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SPECIFYING AND TESTING FIBRE REINFORCED SHOTCRETE: ADVANCES AND CHALLENGES

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ABSTRACT

Although fiber reinforced shotcrete (FRS) has been around for many years in the tunneling and mining industry, there are still difficulties in many areas to bring owners and specifiers to take full advantage of the properties of this material in their ground support programs. These difficulties are often associated with the fact that the technical information or material properties reported (such as energy absorption or cracking load) do not necessarily reflect the actual need of the ground support engineer. This paper offers an overview and a discussion on the question: ‘’How can we take full advantage of FRS in ground support programs?’’. Ideas in relation with the main challenges of the industry are presented in the hope of improving and increasing our understanding and use of FRS. Ultimately, using the full potential of FRS in ground support programs will contribute to higher safety in mines and tunnels; provide safer access to previously inaccessible areas and at greater depths; optimize ground support materials needed underground and improve productivity with faster production cycles.

INTRODUCTION

Fibre Reinforced Shotcrete (FRS) has now been around for many years in the tunneling and mining industry. It can be used to prevent rockfalls and control deformations for the safety of men and equipment without the complex process of mesh installation. However, the approaches to design in mines are often experience driven and empirical, and as such, there are still difficulties in many areas to bring owners and specifiers to take full advantage of the properties of FRS in their ground support programs. Even though FRS has proven its potential in various conditions, there are still misunderstandings around the shotcrete process and the material that is FRS. The historical rivalry between steel and synthetic fibres, although incentive for developments, may have brought confusion in the industry on the potential roles of fibres. To some extent, the same could be said about the wet-mix and dry-mix processes apparent opposition. Without turning this paper into a long editorial on the steel/synthetic or wet-mix/dry-mix opposition, it is important to take time and try to answer the main question: ‘’How can we take full advantage of FRS in ground support programs?’’

There appears to be four main challenges that prevent engineers to answer this question properly:

- Communication/language problem between the mining and the material engineer;
- Understanding of the technical specificities of the shotcrete process;
- Testing and interpreting results for FRS;
- Absence of a common approach to the design and specifying of FRS.

The following sections offer discussion points in relation with the four challenges above in the hope of improving and increasing our understanding and use of FRS.

MINES VS. MATERIALS

On one hand, the technical information or material properties reported by the testing (such as energy absorption or cracking load) do not necessarily reflect the actual solicitation requirements of the ground support engineer. On the other hand, the actual ground conditions in mines are not necessarily reported in a way that facilitates proper design of FRS. Thus, the implementation of a common language between the ground support and the FRS specialists, combined with proper data collection would lead to an optimal use of FRS in various underground conditions.

Furthermore, shotcrete is more than a single material, it is a versatile placement process. Shotcrete and FRS can respond to a variety of requirements depending on the mix-design, the placement process and in combination with other systems. With the variety of products available on the market at the moment, there are endless possibilities in obtaining different behaviours to properly suit specific needs. Different mesh types and fibre types in shotcrete can offer different behaviours, but they are often not used at their full potential because of misunderstandings or lack of technical information in the industry. This appears to be an obstacle for the use of FRS in mines and tunnels as a replacement for conventional support methods even though FRS specialists are convinced of similar or even better performances. As new and improved technologies are always emerging; it is all our responsibility to make the extra effort to truly consider them.

FRS TECHNOLOGY

The mechanisms through which FRS controls deformations and absorbs energy are complex and involve the technicalities of the spraying process, the specific rheology of the mixture, the properties of the concrete/fibres and the influence of admixtures. The use of fibres in shotcrete transforms the original brittle material, plain shotcrete, into a ductile composite after cracking. This composite can then control deformations and absorbs energies imposed by ground movements. Different material, shape, length, finish and dosage of fibres can lead to various behaviours of FRS. For the FRS to have the highest flexural strength and toughness, there must be an optimal design and combination of concrete strength, fibre anchoring, fibre friction and placement method (Bentur & Mindess, 2006).

A good example of the complexity of FRS has been demonstrated for dry-mix shotcrete by Jolin et al. (2015). As shown in Fig. 1, the ‘’drier’’ the shooting consistency of the dry-mix shotcrete is, the higher the compressive strength is (red data points). Also, since a drier consistency leads to higher rebound (aggregates and fibres), the drier the shotcrete is, the lower the in-place fibre content will be (fibre content is on top of histogram bars). What is seen is an optimum between the compressive strength (fibre anchoring and friction) and the in-place fibre content of the dry-mix FRS to obtain the highest energy absorption. To further illustrate the impact of *process*, the wet-mix section on Fig. 1 corresponds to the same mixture (concrete and fibre content) shot with the wet-mix process. The equivalent compressive strength, but relatively lower energy absorption supports other work where it was shown that dry-mix process creates a higher quality bond with reinforcing bar (Basso et al., 2016).This is presented only to illustrate that it is essential to consider the entire shotcrete process, all ingredients and their combination to thoroughly evaluate, design and specify FRS.

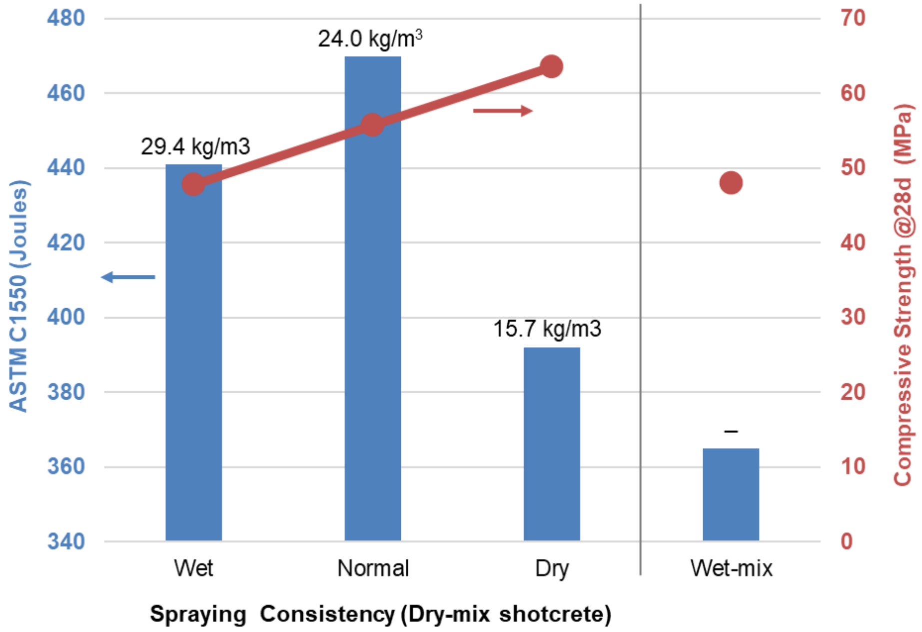

Figure 1: Cumulative energy absorption recorded after a 40 mm vertical central displacement (solid bars) and 28 d compressive strength (data points) expressed as a function of the shooting consistency level; the corresponding in-place fiber content is displayed above each bar (adapted from Jolin et al., 2015)

FRS TESTING

There is a variety of test methods available for the evaluation of the flexural strength and energy absorption of FRS: American test methods (ASTM C1609, ASTM C1550), European (EN 14651, EN 14488-5), Japanese (JSCE-SF4) and others (ASTM C1550-12a, 2012; ASTM C1609-12, 2012; EN 14488-5, 2006; EN 14651, 2005; JSCE-SF4, 1984). The challenge is to know *what question is being asked* when running a given test; indeed, the test may be giving information about crack opening control or energy absorption, flexural strength or shear strength, overall behaviour or ultimate load, etc. Naturally, one must reflect on the test being conducted if he hopes to understand and make proper use of the result (*answer*).

This is important because these test methods do not reflect in the same way the changes in the behaviour and properties of FRS. The results from these test methods can hardly be directly compared. For example, the ASTM C1550 (Round Determinate Panel) and the EN 14488-5 (EFNARC Square Panel) are two test methods often compared even though their geometrical and testing conditions are quite different (Tab. 1 and Fig. 2).

Table 1: Characteristics comparison between ASTM C1550 and EN 14488-5

Characteristic	**ASTM C1550**	**EN 14488-5**
Geometry	Round (Ø 800 mm x 75 mm)	Square (600mm x 600mm x 100mm)
Support conditions	3 supports	Continuous support
Stress type	Flexure	Flexure and punching shear
Behaviour type	Material	Material and structure
Cracking pattern	Determinate	Varying
Deflection	Up to 40 mm	Up to 25 mm
Disadvantage	Not the best simulation of the actual solicitations	More susceptible to support conditions
Advantage	Robust and repeatable	Better simulation of the actual solicitations

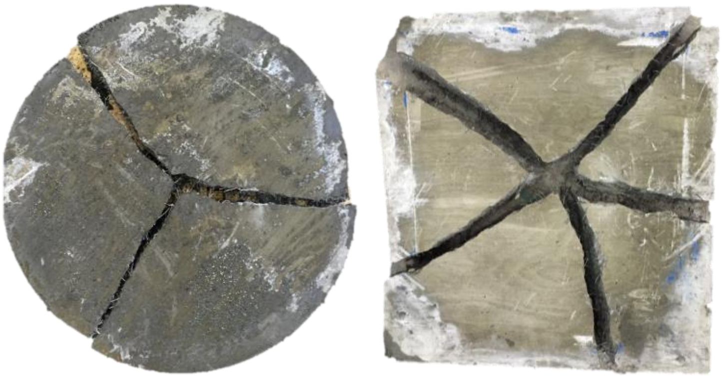

Figure 2: ASTM C1550 (left) and EN 14488-5 (right) panels

There has been a correlation reported between the results of the two test methods; there would be a factor of 2.5 between the ASTM C1550 energy absorption at 40 mm deflection and the EN 14488-5 energy absorption at 25 mm deflection (Bernard, 2002). However, it seems that new mixtures and fibres do not show the same potential with one test method or the other. For example, test results showed a correlation factor of 2.9 (approx. 350 to 1000 J) for a mixture with a simple anchoring system steel fibre and a correlation factor of 3.5 (approx. 600 to 2100 J) for a mixture with a more complex anchoring system and strain hardening steel fibres. The fact is, the test methods do not translate the potential of FRS in the same manner and are, therefore, not directly comparable.

Furthermore, there is actually no reliable and accepted test method for the evaluation of FRS under *dynamic loading*, even though it appears to be of critical importance in the further development and efficient use of FRS. A new method that will be investigated at *Université Laval* is a *pseudo-dynamic* approach. The principle of *pseudo-dynamic* tests has been used since the 1980s for the evaluation of structures subjected to seismic loads (Donéa et al., 1990). It is a method that simulates dynamic loadings and measures the response of a structure without having to perform complex and expensive large-scale dynamic tests. It seems that this approach could have an interesting potential in the analysis of FRS under dynamic loadings.

DESIGN AND SPECIFYING

The criteria for the *design* and *specifying* of FRS are generally based on flexural strength, post-cracking residual strength, energy absorption (toughness) or moment-normal force diagram. It is generally accepted that a *toughness* criterion is used for rock support and that moment-normal force diagrams are used for arches and soft grounds (Nitschke, 2017). However, there is no specific, detailed and broadly accepted design guide for FRS as ground support.

Moreover, experience shows that it is more important to focus on the system performance rather than isolated concrete and fibre properties. For example, a fibre content does not necessarily lead to a sufficient energy absorption. Test results showed that different fibres (anchoring system, tensile strength and length), a same fibre content (25 kg/m^3) and a same concrete (50 MPa) lead to different behaviours (strain softening and strain hardening) and different toughness values (from approx. 350 to 600 J).

Also, test results showed that different fibres (steel and synthetic) and different fibre contents (in this case 25 kg/m^3 and 6 kg/m^3 respectively) can lead to *different behaviours*, but at the same time an *equivalent toughness* (approx. 450 J). The behaviours of steel and synthetic fibres in shotcrete are often misunderstood in the industry. Synthetic FRS typically reaches a load capacity plateau after cracking and allows larger deformations as compared to steel FRS that more rapidly supports the load after cracking and limits the deformations. Consequently, the choice of fibre type and content must correspond to the ground conditions of a specific area and the expected concrete mixture design. For example, for a final lining where minimal deformations are acceptable, it is better to focus on flexural strength and energy absorption at small deflections and crack opening. For an initial or temporary lining, where large ground deformations are expected, it is possible to consider energy absorption at large deflections.

Dynamic loads associated with seismic activities and high stresses, mainly rock bursts/strain bursts, appear to be of critical importance in the further development and efficient use of FRS. These events are known to be powerful and unpredictable, especially in deep mines. Unfortunately, there is no specific requirements for FRS mixtures for this type of solicitation nor a design method or a test method. However, recent studies have opened the doors for this kind of approach with dynamic loading (Vollmann et al., 2015).

CONCLUSION

Ultimately, using the full potential of FRS in ground support programs will contribute to higher safety in mines and tunnels. It will also provide safer access to previously inaccessible areas and at greater depths. A better understanding of the FRS will contribute to optimize ground support materials needed underground and improve productivity with faster production cycles. The objective of the new research project at the *Shotcrete Laboratory* at *Université Laval* is to provide tools for designing, specifying and testing FRS. It will be made possible by evaluating current methods, and offering new guidelines and test methods. The biggest challenge remains to improve communication between material engineer and ground support engineer. How can we speak the same language? What kind of tool do we need? It is the hope of the authors that the upcoming research effort will answer some of these questions.

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