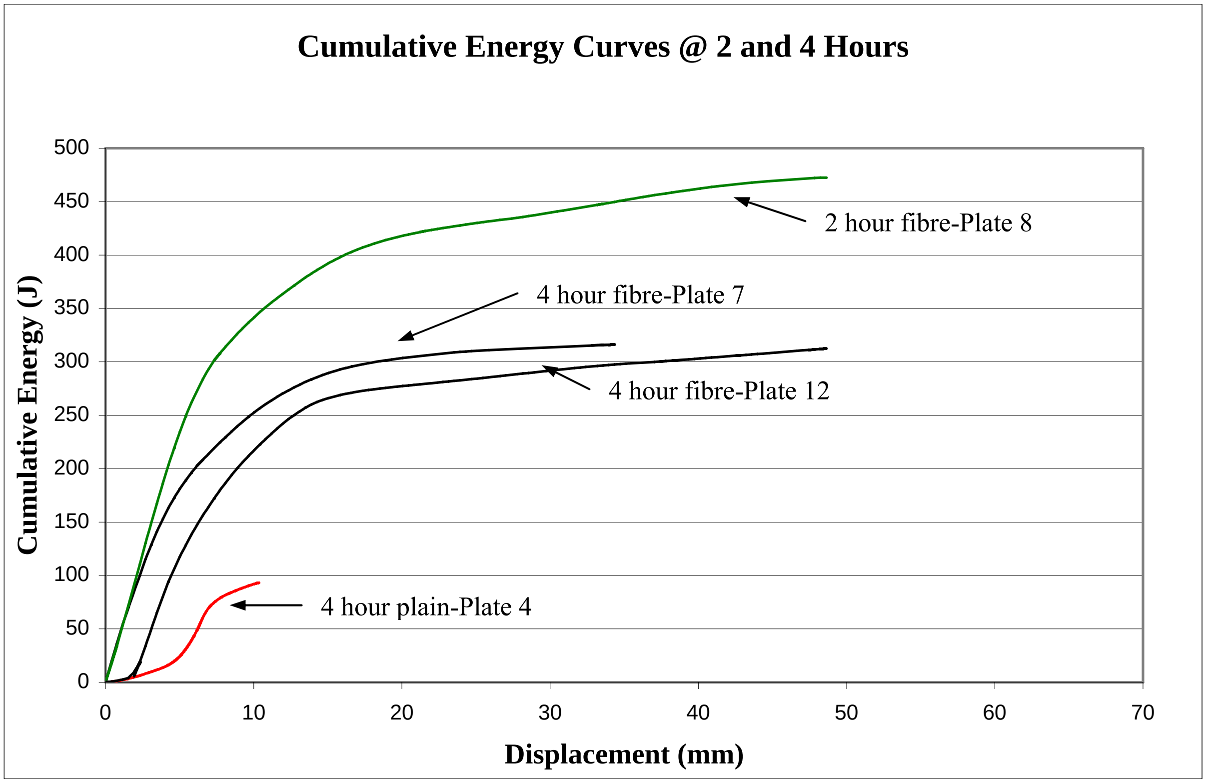

Figure 5: Cumulative energy curves @ 2 and 4 hours of hydration

A load-deformation graph for the 8 hour tests is also presented in Figure 6, and Figure 8 illustrates the response of the tests conducted at 12 hours. Again, at both of these curing times, the plain shotcrete carries very little load capacity when compared with the steel fibre reinforced shotcrete and it exhibits a much more abrupt loss of load carrying capacity. The cumulative energy curves displayed in Figures 7 and 9 for the respective curing times (8 and 12 hours) provide a better indication of the physical behaviour of the steel fibre reinforced shotcrete, absorbing more energy when force is applied than the plain shotcrete.

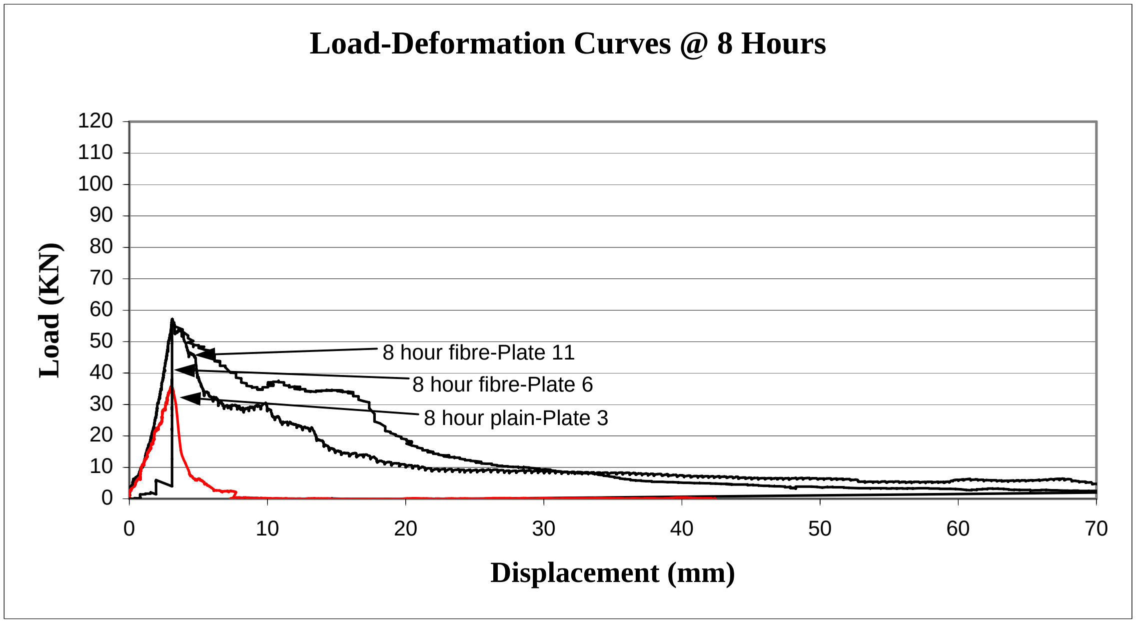

Figure 6: Load-deformation curves @ 8 hours of hydration

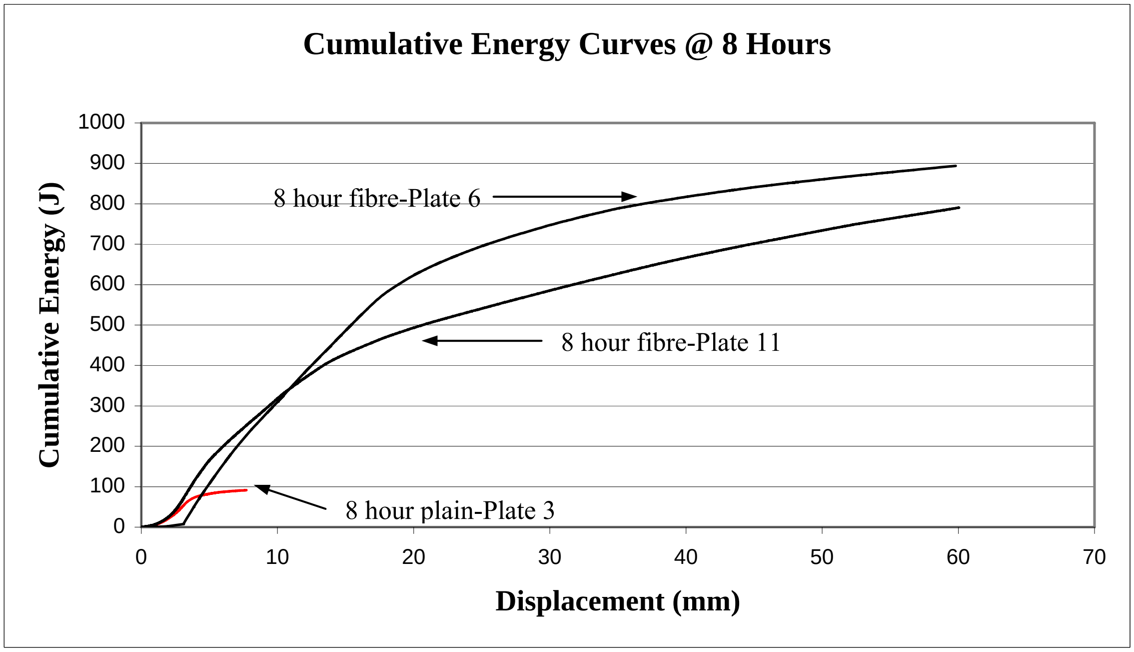

Figure 7: Cumulative energy curves @ 8 hours

The thickness of shotcrete applied at the centre of each plate was approximately the same at just over 100 mm (4”), down to 75 mm (3”) at edges of failure. It should be noted that test carried out with the steel fibre reinforced shotcrete at 8 hours (Plate 11) showed a 60% adhesion failure, with an area of failure greater than 1 m^2 (which is 4 times greater than the area of failure of the plain mix). More information is provided on the assessment of various modes of failure in section 5.0.

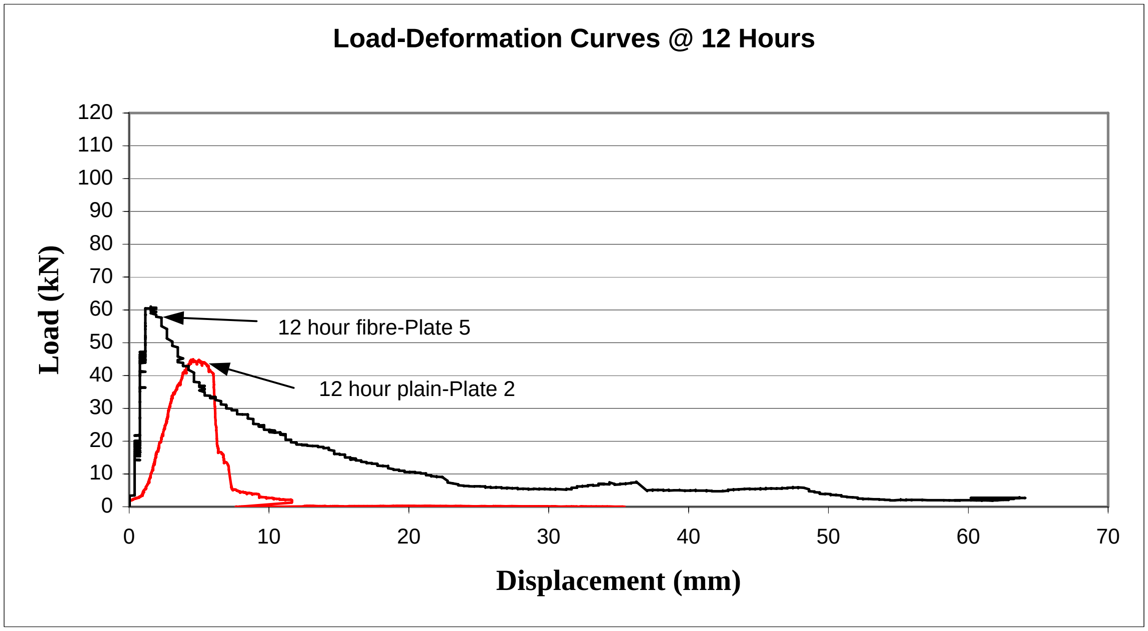

Figure 8: Load-deformation curves @ 12 hours of hydration

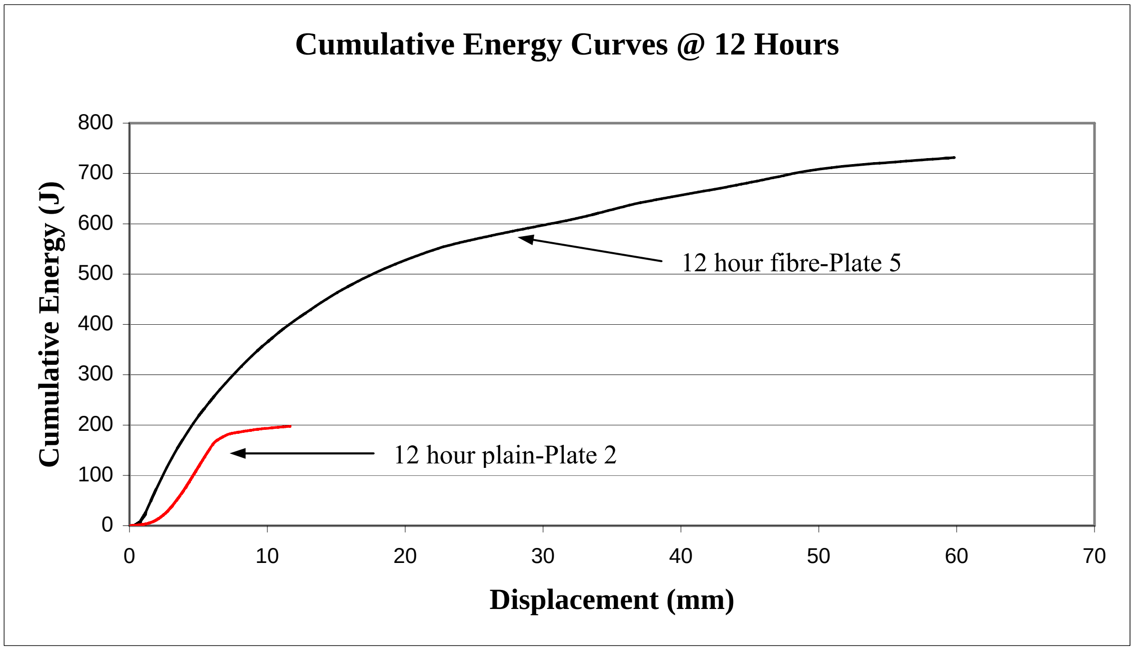

Figure 9: Cumulative energy curves @ 12 hours of hydration

With approximately the same area of failure (~0.5 m^2), the behaviour displayed on Figure 9 of the steel fibre reinforced shotcrete presented a much higher load carrying capacity than the plain shotcrete, which is also comparable to the response obtained with the 8 hour tests. The thickness of shotcrete at the centre of plate 5 however was slightly thinner than the thicknesses observed for the 8 hour tests. The plate originally dedicated for the second steel fibre reinforced test at 12 hours was used for the 2 hour test presented in Figure 4 and 5.

Figure 10 shows the load-deformation graphs for the 24 hour tests. The test conducted on plate 10 does not provide a good indication of the performance of the steel fibre reinforced shotcrete mix at 24 hours of age. The results were inconsistent with the other tests in that the peak-load and the carrying load capacity of the steel fibre reinforced shotcrete did not exhibit the general trends found previously. It is noted however that the previous test at adjacent plate 9 disturbed the site where plate 10 was located. Another possible explanation lies in the difficulties encountered during shotcrete application (reference in Table 6). Despite exhibiting a lower peak strength, the steel fibre reinforced shotcrete did retain its superior post-peak load carrying capacity when compared with the plain shotcrete. The cumulative energy curves are also shown in Figure 11.

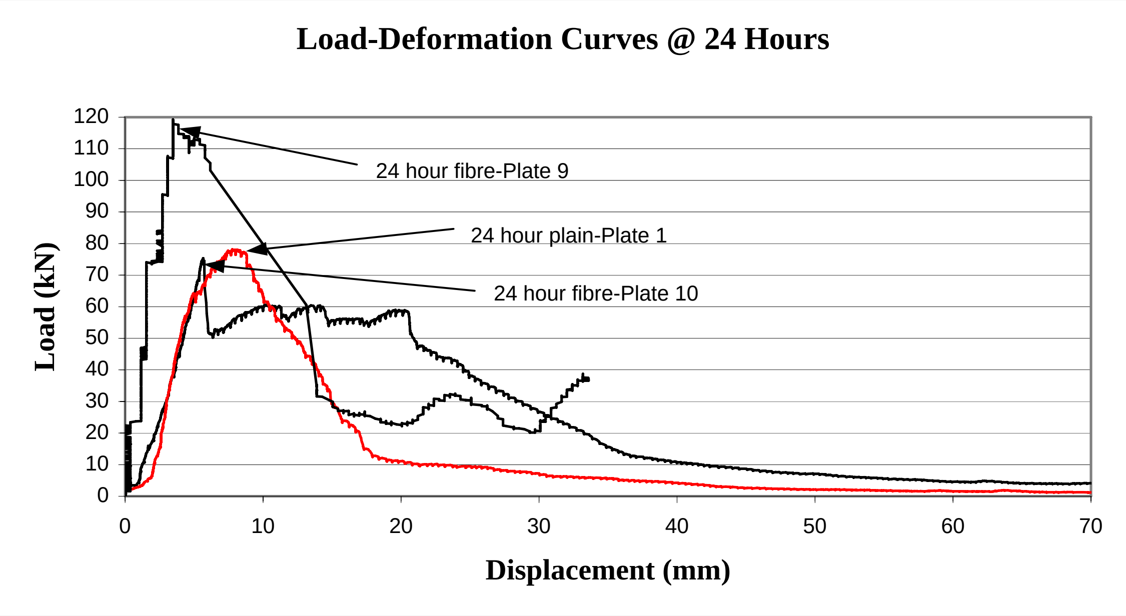

Figure 10: Load-deformation curves @ 24 hours of hydration

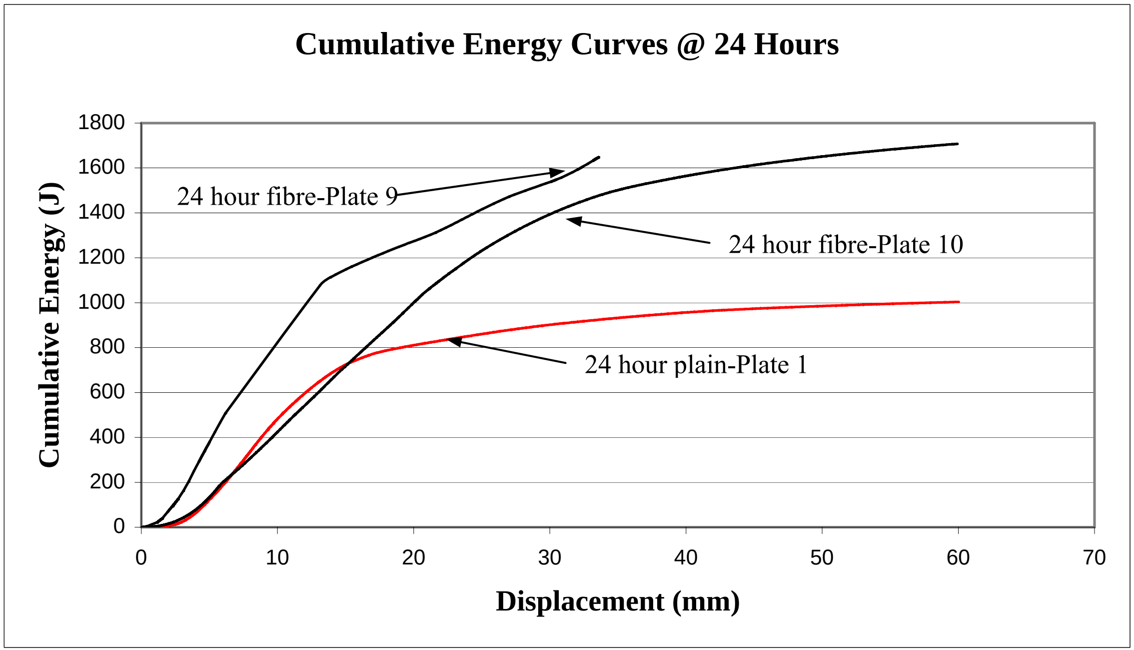

Figure 11: Cumulative energy curves @ 24 hours of hydration

4.2 EFNARC Test

The following figures represent the performance of the same steel fibre reinforced shotcrete mix tested at 28 days according to the flexural toughness plate EFNARC 10.4 test. The results presented are the load-deflection and cumulative energy curves (average of three measurements) and they are only used to provide corroborative data. These results indicate that the testing method used in situ seems to provide representative results, despite the harsh conditions and environment underground.

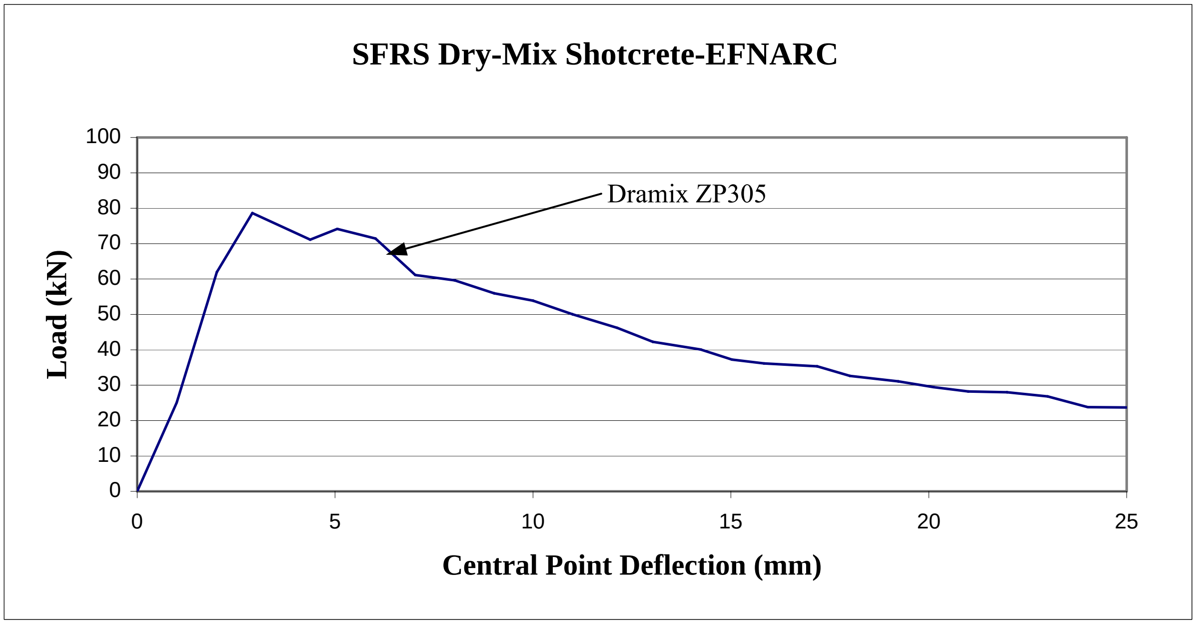

Figure 12: EFNARC load-deformation curve – Steel fibre reinforces shotcrete

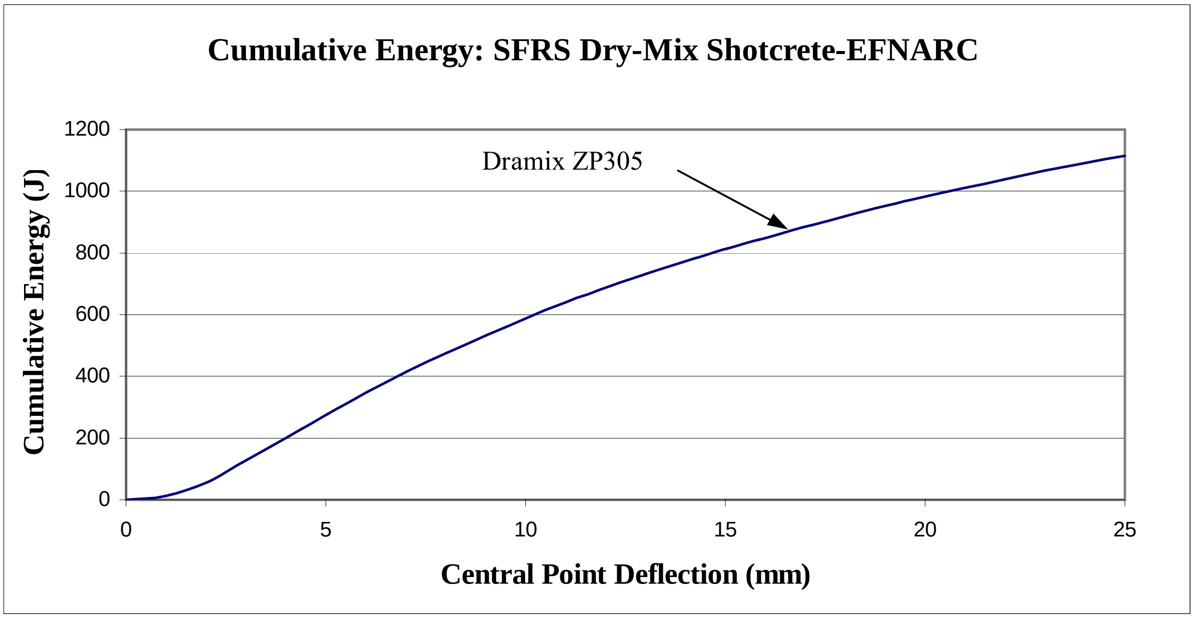

Figure 13: EFNARC cumulative energy curve – Steel fibre reinforced shotcrete

5.0 FURTHER ANALYSIS

The peak loads and energy dissipation capacities are listed in Table 4. A sheet of mine screen with 100 mm x 100 mm mesh was placed in front of the failure zones prior to photographing in order to facilitate the estimation of the area of failure. The various angles and failure planes made with the shotcrete-rock contacts were determined. The highest value and lowest value were disregarded giving a range of 11 to 18 degrees and an average of 14 degrees. The areas of the failure surfaces were calculated and divided into the load providing a relationship of peak load to failure area. The minimum and average values determined were 4.5 and 8.2 tonnes/m^2 respectively.

6.1 Safety Factors

The area of failure is related to the shotcrete thickness, the angle of failure and the perimeter of the block or plate causing the failure. Using the minimum peak load to failure area value of 4.5 tonnes/m^2 and a failure angle of 18 degrees we can determine the minimum support pressure that can be generated by various thicknesses of shotcrete to blocks of varying perimeters. By calculating the weight of a square based wedge bounded by two joints dipping at 60 degrees and dividing it into the value of the minimum support pressure, a conservative safety factor can be determined for 4 hour re-entry. Figure 14 demonstrates a safety factor plot for wedges with square bases of 2 to 9 m on a side using the conservative values of 4.5 tonnes/m^2 and 18 degrees for thicknesses of 62.5 and 100 mm of steel fibre reinforced shotcrete using a dosage rate of 45 kg/m^3 Dramix fibres. The graph also shows that with a short term safety factor of 1.3, a thickness of 62.5 mm of shotcrete can be expected to support a wedge with a square base of 6 m on a side and bounded by two planes dipping at 60 degrees. Similarly, a thickness of 100 mm of steel fibre reinforced shotcrete will support a wedge of similar geometry with 8 m on a side, with a safety factor of 1.3.

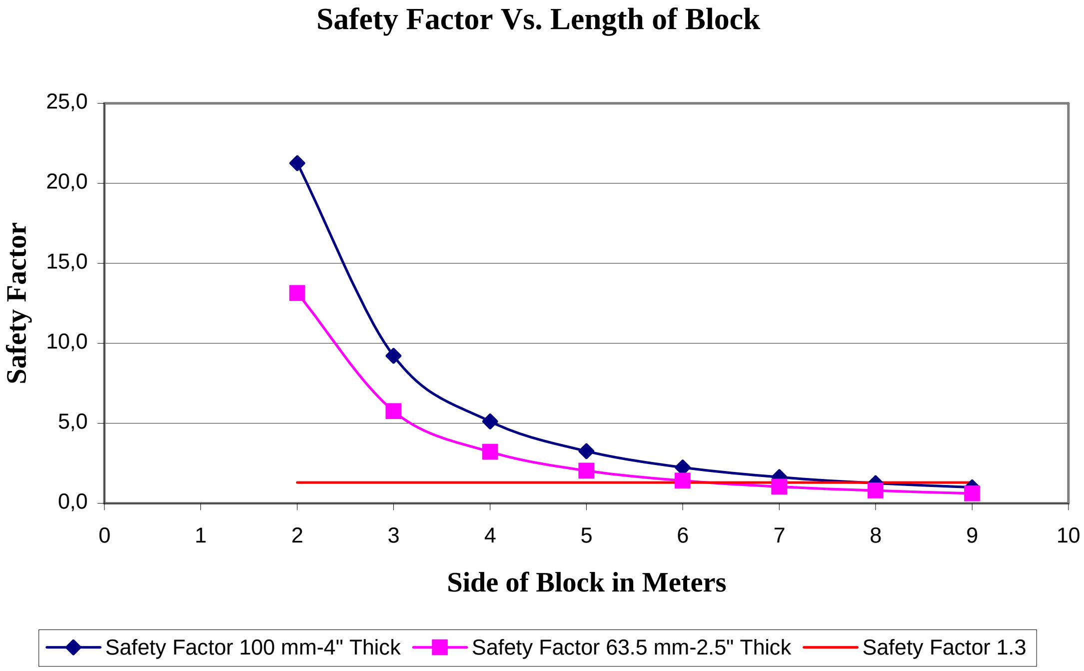

Figure 14: Safety factor plot for wedges with square bases of 2 to 9 m on a side using values of 4.5 tonnes/m^2, 18 degrees and thicknesses of 62.5 and 100 mm of shotcrete

6.0 CONCLUSIONS

This in-situ study of the post-crack capacity or the energy absorbing capacity of accelerated steel fibre reinforced shotcrete at early age proved that this method testing can be used to:

1) Demonstrate to underground personnel, in a tangible (factual) way, the support pressure that can be developed by King Packaged Materials' dry-mix shotcrete reinforced with Dramix fibres at a dosage of 45 kg/m^3 from 2 to 24 hours after application.
2) Provide numerical load-deformation data from 2 to 24 hours after application.
3) Provide data to calculate safety factors that permit 4 hour re-entry into mine headings with wedges of various sizes.

7.0 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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