Summary of *'Guideline on the Applicability of Fiber-Reinforced Shotcrete for Ground Support in Mines'*

By Rym Msatef and Marc Jolin

Since the early days of industrial mining, one of the biggest challenges has been to reliably support the underground excavations to allow safe access for workers and efficient production. Engineers design support systems based on the surrounding ground conditions, service-life, and the most significant loads. Fiber-reinforced shotcrete (FRS) is an important tool needed to achieve the desired performance. However, ground support engineers often face challenges with properly integrating the properties of shotcreted concrete into the design or navigating the different testing methods and their associated specifications.

This paper is a summary of the *Guideline on the Applicability of Fiber-Reinforced Shotcrete for Ground Support in Mines (see citation at the end of this article)*, which is intended to provide guidance to unlock the full potential of this composite material. The section below presents some of the key points addressed in the guideline.

The use of shotcrete as underground support became common with the introduction of the New Austrian Tunneling Method (NATM) in the 60s[1]. Subsequently, steel fibers were introduced in shotcrete in the early 70s, and their potential in underground support was rapidly identified (Parker, 1974 and Poad et al. 1975 –in ACI PRC-506.1-21)[2].

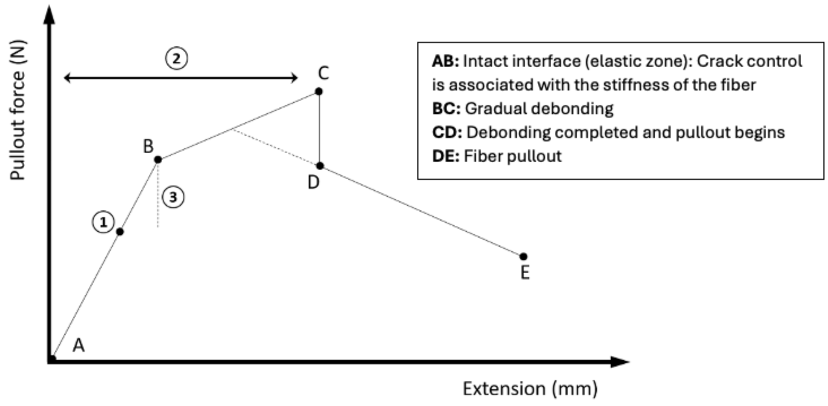
FIBER-REINFORCED SHOTCRETE

There are many different types of fibers available, each with different properties. Most fibers can be categorized as either macrofibers or microfibers depending on their diameter, and steel fibers or synthetic/polymer fibers. It's important to choose the right type based on the design's need for the surrounding ground: For example, the tensile strength of a steel fiber can go from 350 to 2500 MPa (51,000 to 360,000 psi) and the tensile strength of a macrosynthetic fiber can go from 350 to 650 MPa (51,000 to 94,000 psi).

Their role is to improve the properties of concrete after cracking by (1) controlling the opening of the cracks, (2) absorbing or dissipating energy at the crack location or (3) a combination of both. Simply put, when a crack forms, there is a transfer of the tensile forces from the concrete matrix to the fibers. To have an *efficient load transfer*, three conditions must be satisfied:

1. There must be sufficient transfer surfaces (number, length and diameter of fibers).
2. The nature of the interface between the fiber and the cement matrix must allow for proper load transfer.
3. The properties of the fiber (Young's Modulus, Poisson's ratio, tensile strength, and anchorage mechanism) must allow for force transfer without breakage or excessive deformation.

The *adhesion* and *friction* between the cement matrix and the fibers are important factors for achieving an effective post-cracking response and energy absorption mechanism.



1: Fiber snaps if too weak
2: Related to fiber stiffness
3: No friction, fiber is too short

Fig. 1: Ideal pull-out curve of a single fiber (adapted from [3]).

The shape and the texture of the fibers can maximize these effects, but the strength of the cement matrix also has an impact: The *pull-out behavior* of a single fiber is intimately related to the properties of the cement paste around it. A matrix that is too weak may not allow the fibers to reach their full capacity and potential. However, if a matrix is (relatively) too strong and provides too much adhesion and friction, it could cause the fibers to break, which is an undesirable behavior. In fact, it is often better to have a fiber that pulls from the shotcrete rather than one that breaks. Fig. 1 illustrates the idealized pull-out curve of a single fiber.

MINING AND GROUND SUPPORT

The objective of mining operations is to extract and process ore in a profitable and safe manner. Ensuring the safety of workers and equipment is essential, as it is constantly at risk from the instability of the rocks surrounding the underground excavations. Ground support assures this safety, and fiber-reinforced shotcrete often plays a significant role in it.

Several approaches exist for underground excavation and ground support. Thompson, Villaescusa, and Windsor[4] define ground support as a combination of *reinforcement* and *support* systems. A reinforcement system refers to anything integrated into the material surrounding an excavation, such as rock bolts. A support system, on the other hand, refers to anything that is in contact with an excavation face. FRS is classified among the areal support systems, as it is generally used to retain broken rock, similar to wire mesh, and can also be used to hold fractured block.

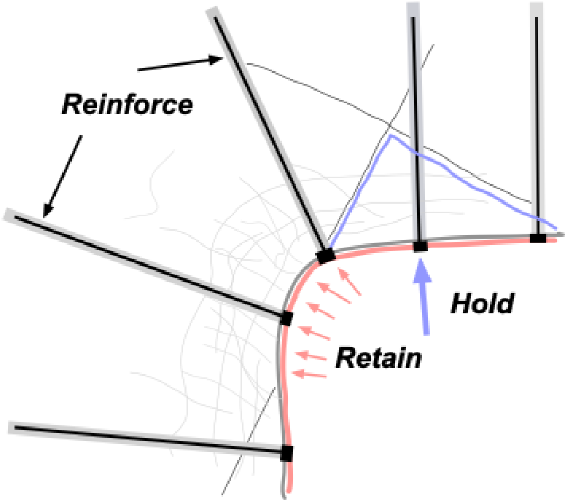


Fig. 2: Visualization of a ground support approach (adapted from Kaiser [5]).

The exact loads and stresses transferred to the FRS are often difficult to exactly predict. It is often a complex combination of stresses, where one area can be in flexure, the next one in shear, or compression, or tension, or a combination!

FRS FOR GROUND SUPPORT

There are several testing methods used in the industry to evaluate the behavior of fiber-reinforced shotcrete. Some methods are better suited for design, while others are more appropriate for quality control. Similar to the choice of fibers, the selection of a test method must be made carefully — the engineer must consider the objectives of the test (design, QA, QC, R&D, etc.) and identify an appropriate test method that will provide meaningful results.

Because the average distance between fibers is usually much smaller than that of reinforcing bars, fibers are mobilized earlier in the cracking process and will greatly influence the crack pattern and its evolution under load. Indeed, fiber reinforcement can change the post-crack response of concrete from brittle to ductile. The biggest improvements are in the tensile strength of concrete. However, testing *post-cracking behavior in pure tension* is experimentally very challenging, which is why most of the test methods presented below focus on evaluating improvements in flexural performance. The stress vs. crack width curves are the most relevant characteristics of FRS in flexural design. These curves represent the true behavior of the material, regardless of the size of the structural member or the loading conditions. Nevertheless, it is crucial to understand that the failure mechanism of FRS is not always purely flexural, as shear and compressive loads are also present.

Multiple tests are presented in the original guideline, their key elements are briefly introduced in Table 1. To gain further insight, the section below explains two of the most commonly used tests in more detail.

ASTM C1550 - STANDARD TEST METHOD FOR FLEXURAL TOUGHNESS OF FIBER REINFORCED CONCRETE (USING CENTRALLY LOADED ROUND PANEL) – A.K.A. “RDP TEST”

The ASTM C1550 test method is an ASTM standard that is used to evaluate the flexural toughness (or energy absorption) of fiber-reinforced concrete (FRC) and particularly FRS[6]. Because the crack pattern is *determinate* (three cracks or the test is deemed invalid), it is possible to determine the post-cracking moment capacity, flexural strength, and therefore the stress-crack width relationship of FRS using yield-line theory[7][8]. The results can be used in several ways; in design regardless of the specific loading conditions, the energy absorption in the Q-system design method[8], and in quality control of FRS.

EXECUTION AND RESULTS

In this test, an FRS round panel specimen is loaded in its center with a rounded steel head and supported on three articulated points placed 120° apart on the perimeter (Fig. 3). The central deflection is measured to produce a load-deflection curve (Fig. 4) that represents the post-cracking flexural behavior. The values of energy absorption are typically reported at central deflections of 5, 10, 20, and 40 mm (0.2, 0.4, 0.8 and 1.6 in.). Depending on the type of application (for ex.: slab vs. deep mining tunnel face), the order of magnitude for the energy absorption at 40 mm deflection is typically ranges between 300-1000 Joules.

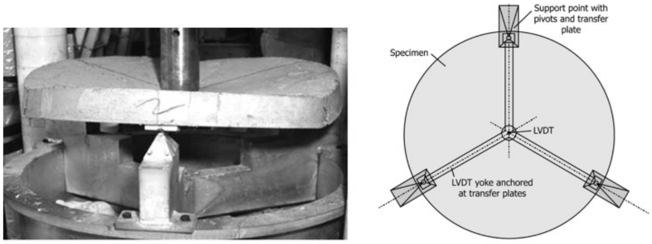


Fig. 3: Illustration and schematics of the ASTM C1550 test specimen under load (from [6]).

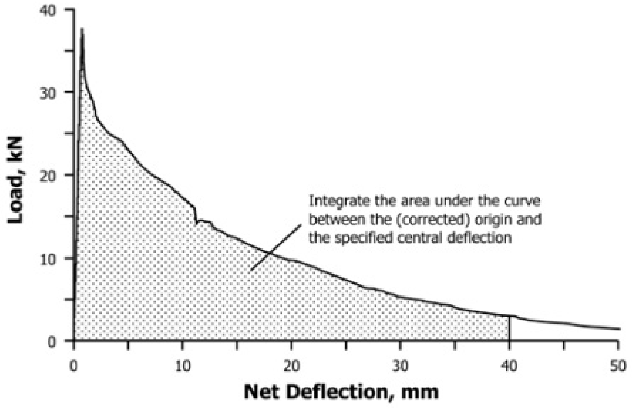


Fig. 4: Example of a Load-Deflection curve in an ASTM C1550 test; the area under the curve — or energy absorption — at 40 mm central deflection is represented by the shaded area (from [6]).

ENGINEERING VALUE

It is possible to calculate the stress-crack width relationship in an inverse analysis from this test method. These parameters can eventually be used to determine the bearing capacity and energy absorption of the deformed lining. The maximum crack width in this test is somewhat closer to what can be observed in mines compared to other tests. Indeed, on a 1.5 m (5 ft) span between rock bolts, the equivalent out of plane displacement could be almost 140 mm (5.5 in.) for the same approximated crack rotation. This test has the advantage of giving a lower variability in the results and the material behavior can easily be analysed from the results.

EN 14488-5 TESTING SPRAYED CONCRETE – PART 5: DETERMINATION OF ENERGY ABSORPTION CAPACITY OF FIBER REINFORCED SLAB SPECIMENS – A.K.A. "EUROPEAN PLATE TEST"

The EN 14488-5 test method is a European standard meant for the determination of the energy absorption capacity of FRS[10]. This test is used in the ground support design method Q-system[11] and for quality control of FRS.

This test allows for stress/load redistribution in the panel. Therefore, the number of cracks and their pattern can vary from one test to another. While this makes the strict interpretation of the results difficult, it also enables the FRS to better express its true behavior. Indeed, it has been shown that a specimen will evolve from a pure shear failure to a combined shear/flexural failure as the fiber content increases[12].

EXECUTION

In this procedure, a FRS square slab specimen is loaded in its center with a square steel head and continuously supported by a rigid steel frame on its entire perimeter (Fig. 5). The slab is loaded and the central deflection measured to produce a load-deflection curve (Fig. 6a), which is analysed and converted into an energy absorption-deflection curve (Fig. 6b).

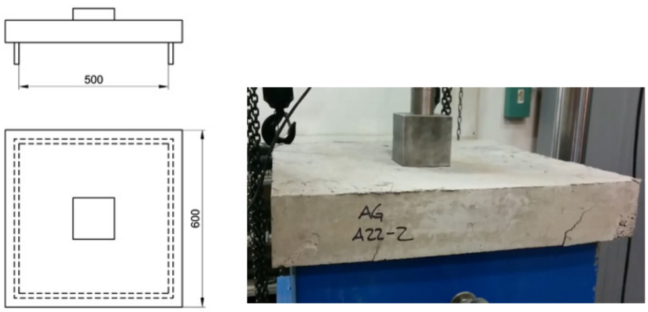


Fig. 5: Schematics of the EN 14488-5 test specimen under load (from [10])

RESULTS

This standard gives a load-deflection curve and an energy absorption-deflection curve that represent the behavior of FRS under a combination of flexural load and punching shear load. The most relevant values that are retrieved are the maximum load and the energy absorption at a 25 mm (1 in.) deflection. The order of magnitude for the energy absorption is hundreds and thousands of Joules and typically ranges between 500-3000 MPa (72,000 to 434,000 psi).

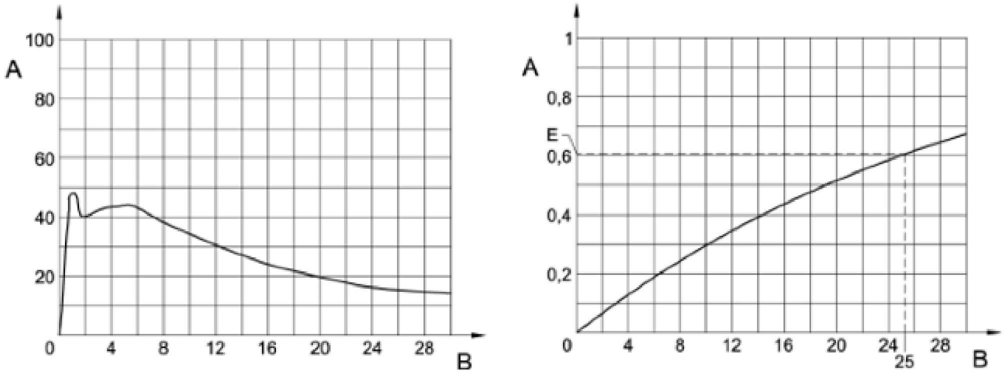


Figure 6a and b: Example of (a) a Load-Deflection curve and (b) an Energy-Deflection curve in an EN 14488-5 test (from [10])

ENGINEERING VALUE

This test method is probably the closest to the actual loading conditions found in a ground support scheme with rock bolting. It is a *statically indeterminate* setup allowing for load redistribution, and creates both flexural and punching shear stresses, leading to more realistic, albeit complex, failure modes. The complex failure modes and the variable crack pattern make it more difficult to understand how the material performs when analyzing the results. Also, the maximum deflection (25 mm) at which the test is performed is relatively small in a mining support context. However, since the span is also relatively small, the actual crack rotation is closer to what can result underground. For example, if we consider a span of 1.5 m between rock bolts, the equivalent out of plane displacement would be 75 mm (3 in.) for the same approximated crack rotation.

Test Method	**Information**	**Typical Results**	**Main Advantages**	**Main Disadvantages**	**Comments**
EN 14651	Flexural tensile strength on a notched beam	Load-CMOD curve Limit of Proportionality Residual strengths	Results can be used in fib Model Code	Necessity to saw and notch beams Small crack opening	Performed under closed-loop control
ASTM C1609	Flexural performance on a beam	Load-deflection curve Peak strength Residual strengths Toughness (J)	Results can be used in ACI 318 design code No need to notch beam	Necessity to saw beams Small crack opening	Performed under closed-loop control
ASTM C1399	Average residual flexural strength on a beam	Residual strengths Average residual strength	No need for closed-loop control	Necessity to saw beams Incomplete loading curve Small crack opening	Almost disappeared from specification
EN 14488-5	Energy absorption capacity on a square panel	Energy absorption-deflection curve Maximum load Energy absorption at 25 mm deflection (J)	Structural test Multi-cracking No need to saw specimen Larger crack openings	Difficulty in using results for design	Flexural as well as punching shear stresses are induced
Norwegian Round Panel	Energy absorption capacity on a round panel	Energy absorption-deflection curve Maximum load Energy absorption at 25 mm deflection (J)	Structural test Multi-cracking No need to saw specimen Larger crack openings	Difficulty in using results for design	Flexural as well as punching shear stresses are induced
ASTM C1550	Flexural toughness on a round panel	Load-deflection curve Peak load Energy absorptions at 5, 10, 20, and 40 mm central deflection (J)	Lower variability No need to saw specimen Larger crack openings	Difficulty in using results for design	Very common test in FRS
EN 14488-3	Flexural tensile strength on a notched square panel	Load-CMOD curve Limit of Proportionality Residual strengths	Larger panel with a notch allows for a longer crack monitoring	Only saw notch on underside	*New test not included in the original table*

Table 1: Overview of the different test methods for FRS

CONCLUSION

The original guideline document explores fiber-reinforced shotcrete and offers guidelines on testing in the context of ground support. It provides insights to help owners, engineers, material suppliers, and key players in making the most out of FRS in their ground support programs. The performances of FRS vary with the type of fiber and their dosage, and with the properties of the concrete they are added to. This guide examines and provides a description of the common testing methods used for FRS and how to interpret the information generated. The choice of a test method is a crucial step: Engineers must reflect on the objective(s) of the test and identify a test method that will allow you to truly discriminate successful or meaningful results.

This complete *Guideline on the Applicability of Fiber-reinforced Shotcrete for Ground Support in Mines-MIG III-WP24* was originally published in 2019 by the *Rock Tech Center (RTC)* based in Sweden. The original authors and collaborators of the guidelines are: Antoine Gagnon, Marc Jolin, Pascal Turcotte, Robert Harris, Nicolas Ginouse, Daniel Sandström and Benoit de Rivaz.

Scan or Click
to view the full guidelines

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