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ABSTRACT

In underground excavation projects using drill and blast methods or tunnel boring machine (TBM), the installation of ground support has become one of the longest components of the development cycle. In many applications, fiber reinforced shotcrete has been used successfully for several decades as temporary or permanent ground surface support. For priority headings and critical permanent underground infrastructures, the reduction of the time required to spray and cure fiber reinforced shotcrete before re-entry is critical to increase the development rate. In addition, from an environmental, logistical and economic viewpoint, minimizing the amount of material to produce, transport and handle from the surface has become critical as well. In this context, this paper discusses the development of an engineered shotcrete providing rapid strength and toughness development to allow fast re-entry and enhanced energy absorption capacity. Working on cement chemistry, fiber selection and dosage, matrix/fiber synergy, fiber rebound reduction, equipment and shotcrete process overall, this paper presents a new alternative ground support solution for challenging ground conditions.

KEY WORDS

Fiber Reinforced Shotcrete, Engineered Cementitious Composite (ECC), High Flexural Toughness, Energy Absorption, Dynamic Ground Support, Fast Re-Entry, Challenging Ground Conditions

INTRODUCTION

Sprayed concrete (shotcrete) is a well established and proven component of ground support systems used worldwide in underground excavation projects.

Nowadays, headings size has become larger and larger with the use of larger and more sophisticated equipment. In parallel, mining projects become deeper and deeper involving more and more challenges to extract the ore and keep the development cycle as short as possible.

In this context, the installation of ground support has become one of the longest components of the development cycle. In addition, larger headings and deeper excavations lead to larger amount of material to transport from the surface on longer distance, which increases lead time to production, logistics and labor.

Fiber Reinforced Shotcrete for Ground Support

The use of fiber reinforced shotcrete (FRS) has been adopted for many years in underground applications to replace mesh in gravity failure conditions and to manage rockbursts and ground deformations in moderate stress conditions. FRS is also used as temporary ground support with tunnel boring machine or as first pass support in dynamic (high-stress) conditions to manage seismicity and ensure safer re-entry before permanent ground support installation.
In all cases, FRS is one element of the ground support system (static or dynamic) and its performances should be analyzed in that perspective rather than individually. In other words, its design and performances should be optimized in order to maximize its contribution to the selected ground support system.
On the other hand, the design of the ground support system should also take into account how the use of FRS can enhance or limit the system performances.
For example, in high-stress conditions where seismic events can produce high intensity rockbursts and deformations exceeding 100 mm the low strain (ductility) capacity and the limited load bearing capacity of FRS at such large deformations, limits its contribution to the dynamic ground support system. Its more brittle behavior under dynamic loading (high strain rate) and low tensile strengths limit also its use in such high stress conditions because of the risk of surface spalling. In such conditions FRS or plain shotcrete must be combined to other systems such as yielding bolts, mesh, cable lacing or mesh straps that increases energy absorption and provides a better control of large ground displacements.

Development of Engineered Fiber Reinforced Shotcrete

The enhancement of FRS tensile/flexural performances under dynamic loading seems to be critical in high stress conditions to improve its contribution to the dynamic ground support system performance and its spalling resistance.
In this context, King Shotcrete Solutions (Canada) has conducted a testing program on an Engineered Cementitious Composite (ECC) for ground support in challenging ground conditions. ECC is a high performance fiber reinforced cementitious materials, which undergoes pseudo-strain hardening ductility under uniaxial tensile loading. The ultimate tensile strength of ECC varies between 3-8 MPa with a ductility ranging from 1-5% (Li, 2003). This improved tensile and flexural ductility is provided through a multi-cracking mechanism that keeps the cracks tight and limits localized cracking leading to brittle failure. For these reasons, ECCs have been used in several civil and tunneling applications such as retrofitting surface repair, tunnel lining, irrigation channel lining and seismic reinforcement (Li, 2003).

METHODOLOGY

Material

Even if ECC mix design is relatively well known from the literature (Li, 2003), its practical use and process ability in underground conditions including delivery, mixing, pumping and spraying can be challenging and requires a good understanding of the shotcrete placement process.

Based on its strong expertise in shotcrete material, equipment and shotcrete process, King Shotcrete Solutions has conducted a testing program organized around the following objectives:

- Developing a shotcrete material with enhanced tensile/flexural performances to increase energy absorbing capacity and potentially reduce shotcrete thickness layer.

- Providing rapid performance development to reduce curing period before re-entry in order to speed-up the development cycle and reduce lead time to production.

- Guarantying robust practical application of the developed mixture including delivery, mixing, pumping and spraying in underground mining conditions.

In order to provide enhanced tensile/flexural strength and ductility such as strain-hardening behavior, an in depth analysis and optimizing the cementitious matrix / fiber synergy must be conducted (Li, 2003).
Because such high tensile/flexural cementitious materials generally require must higher fibers dosage (selected with special cares) than typical FRS, its process ability becomes quickly a challenge. In addition to an high dosage of fibers, the development of a rapid strength shotcrete requires a very reactive cement chemistry that does not gain leads to some additional serious challenges in terms of pumpability and sprayability (Reny & Ginouse, 2014) (Lemay, Jolin, & Gagné, 2014). For these reasons and as demonstrated in previous works (Ginouse & Reny, 2015) the use of dry-mix shotcrete process appears more adequate than wet-mix process to guarantee robust pumpability and rapid performances development after spraying.
Indeed, in dry-mix process the contact period between the dry pre-blended material conveyed using compressed air, and the mixing water added to the dry mixture via a watering placed about 3 m from the nozzle outlet, represent a second fraction as opposed to several minutes and even hours when using wet-mix process. This unique feature makes dry-mix shotcrete a very robust process for conveying and placing/spraying low workability materials such as highly fibered rapid hardening mixtures.
Moreover, for thin shotcrete layer applications dry-mix shotcrete is once again very adequate due to its capacity to provide smooth/consistent material flow at low output, which facilitates greatly the application and the control of thin shotcrete layers.
In spite of these numerous advantages, the use of dry-mix shotcrete requires some special cares to ensure consistent material flow into the machine/delivery hoses and for limiting dust production at the nozzle.
After several tests, all these aspects have been taken into account to produce an engineered fiber reinforced shotcrete, pre-blended and bagged in 20 kg bags containing dry ingredients only to avoid cement hydration before use.

Methods and Equipment

Different types of test panels illustrated in Figure 1 have been filled with the considered shotcrete material using full-size dry-mix shotcrete equipment shown in Figure 2.
Since the dry pre-blended shotcrete mixture has low flowability due to the considered mix formula, the shotcrete equipment has been adjusted to ensure smooth and consistent shotcrete operations (see Figure 2 – left).

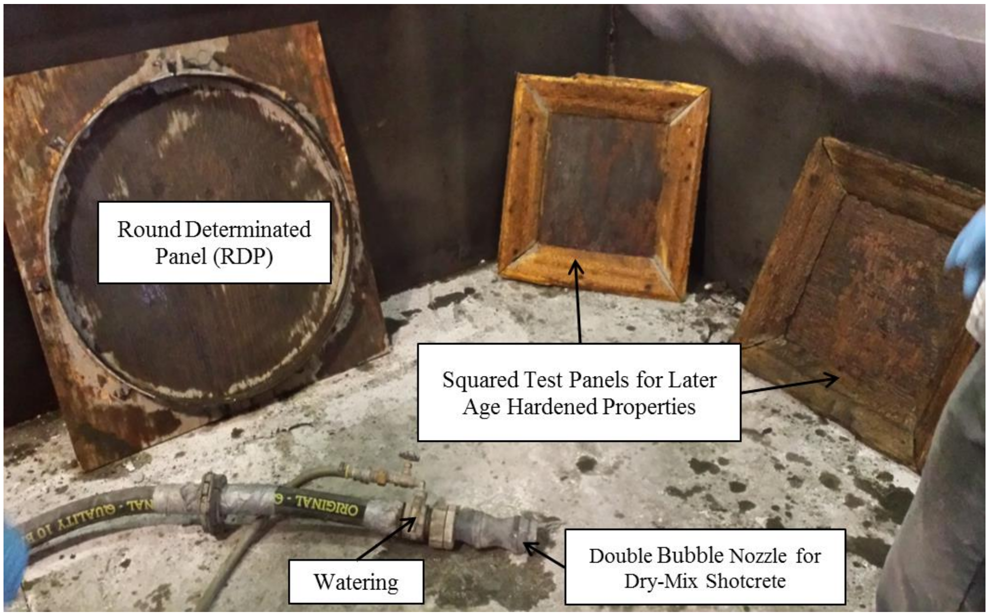

Figure 1: Shotcrete nozzle and test panels used to produce shotcrete specimens

Once the nozzle has manually adjusted the shooting consistency, all test panels were filled without interruption in one single shotcrete operation conducted in accordance with the ACI 506R-05 *Guide to Shotcrete* guidelines. This ensured good uniformity and quality of the shotcrete specimens produced.

Moreover, in order to reproduce curing conditions similar to the one found underground, no wet curing has been conducted on the hardened specimens. Test panels have been only covered using plastic sheets after completion of shotcrete operations in order to prevent excessive surface drying. All specimens have been placed in 50% relative humidity environment after 24 hours and kept covered with plastic sheets until testing without moisture intake.

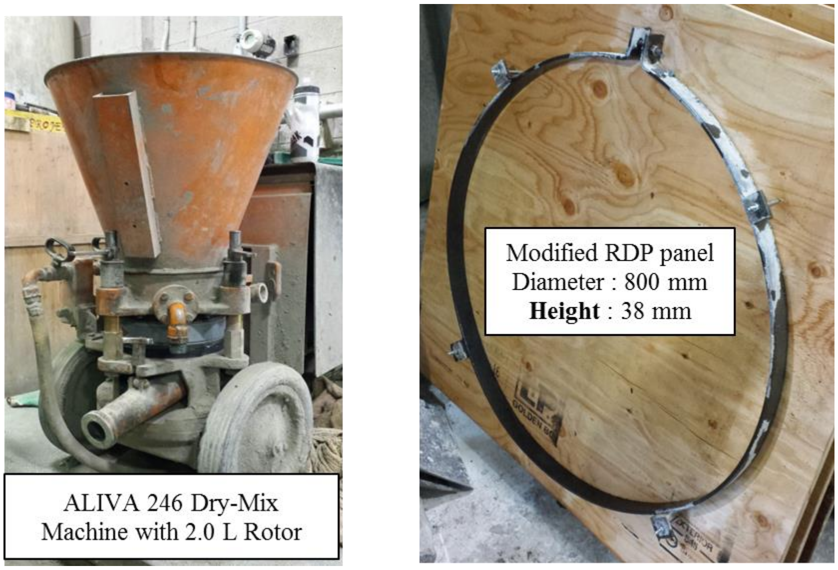

Figure 2: (Left) Dry-mix shotcrete machine; (Right) Modified round determined panel to produce 38mm thick test specimens

Three (3) test specimens per age and per tests have been produced in a controlled environment and tested at early and later age as listed in Table 1.

Table 1: Testing program summary for evaluation of early and later age material properties

	Age	Material Properties	Test Procedure
Early Age	1h, 2h, 4h, 6h, 24h	Compressive Strength (UCS)	Adapted from ASTM C-116*
	24h	Flexural Toughness	ASTM C-1550
Later Age	7days & 28days	Compressive Strength (UCS)	ASTM C-1604
		Flexural Strength	ASTM C-78
		Splitting Tensile Strength	ASTM C-496
	28days	Flexural Toughness	ASTM C-1550 ASTM C-1550 modified**
		Uniaxial Tensile Strength	See details below

*Known as the End Beam Test (Heere & Morgan, 2002)
**Using 38 mm (instead of 80 mm) thick round determinate panels (see Figure 2 – right)

Three (3) 38 mm thick round determinate panels (RDP) have been fabricated for evaluating at 28 days the flexural toughness obtained in thinner layer applications (see Figure 2 – right). In this scenario, half thick RDP panels were considered due to the practical difficulties to control lower thickness layer in mining conditions. Despite the panels' thickness, the testing procedure conducted on the 38 mm thick RDP panels was exactly the same as the one specified by the ASTM C1550.
Because the uniaxial tensile test is more sensitive to the testing configurations and conditions than the other test conducted, five (5) test specimens have been cored from the test panels presented in Figure 3 (left).

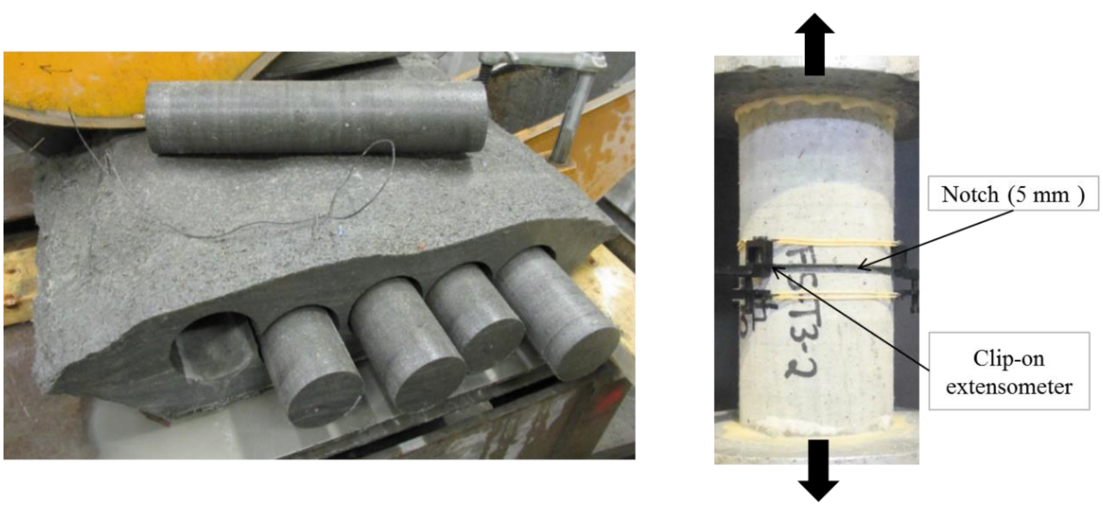

Figure 3: Shocrete cores extracted from test panel (left) and tested for direct tensile strength evaluation (right)

As shown Figure 3 (Left) special cares have been taken to ensure that the cores were extracted from the panel perpendicularly to the spraying direction, and this in order to evaluate the actual contribution of the fibers orientation in the material tensile properties.

Once cored, each specimen was grinded in accordance with the ASTM C-39 in order to guarantee perpendicularity between core axle and the superior/inferior flat faces. Then a 5 mm wide x 10 mm depth notch was sawn at half height to localize the failure in tension to one cross-section (see Figure 3 – right). The uniaxial tensile test was conducted after 28 days using a tensile loading setup composed by a 220kN load cell and clip-on type extensometers illustrated in Figure 3 (right) recording the notch opening. Each core (Figure 3 - right) is about 160 mm height with a nominal diameter of 75 mm and a notched section of 65 mm. Once notched the specimen is glued to aluminum cylinders illustrated in Figure 3 (right) and fixed to the loading device. The tensile loading rate is adjusted in real-time based on the notch opening and varies from 0.01 mm/min initially to 0.1 mm/min once the peak load is achieved.

RESULTS and DISCUSSION

The following section discussed the test results representing the average of at least three (3) experimental values issued from the testing program presented above.

Rapid Strength Development

A rapid strength gain is often aimed when a fast re-entry after shotcrete operations is required. This is particularly true in deep mining/high stress conditions involving seismicity. In a such situation where FRS is typically used as a first pass support or in double pass system, it is quite critical to reach as quick as possible the minimum strengths ensuring a safe re-entry and reducing by means the waiting period before installation the other components of the dynamic ground control system. In this way, a rapid performance development shotcrete will allows a safer and faster ground support installation.

Re-entry criteria used for FRS are usually based on its uniaxial compressive strength (UCS) that is relatively easy to measure in practice and that is related to its shear resistance governing its failure mode at early age (Bernard E. S., 2009).

In Canadian mines located in Northern Ontario, a minimum UCS value of 5 MPa is usually required before re-entry underground area supported with shotcrete (Dufour, O'Donnell, & Ballou, 2003). This value is typically achieved after a curing period of 4 to 6 hours in the best case scenario and after 8 hours in more conservative but still realistic approach.

As shown Table 2, this re-entry value (5 MPa) is achieved after 1 hour using the developed ECC shotcrete, which is 4 to 8 times faster than what the typical FRS technology can provide. From an operation/production standpoint, this rapid strength development represents a serious option to speed-up the ground support system installation and therefore reduce lead time to the next development phase.

Table 2: Early-age compressive strengths obtained from End-Beam Test

Age	*Compressive Strength (MPa)*
1 hour	5.5
2 hours	6.5
4 hours	10.9
6 hours	20.3
24 hours	36.8

Moreover, as illustrated in Figure 4 a very gradual and smooth failure in compression with multi-cracking were observed as opposed to a brittle and sudden rupture with localized cracking usually obtained with typical FRS tested using the end beam tester. In other words, when the peak load was achieved the material didn't collapse suddenly but it continued to support the load while deforming. A fiber bridging mechanism producing multi-cracking instead of localized macro-cracking can explain the more ductile behavior observed during the end beam test.

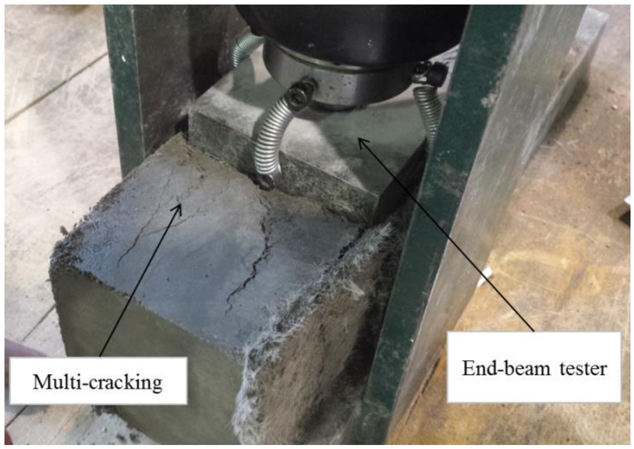

Figure 4: Hardened specimen tested in compression at 1 hour using end-beam tester

Enhanced Flexural and Tensile Performances

At later age (28 days) the shotcrete mixture tested also shown superior performances with respect to typical FRS mixtures.
This performances improvement is particularly pronounced when looking at the flexural and tensile properties presented in Table 3 to 6. Indeed, in addition to a quite high UCS value measured at 28 days (57 MPa), the uniaxial tensile properties presented in Table 4 and illustrated in Figure 5 distinguish the developed shotcrete mixture from the typical FRS.

Table 3: Later age hardened properties

Properties	*Age*	
	7 days	*28 days*
Compressive Strength (MPa) - ASTM C1604	48.8	57.2
Flexural Strength (MPa) – ASTM C78	8.5	8.2
Splitting Tensile Strength (MPa) – ASTM C496	6.25	6.55

Under uniaxial tensile loading, the shotcrete material achieved a maximum tensile strength of 4.1 MPa and exhibited an improved post-behavior (see Figure 5).

Table 4: Uniaxial tensile test results

Tensile Properties	*Age*
	28 days
$P_{max}(kN)$	14.5
$\sigma_{max}(MPa)$	4.1

As illustrated in Figure 5, once the uniaxial peak load was reached no brittle tensile failure occurred and the tensile load was maintained while the notch opening increased and cracking development at the notched section continued.
This enhanced tensile behavior can also explain the very high flexural toughness values reported in Table 5 and 6.
Indeed, using 80 mm thick RDP panels and following the ASTM C1550, over 1000 Joules at 40 mm displacement were obtained after only 24 hours curing and over 600 Joules at 28 days. These values are significantly higher than the typical values required for poor rock quality in challenging ground conditions (Bernard E. S., 2009) (Grimstad, & al., 2002).

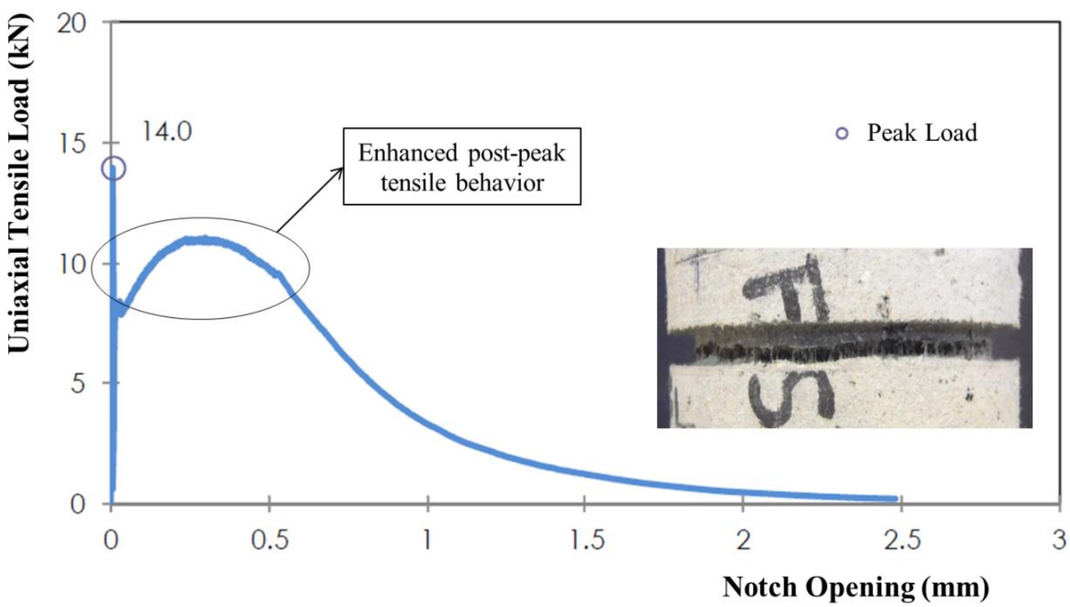

Figure 5: Uniaxial tensile load curve versus notch opening obtained at 28 days shotcrete cores

The loss of flexural toughness between 24 hours and 28 days requires however further explanations. Indeed, while a typical cracking pattern was observed on RDP specimens tested at 24 hours, none of the three (3) 80 mm thick panels tested at 28 days exhibited the typical three (3) fully developed cracks. As a result a loss of toughness to 673 Joules at 40 mm was measured and was attributed to a possible material embrittlement due to a stiffer cementitious matrix developed after 28 days (Bernard E. S., 2008).

Table 5: Flexural toughness results – ASTM C1550

Properties	*Age*	
	1 day	*28 days*
Corrected Peak Load (kN)	47.1	50.1*
Corrected Energy Absorption (Joules) @ 40 mm	**1068**	**673***

*Cracking pattern not following the ASTM C1550: only two fully developed cracks with minor cracks.

As illustrated in Figure 6 a higher residual post-peak loading capacity was observed on RDP panels tested at 24 hours compared to those broken at 28 days. As indicated the UCS value obtained at 28 days was much higher than at 24 hours (57 MPa and 38 MPa respectively) leading usually to a stiffer material with stronger fiber/matrix anchoring that may resulted in fiber breaking instead of fiber bridging mechanism.
Despite the lower peak load, the half thick panels provided 378 Joules at 40 mm (see Table 6) with a post-peak strain-hardening behavior until 20 mm net deflection (see Figure 6).

Table 6: Flexural toughness results – Modified ASTM C1550

Properties	*Age*
	28 days
Panel Thickness (mm)	44
Peak Load (kN)	16.51
Energy Absorption (Joules) @ 40 mm	378.5

Therefore, even using about half thick thickness layer, the considered shotcrete material will provide a fair energy absorbing capacity to the ground support system and an enhanced ductility. The level of energy absorption obtained with half thick RDPs open the discussion on reducing the FRS thickness layer by using this new shotcrete material.

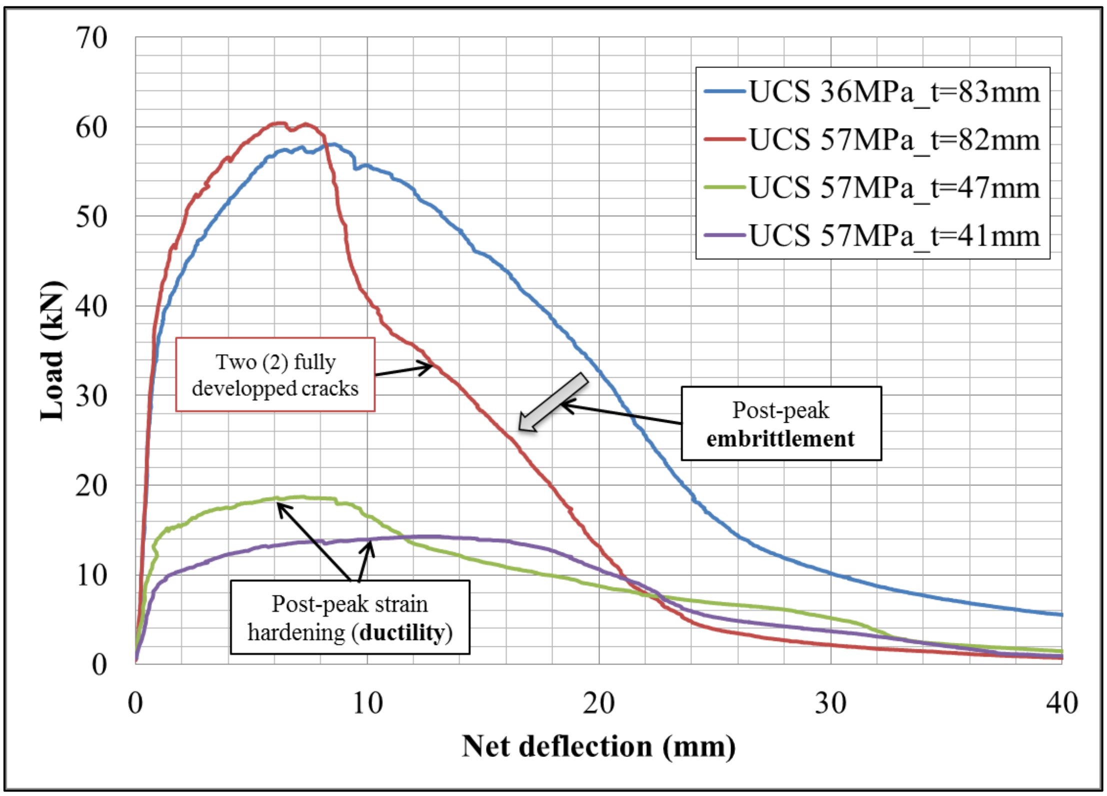

Figure 6: Post-peak embrittlement observed on 80 mm thick RDP panels and Post-peak strain hardening ductility observed on 40 mm thick RDP panels tested according to the ASTM C1550

In spite of this possible embrittlement phenomenon observed on 80 mm thick RDPs, the tests conducted on half thick RDPs allows for discussing this point from a more structural angle. Indeed, as shown Table 5-6 and Figure 6, the post-peak behavior obtained at 28 days seems to be also function of the specimen thickness and not only governed by the intrinsic material properties such as compressive and tensile strengths. While as expected the half thick RDPs provided lower peak load capacity than 80 mm thick RDPs, thinner specimens were able to maintain the peak load over 10 to 20 mm deflection before gradually failing according to a typical cracking pattern. The post-peak behavior observed on thinner and thicker RDPs at similar age points out ASTM C1550 limits of testing intrinsic material properties. The flexural toughness results issued from this testing program do not seem to be only function of material properties but it seems to be also affected by the testing conditions such as stress distribution during loading and boundary conditions that may explain the obtained results.

CONCLUSIONS

The enhanced flexural/tensile performances obtained with the developed shotcrete material and its rapid UCS development can significantly increase the energy absorption/loading capacity of the ground support system while reducing lead time to re-entry in safer conditions. With over 1000 Joules in flexural toughness measured only after 24 hours the used of this engineered fiber reinforced shotcrete could represent a new important element of a dynamic ground system designed for challenging ground conditions with high seismicity and rock bursts activities. Moreover, because of its enhanced tensile strength and post peak behavior under tensile/flexural loading its resistance against spalling caused by seismic events should be definitely increased, reducing by means the risks of damage and potential injuries.

If used as a first pass support, the material will also guarantee a faster re-entry after completion of shotcrete operations due to its rapid strength development, leading by means to a safer and faster support installation.

In addition, because of the higher tensile, flexural and compressive performances obtained in this testing program, a potential reduction of the shotcrete thickness layer should be investigated for gravity failure and moderate stress conditions. In this scenario, thin layer applications using this new shotcrete material will results in additional benefits from economical, logistical and operational standpoint.

Finally, in-situ trials on this new material are currently in progress in Northern Canadian mines to confirm its performances in underground conditions and also evaluate its actual contribution to the current ground support system used in high stress/seismic zones.

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