ROCK TECH CENTRE

Version 3.3 Final

GUIDELINE ON THE APPLICABILITY OF FIBRE- REINFORCED SHOTCRETE FOR GROUND SUPPORT IN MINES

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Table of Content

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1. Introduction

Since the early days of industrial mining, one of the biggest challenges has been to reliably support the underground openings to allow for safe access for the workers and efficient development. In this vast and sometimes complex domain, today's engineers design support systems that consider elements such as the nature of the surrounding ground, and the depth and stresses encountered, and that also include design requirements such as allowable ground movement, service-life of the support and extreme loads. One important tool available to the engineer in this design process is to use shotcrete, and particularly *fibre-reinforced shotcrete*, to reach the desired performances.

Fibre reinforced shotcrete (*FRS*) is the result of pneumatically spraying concrete at high velocity onto receiving surfaces; in this particular case, the concrete mix design incorporates discrete reinforcing elements known as fibres. The particularities of FRS are such that this concrete will not only deliver the usual high compressive strengths expected from sprayed concrete but also provide some load bearing capacity after (sometimes substantial) cracking due to the composite behaviour of the fibres and the concrete matrix.

Ground support engineers may however face challenges or difficulties in specifying FRS. Whether these difficulties have to do with properly integrating the properties of these concretes in design or navigating the different testing methods and their associated specifications, the intent of this guideline is to provide a clear view of the applicability of fibre-reinforced shotcrete for ground support in mines. Ultimately, the goal is to facilitate the specification and uses of FRS and to unlock the full potential of this composite material to enhance worker safety and provide efficiency and economic benefits to the mines, particularly by supplementing or even replacing the mesh reinforcement.

1.1. Situation in the Industry

Clearly identifying how FRS is being used in the mining industry can be quite complex and remains an open question. Suffice to say for the moment that the 80s saw the convergence of interesting factors in shotcrete technology: the hydraulic swing tube pump were then powerful and reliable enough to adequately pump concrete inside small diameter hoses, water reducers/plasticizers were finally available to allow for the pumping of high-quality concrete and, obviously, high-quality steel fibres appeared on the market. This led to an increase use of FRS in numerous mining operations where the initial goal was to replace the time-consuming and often hazardous installation of mesh.

While in many areas the use of FRS in mining ground support makes a lot of sense, it is sometimes difficult to adapt the design of the ground support system or the construction cycle to fully evaluate the cost-benefits of using fibres and shotcretes. In parallel, the development of new fibres along with the almost never-ending new offers on the market have rendered the task of selecting the "right shotcretes" and the "right fibre" sometimes overwhelming for the engineers.

1.2. Objectives

The main objective of the present guide is to offer guidelines on the applicability of fibre-reinforced shotcrete for ground support in mines. This should be accomplished by tackling these specific objectives:

1. To specify the various performance requirements of FRS that need to be met for its use as an effective component in a mine’s ground support system;
2. To explain the basic mechanisms whereby FRS is able to function as a support component;
3. To provide a description of the types of fibres available, detailing and accounting for their different properties;
4. To provide a description of the different FRS testing methods and how to interpret results with respect to the desired mine application as stated in a contractual specification;
5. To present some relevant case studies and examples of best practices in mining;
6. To identify gaps in knowledge and capabilities of FRS in meeting desired requirements.

2. History

Dry-mix shotcrete, then known as *Gunite*, made its apparition in the industry in 1910 in the USA. It gained in popularity and became widely accepted in the first half of the 20th century. The use of shotcrete as underground support became more common with the introduction of the *New Austrian Tunneling Method* (NATM) in the 60's [1]. In 1966, the American Concrete Institute (ACI) coined the word *"shotcrete"* to all mortars and concretes applied using high velocity pneumatic systems (including both the dry-mix and the wet-mix processes). The arrival and later improvements of concrete pumps led the way in the 70's and 80's to the wide use of the wet-mix process; it was then possible to pump low slump concrete mixtures over longer distances and, most especially, at larger volumes. Along with marked innovations in admixtures, this has enhanced the utility and flexibility and general effectiveness of the process.

Steel fibres were first introduced in shotcrete in the early 70's and their potential in underground support was rapidly identified (Parker, 1974 and Poad et al. 1975 – *from 506.1R-08*). Since that time, FRS has been used throughout the world. When synthetic macrofibres became available in the 1990's, they were also readily adopted in many areas such as in ground support and slope stabilization. This evolution into structural applications is mainly the result of progress with the technology, as well as research conducted in different universities and technical institutes to better understand and measure FRC properties. In the early 90's, recommendations for design guidelines for steel fibre reinforced concrete started to be developed. In 2003, *Rilem TC 162-TDF Recommendations for design rules* were made available for the design of steel fibre reinforced concrete.

In 2013 a major milestone for the increased acceptance of steel fiber reinforced concrete in structural applications was achieved by the publication by *fib* of the *2010 Model Code*. The *fib 2010 Model code* includes specific sections for the design of FRC elements with emphasis on structures where significant stress redistribution occurs. This *2010 Model Code* has been a catalyst globally for increased acceptance of the use of steel fiber reinforced concrete in underground applications such as in the final lining of tunnels and shafts. Indeed, it provides today a sound and reliable basis for the design of structural elements made with fibre reinforced concrete or shotcrete.

3. Fibre-reinforced shotcrete

3.1. Fibres in Concrete

Before exploring the mechanisms behind the reinforcement provided by the introduction of fibres in concrete or shotcrete mixtures, it is interesting to look at a few practical definitions. Indeed, while fibres come in many shapes, lengths, textures and even materials - it is not the intent of this document to review each of them! -, the following definitions and classifications help draw a consistent technical image of what the industry has to offer.

The *American Concrete Institute* (ACI) proposes the following relevant definitions on fibres themselves [2]:

- *Fibre:* a slender and elongated solid material, generally with a length at least 100 times its diameter
- *Fibre aspect ratio:* the ratio of the length to diameter of a fibre in which the diameter may be an equivalent diameter
- *Equivalent fibre diameter:* diameter of a circle having an area equal to the average cross-sectional area of a fibre

With regards to the size of the fibres, the following two definitions are also proposed:

- *Macrofibre:* a fibre with an equivalent diameter greater than or equal to 0.3 mm for use in concrete
- *Microfibre*[1]*:* a fibre with an equivalent diameter less than to 0.3 mm for use in concrete

And finally, the committee dedicated to fibres within the ACI [3] goes further and defines two types of (macro)fibres based on the material used in their production:

- *Steel fibres:* discrete fibres made of steel, used as reinforcement in concrete
- *Synthetic fibres:* chopped fibres made of polyolefin, such as polypropylene and polyethylene materials, used as reinforcement in concrete

In Europe, the *European Committee for Standardization* (CEN) proposes definitions for fibres for use in fibre-reinforced sprayed concrete based on their material [4]. Overall, the concepts presented are essentially the same presented above. Polymer fibres and synthetic fibres are two ways to refer to the same category of fibres. The CEN definitions are as follows:

- *Steel fibres*: straight or deformed pieces of cold-drawn steel wire, straight or deformed cut sheet fibres, melt extracted fibres, shaved cold drawn wire fibres

[1] Microfibres are often used in prefabricated thin elements such as tiles or architectural wall elements – they are not covered in this document as they are very rarely used in ground support.

and fibres milled from steel blocks which are suitable to be homogeneously mixed into concrete or mortar
- *Polymer fibres*: straight or deformed pieces of extruded orientated and cut material which are suitable to be homogeneously mixed into concrete or mortar and which are not affected over time by the high pH of concrete

These definitions illustrate particularly well the scope of products the ground support engineers may have to deal with: macrofibres with typical lengths varying from 30 mm to 60 mm and of diameters ranging from 0.3 mm to 1 mm, either made of steel or synthetic material. The various nuances of steel or types of polyolefin in turn make fibres available over a wide range of physical properties, and the various shapes or surface textures offered will complete the picture of an industry that has hundreds of different products available.

A simple yet very important question must be addressed before exploring how fibres can be used in ground support: what are the roles of fibres in concrete? In concrete technology, (macro)fibres are used to improve the properties of concrete *after* cracking. In practice, the effects of fibres on this *post cracking behaviour* will be to (1) control the opening of the cracks, (2) absorb or dissipate energy at the crack location or (3) a combination of both. The extent of these effects will greatly depend on the quality of the concrete and the type and dosage of fibre used. The following section presents some aspects of the mechanisms involved in such a case.

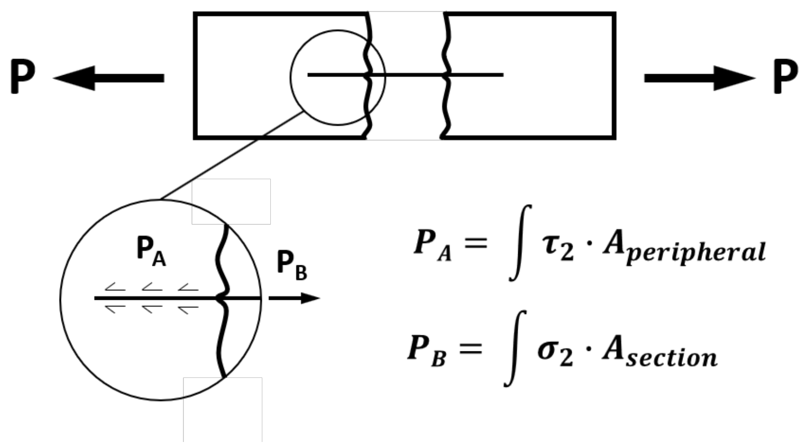
3.2. Mechanisms of fibre reinforcement

It is interesting to initiate the discussion on the mechanisms of *fibre reinforcement* by studying a single straight fibre embedded in concrete paste[5]. This approach allows for a generic analysis of fibre behaviour and will in turn illustrate how manufacturers have addressed different technical challenges in designing their fibres.

The first step of the discussion is to consider the stresses encountered immediately after cracking at the vicinity of a single fibre; for the moment, let us assume the fibre is made of a perfectly elastic brittle material. Placing the fibre perpendicular to the crack formed and given that cracks appear perpendicular to the tensile stresses in the concrete, the stresses transferred across the crack must therefore be transmitted *through* shear stresses at the interface between the fibre and the concrete and then *through* pure tensile stresses in the fibre itself (Fig.1).

The intrinsic mechanical properties of each of the materials in the composites must be considered as well as *how* the transfer of the tensile forces from the concrete matrix to the fibre takes place. Indeed, fibre reinforced concrete or shotcrete is a composite material and its performances are (far) more complex than just the quantity, physical properties and location of the fibres in the concrete matrix or element. It has been determined that for efficient load transfer of the tensile forces from the concrete to the fibres, the following three (3) conditions must be satisfied:

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



$$P_A = \int \tau_2 \cdot A_{peripheral}$$

$$P_B = \int \sigma_2 \cdot A_{section}$$

Figure 1: Stresses distribution in a fibre immediately after cracking (adapted from [5]).

The exact distribution and magnitude of the stresses around the fibre are not relevant here, it is important however to realize that if the fibre is *strong* and *long* enough, it will be gradually pulled out by a combination of *adhesion failure* and by *interface friction*. The *idealized* pull-out curve of this single fibre is represented in Figure 2.

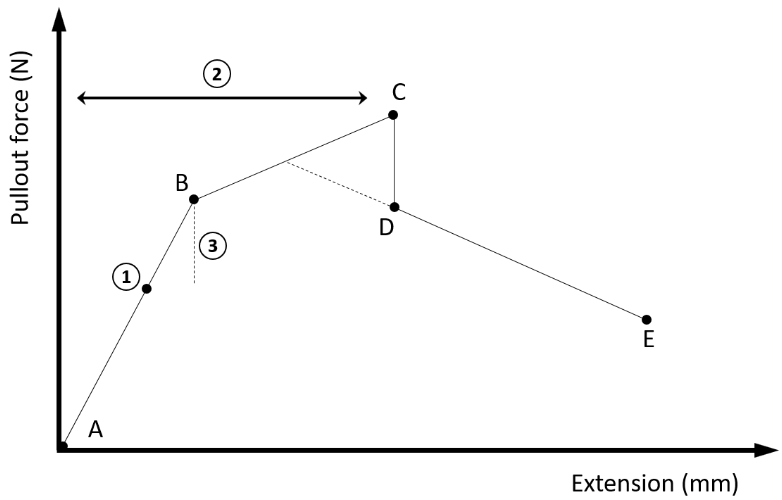


Figure 2: Ideal pull-out curve of a single fibre (adapted from [5]).

The solid line in figure 2 represents the ideal behaviour for the pulling of a fibre out of the cement matrix. The four segments of the curve respectively represent the elastic phase (A – B; adhesion or elastic response), the combined progressive adhesion failure and friction phase of the fibre gradually debonding (B – C), a short drop in sustained load when all the remaining adhesion is lost (C – D), and finally the friction pullout of the fibre itself which slowly decreases as less and less of the fibre length is embedded in the cement paste (D – E). The behaviour depicted in figure 2 is often deemed the ideal behaviour because it is the response that creates the largest area under the curve i.e. the highest amount of *energy absorbed* (or the largest *work of fracture*) while the fibre is being pulled out.

There are however a few very interesting points along the curve (circled numbers: ①, ②, ③) that represent non-ideal behaviours and serve here to illustrate some of the biggest technical challenges in the industry:

- ①: at any point between A and C, if the fibre is not strong enough to support the load transferred, it will break leading to immediate failure. It illustrates the importance of working with strong fibres to prevent them from snapping too easily once the load is transferred,
- ②: the slope of the two initial segments would also be linked to the stiffness of the fibre bridging the crack; a stiff fibre will better control crack opening then a softer fibre for a given load transfer (i.e. the horizontal scale can vary greatly),
- ③: if the (embedded length of the) fibre is too short, the contribution of friction is too little relative to the load it has to pick up after complete adhesion failure, leading to an immediate failure by complete pullout of the fibre. The reader can appreciate

here the existence of a "*fibre critical length"* below which the desired behaviour can simply not be attained.

A different way to look at Figure 2 is to study it while considering the *strength of the cement matrix.* Indeed, the pull-out behaviour is intimately related to the properties of the cement paste present around the fibre. Too soft or weak a matrix may not allow for the full development of the potential of the fibre. Inversely, too strong a matrix may lead to more fibres breaking instead of pulling out (*ref.* ① in Figure 2), leading to an often difficult to understand (or apparently paradoxical) *reduction* of the energy absorbed.

The discussion of these few last paragraphs are taking for granted that the *adhesion* and the *friction* are both present and sufficiently important to reach this effective post cracking response and energy consumption mechanisms. This is where manufacturers have been very creative over the years by creating fibres *shape* or *texture* that maximize adhesion and particularly friction. Here are a few classic examples:

– *Fibre shape*: the hooks at both ends of the fibres or the undulations along its length will require more work to extract them from the cement paste, i.e. more friction,
– *Fibrillating* synthetic fibres: a fibre configuration where ends of the fibres splits and create a number of finer fibre thread or branches, improving anchorage in the cement paste,
– *Surface texture or treatment*: by working on the shape of the fibre surface itself or by applying a special surface treatment, the idea is to promote better anchorage and/or friction.

In these instances, the transformation from a simpler cylindrical shape are made to generate what can usually be associated with improved adhesion and more efficient friction. In turn, these improvements will translate into a better uptake of the loads after cracking (crack opening control) and/or a higher work required to fracture completely the concrete/shotcrete element (energy absorption). Although the discussion started in this section with the -albeit *idealized*- behaviour of a single fibre, the reader can imagine the rationale involved in extrapolating to a complete shotcrete layer. Indeed, concepts such as *critical fibre length* above which fibres would break instead of pulling out, or concepts related to the close interactions between the properties of the cement paste and the anchorage of a fibre are key in this exercise. In fact, the particular properties of the cement paste at the vicinity of the fibre, the complex geometry (or surface texture) of some fibres, their stiffness and ductility, and the angle of the fibre with regards to the crack orientation and propagation will produce debonding and pull-out characteristics that can be quite different from the ideal behaviour presented in Fig.2. Nonetheless, the basic observations are still valid: the post-crack behaviour of FRS will be dependent on the type and dosage of the fibre *and* the properties of the cement matrix surrounding them.

3.3. Shotcrete

Shotcrete or sprayed concrete is usually defined as a pneumatic method of placement of concrete where compressed air is used to impart high velocity to the particles to achieve proper consolidation on the receiving surface. Although usually strictly defined as a *placement method*, the word shotcrete is also often used to describe the material itself.

There are two processes recognized for the application of shotcrete: the wet process and the dry process. The fundamental difference between the two processes has to do with the location of the addition of water to the concrete mix; in the dry process, the majority of the water is added through a water-ring positioned a short distance before the exit point (the nozzle) whereas for the wet process, all of the water is added and mixed in before the fresh concrete is introduced into a concrete pump.

Dry-mix shotcrete[6],[7] – With the dry process, a dry-mix “gun” or machine is used to push the dry material into a hose all the way to the nozzle. The advantages of this method are that the nozzleman has immediate control over the water addition through a valve placed at the nozzle. Because air is used to transport the dry material in the hoses, they are lighter and easier to move and allow for simple start and stop operations since there is no wet concrete remaining in the hose after stopping. Since modern day dry-mix shotcrete favours the use of pre-bagged material, it also offers a great logistical advantage since these (up to 1000 kg) bulk bags can be transported where they will be needed days or weeks in advance. It should be noted however that dry-mix shotcrete usually generates more rebound losses and offers less output than wet-mix shotcrete.

Wet-mix shotcrete[6],[7] – With the wet-mix process, it is a thoroughly mixed fresh concrete that is introduced into a piston pump and transported in the hose to the nozzle. At the nozzle, the operator controls the amount of compressed air introduced through the air ring, breaking down the fresh concrete mass and accelerating the particles toward the receiving surface. In some cases, especially in underground applications, a set-accelerating admixture is introduced at the nozzle to help improve build-up thicknesses and prevent dangerous fall-outs. The advantages of this method are a higher placement output and lower rebound losses. However, delivering fresh workable concrete at the pump often located a far distance from the production point can be especially challenging, particularly in a mining environment.

Mix design and admixtures – The general principles for the production of high-quality concrete will apply to shotcrete: sound aggregates, low water/cement, use of supplementary cementing material (SCM), proper consolidation and curing.

From a proportioning point of view, the main differences however are that the maximum size of aggregates used are limited to 10 – 12 mm (to allow for transport through a typical hose diameter of 50 mm) and to a relatively higher binder content in order to facilitate pumping (in wet-mix shotcrete) and to control rebound losses.

While less than optimal mix designs should go through the shooting equipment in dry-mix shotcrete, albeit with some placement difficulties, it is quite different for wet-mix shotcrete. Indeed, depending on the complexity of the pumping hose layout (length, inclination, diameter), the pumping itself will often impose the most stringent requirements on mixture design. A lot can be said about the design of a pumpable concrete mixture; without covering all the details, a mixture will be considered pumpable if it remains stable (i.e. no segregation) and can move through the hoses without blocking. In order to readily achieve these goals of *stability* and *mobility*, the designer must select, and maintain, a proper aggregate gradation of the complete aggregate phase and ensure a minimum paste content.

These pumping requirements are often the reasons why special admixtures are introduced into the mix design of wet-mix shotcrete. There is indeed a family of admixture called plasticizers that will increase the workability of a given mix without increasing the water content (which is paramount to high quality concrete). Due to long-term strength requirements, modern-day wet-mix shotcrete will almost always incorporate some plasticizer.
Given that both dry- and wet-mix shotcretes are normally Portland cement based, other types of admixture may be used to help control the hydration process. These can be classified as *set retarders* (and sometimes hydration control admixtures), where one wants to increase the time available to mix, transport and place the material, or *set accelerators*, where one wants to reduce the setting time and even speed up the development of the compressive strengths at early ages.

3.4. Fibre-Reinforced Shotcrete

The pneumatic placement process that is shotcrete is the source of a few particularities that differentiate FRS from conventional fibre-reinforced concrete.
Rebound – Rebound is usually defined as the relative amount of material that ricochets of the receiving surface. The overall amount of rebound is affected by spraying parameters (distance and angle from surface, air velocity, process and type of nozzle) and by mix design parameters (amount of cement, presence of SCM, aggregate size distribution, w/c, presence of set-accelerator)[6],[8]–[10]. Because all the components of a concrete mixture may not necessarily rebound in the same proportions, it is not unusual to find an *in-place* composition that

differs from the initial mix design[11]. In the case of fibres, this means the *in-place* fibre content may be different, e.g. *lower*, than expected. It is generally accepted that fibre rebound will be more important with dry-mix shotcrete than with wet-mix. For these reasons, it is of the utmost importance to carry the testing of fibre performances on the actual sprayed material using full-size equipment.

<u>*Fibre orientation*</u> –The high velocity and energy of the sprayed material impacting has a positive effect on the orientation of fibres as it tends to align them in a 2D plane parallel to the substrate. This favorable orientation plays well as the fibres are positioned to intercept potential cracking going through the thickness. It is considered that a 2D plane orientation may improve efficiency by as much as 100% when compared to a purely 3D random spatial distribution[5].

<u>*Choice of fibre*</u> – The question of the appropriate type of fibre – steel or synthetic – has been and is still the source of animated discussions in the industry. As stated in *Section 3.1*, fibres are added to shotcrete to improve the post-cracking behaviour by helping control the opening of the cracks and/or dissipate energy at the crack location. As such, let us state that neither steel nor synthetic fibre is superior, as it would be too simplistic. Instead, it must be understood that the right choice of fibre (and its dosage) will be the result of an approach combining the properties of the concrete they will be put in and the specified/expected performances of the FRS for a given set of ground conditions.

Indeed, steel and synthetic fibres have both shown their potential in FRS for ground support. Although they can offer the same levels of energy absorption at high deflections, they will display different behaviours. Typically, steel fibres quickly take the stresses in the composite after cracking and slowly reduce their capacity as compared to synthetic fibres that present a rapid drop in the stresses supported after cracking and maintain an albeit lower but steady capacity afterwards. This difference in behaviour can be attributed to the higher Young's modulus of steel fibres and is usually observed through a better control of crack width immediately after cracking. Therefore, synthetic fibres generally need to get to a higher deflection to obtain the same energy absorption as with steel fibres (Morgan et al., 1999). Due to their high stiffness, steel fibres are generally preferred in situations where cracking should be limited such as civil engineering constructions (Papworth, 2002). However, synthetic fibres do not corrode when exposed to the environment after shotcrete cracks. When large cracks (mm) develop, the corrosion can become an issue over time as SFRS can potentially loose some ductility; testing has however shown that steel fibres do not corrode in crack openings smaller than 0.25 mm[12]. On the other hand, synthetic materials tend to be more sensitive to creep. In practice, however, the creep of synthetic fibres does not seem to be an issue in the context of ground support for mine openings. In fact, the deformation due to creep has the potential of reducing stress concentrations, improving the overall performance. Their floatability, on the other hand, can be an issue as some fibres will get in the sump water and drainage system of the mines when they rebound from the walls or get washed from the shotcrete. This is generally not a problem with steel fibres, but it can be with synthetic fibres as they float and tend to create problems with the pumping of sump water.

Type of fibre – Fibres for use in shotcrete can be made of steel, glass, synthetic polymers, and natural materials. Also, as defined earlier, fibres with an equivalent diameter greater than 0.3 mm are identified as macrofibres while those smaller are known as microfibres. Only macro-steel and macro-synthetic fibres are considered herein because they are, by far, the most commonly used for improved post crack performances. One parameter used to characterize macrofibres is the *aspect ratio*. Typical aspect ratios for shotcrete range from 40 to 65 for common fibre lengths of 20 to 50 mm, although steel fibre lengths are generally less than 40 mm. Synthetic macrofibres are usually less than 60 mm long. Figure 3 illustrates steel and macrosynthetic fibres commonly used in shotcrete.

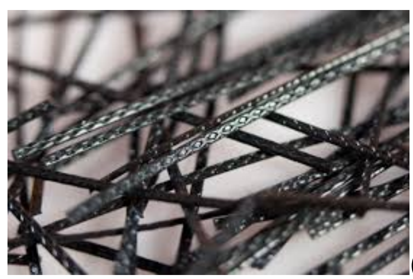

(a)

(b)

Figure 3: Typical (a) steel and (b) macrosynthetic fibres commonly used in shotcrete (a – from Bekaert and b- from Barchip).

Apart from their obvious geometry differences, steel and macrosynthetic fibres will differ substantially in their *mechanical properties*. Indeed, common steel fibres will have a minimum of 350 MPa tensile strength with typical values closer to 1200 MPa and most recently as high as 2500 MPa. Their Young's modulus or modulus of elasticity will vary from 200 GPa to 210 GPa. On the other hand, macro synthetic fibres will offer tensile strength in the range of 350 MPa to 650 MPa with modulus of elasticity markedly lower, with value found to be between 3 GPa and 12 GPa. The Tables below illustrate some of the various properties of steel fibres and macrosynthetic fibres, the most common encountered in the industry.

Table 1: Typical fibre properties

	Steel Fibre	**Macrosynthetic Fibre**
Young's Modulus	200 - 210 GPa	3 – 12 GPa
Tensile Strength	350 – 2500 MPa	350 – 650 MPa
Melting Points	1500 ºC	165 ºC
Significant Creep limit	370 ºC	> 20 ºC

Table 2: Typical fibre usage

	Steel Fibre	**Macrosynthetic Fibre**
Fire protection	No	No (only microsynthetice fibres offer fire protection behaviour to the composite)
Plastic shrinkage reinforcement	No	No
Drying shrinkage reinforcement	Yes	Yes
Load Bearing – Service Limit State	Yes	No
Load Bearing – Ultimate Limit State	Yes	Yes

These differences in fibre types and properties will have a significant impact on the behaviour observed in different FRS characterization tests (*ref. Chapter 5) and in real-life ground support systems.* In fact, in hyperstatic systems such as those found in ground support, an effective control of the crack widths will promote a more efficient multi-cracking process and therefore a more ductile behaviour of the structure, most probably due to the higher degree of hyperstaticity that is maintained.

4. Mining and Ground Support

4.1. Introduction

The purpose of this chapter is to give an overview of the general principles of ground support in underground mines as well as try and identify what the position of fibre-reinforced shotcrete is in the field. The idea here is to consider the situation of FRS from a mine engineering point of view: identify where it can benefit this complex system.

4.2. Why Supporting the Ground in Mining Operations?

In its most simple description, the objective of mining operations is to extract the ore from the mine and to process it. Obviously, this must be both profitable and safe for all parties involved. In particular, the safety of workers and equipment is paramount as it is constantly threatened by the instability in the rock surrounding underground mine openings [13]. From an operational point of view, profitability is dependent on the production capacity and the value of the extracted minerals. This means that the ground support activities in underground mines need to be efficient enough to allow for minimum progression rates, must keep workers and equipment away from accidents and maintain the quality of the ore. Ground support operations are an essential aspect of mining operations and fibre-reinforced shotcrete can play a significant role in it.

4.3. Design Methods in Excavation and Ground Support

There are different ways to approach underground excavation and ground support operations. It should be stressed however that (technical) cultures and local experiences often have a prevalent effect on the ground support schemes adopted and their implementation. Nonetheless, these approaches are influenced by many technical aspects such as:

Nature of ground

- Rock quality
- Rock strength
- Depth of the mine
- Stress fields
- Presence of discontinuities

Mine factors

- Geometry of the excavation
- Roughness of the excavation surface
- Duration of the exploitation
- Seismic activities

Thompson, Villaescusa & Windsor [14] offer an interesting terminology for ground support. They define the *ground support scheme* as the combination of *support system* and *reinforcement system*. A *reinforcement system* is defined as anything

that is embedded within the material surrounding an excavation; it is essentially rockbolts. A *support system*, on the other hand, would be anything in contact with an excavation face. The authors also identify three types of *support systems*: *point*, *strip* and *areal*. Using such a terminology, fibre-reinforced shotcrete belongs to the category of *areal support systems*. Finally, the design of this *ground support scheme* depends on the *rock demand*.
The authors describe the steps of a generic design procedure:

- Identify a mechanism of instability.
- Estimate the *areal support* demand.
- Estimate the reinforcement length, force and displacement demand.
- Estimate the energy demand.
- Select the appropriate *reinforcement* and *support* systems.
- Propose and evaluate an arrangement of reinforcement and support systems.
- Specify the complete ground support scheme.

Kaiser [15] summarize the actions of ground support in a complementary way. In his perspective, the three key functions are to *reinforce* the rock mass, to *retain* broken rock and to *hold* fractured blocks to stable ground. In this terminology, fibre-reinforced shotcrete is generally used to *retain* broken rock like wire mesh does. It can also be used to hold fractured blocks depending on the specific design.

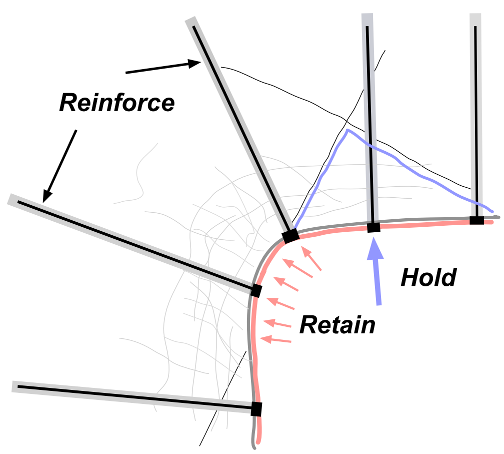


Figure 3: Visualization of a ground support approach (adapted from Kaiser [15]).

If we consider fibre-reinforced shotcrete as a retaining element in this perspective, the importance of FRS in ground support systems can be outlined as follow [16]:

> *‘’In conventional rock support systems, the retaining element is often the weakest link. A chain is only as strong as its weakest link. So, if we want to*

> *increase the overall capacity of the rock support system, the problem of weak retaining elements and its connection to the reinforcing or holding elements must be addressed."*

The most effective ground support scheme is the one that can allow the ground to maintain its strength; this is done in order to reduce the areal support demand [17]. The main idea is to make the rock support itself by reinforcing it [18]. The ground support scheme should follow the bulk movement of the rock mass, but should restrict the displacements between blocks in the rock [19].

In general, the action of a ground support scheme is based on a combination of the actions of both support *and* reinforcement systems. However, the support systems can act alone to support the excavation. For example, in shafts and tunnels, a complete ring can be used for the overall ground support [17].

Ortlepp [19] simplifies the approach by stating two basic requirements for the support elements. They must:

1. be stiff so that they act as soon as possible, but
2. retain the ability to yield through appreciable displacements at load values less than critical.

This introduces the necessity to define the notion of failure in the shotcrete lining and raises the question of possible shotcrete lining failure modes. What is the failure of a FRS lining? Does it occur when the lining cracks or is it when the lining can no longer support any load regardless of its level of deformation? The answer to these questions is highly dependent on what is expected from the FRS lining in a particular situation. If ground water is critical in a mine, failure of FRS can be defined as a maximum crack opening or maximum water ingress. If large displacements are expected in a mine, failure of the FRS lining can be a minimum load bearing capacity at a large displacement of the lining. It is essential to define the notion of failure for every project and application, and sometimes even for particular locations.

Even if the notion of failure can be defined, the question of interpreting failure modes in FRS linings remains a challenge. Indeed, it very is difficult to connect observations of a failed FRS lining (cracks and deformations) to the history and true nature of the actual failure behaviour and mechanisms. Nevertheless, six potential modes of failure for FRS linings have been defined and are presented in Figure 4[20]. Visualizing these failure modes can help determine the requirements for an FRS mixture and a ground support system as well as identify failure mechanisms and understand how to better prevent them. It is however crucial to understand that the solicitation of the FRS lining and its failure mode depend on many factors such as its adhesion to the ground, the roughness of the rock and the friction between materials, the shape of the excavation, the continuity of the lining, etc.

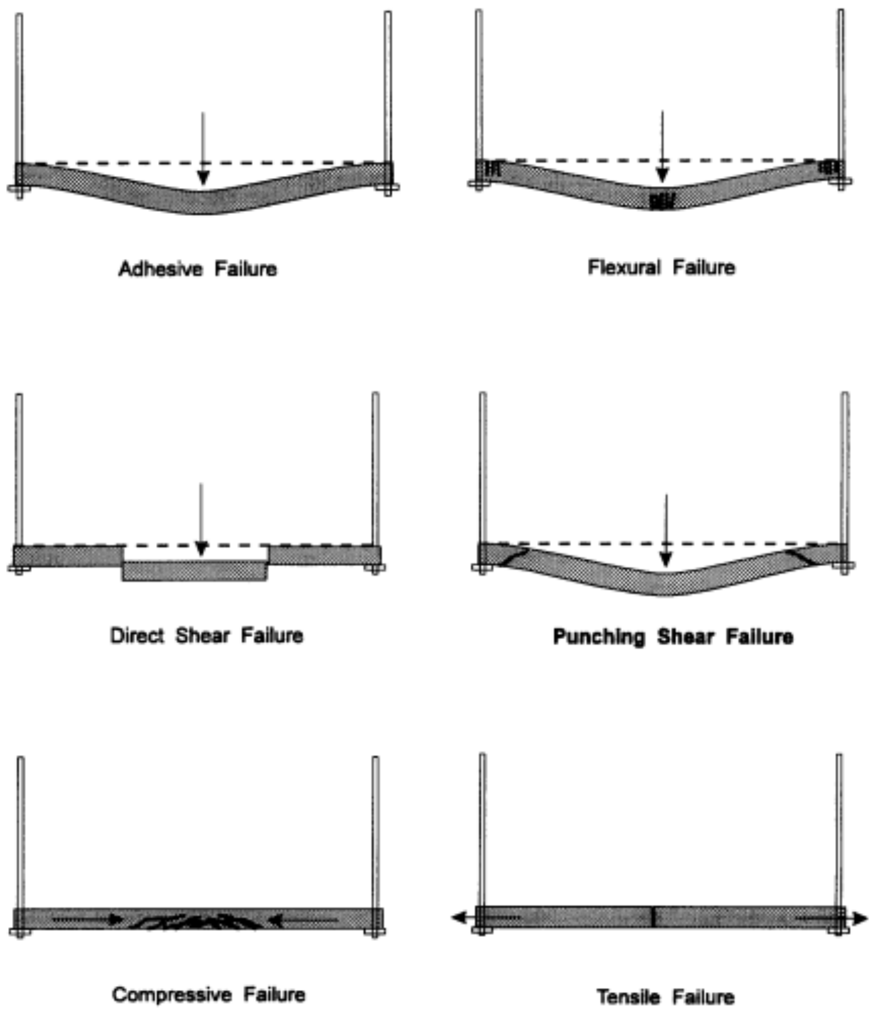


Figure 4: Potential modes of failure for FRS linings (from [20])

As it was previously explained, knowing the rock *demand* is essential for the design of an underground excavation and its ground support. However, one of the biggest challenge is to estimate the rock's strength and behaviour [13]. Kaiser and Cai [16] outline that:

> *''Unfortunately, due to the complexity of rock masses and their boundary conditions, we still do not have great confidence in predictive means and reality repeatedly reminds us of current deficiencies.''*

It is indeed necessary to have an estimate of the rock characteristics in order to estimate a safety factor. Fortunately, the strength and behavior of the ground support system is generally known prior to the design thanks to research and testing. Moreover, the support and reinforcing systems are highly adaptable to changing conditions: extra rock-bolts or thicker shotcrete are often required. In fact, it is this rapid adaptability of the support schemes that makes the *design* of

ground support so complex to learn or standardize; it is based on observation of performance, local experiences and empirical knowledge.
The discussion on design methods can hardly be considered complete without addressing the case of dynamic loadings (rockbursts, microseismic events, blasting, etc.). In such case, it could be said that the support system should not only be able to yield, but also that this yielding should continue at high strain rates while maintaining a minimum amount of load carrying capacity [19].

4.4. Types of ground

Thomas [17] presents a general and simple categorisation of the types of ground:

- *Soft ground*: soils and weak rocks (ex.: sands clays and chalk)
- *Blocky rock*: weak to moderately strong rocks (ex.: limestone and sandstone)
- *Hard rock*: massive strong rocks (ex.: basalt and granite)

Soft ground requires to install ground support, such as fibre-reinforced shotcrete, immediately after excavation. In a blocky rock, the rock is reinforced, and areal support must be installed to keep the blocks from falling. Hard rock mostly supports itself; although basic reinforcement and support is generally installed [17]. As surface support is required in most cases, regardless of the type of ground, it reinforces the idea that fibre-reinforced shotcrete can be an essential element of the mining operations.

4.5. Types of ground support approaches

Generally speaking, the most common ground support approach is one that is empirical and based on the experience in a specific or similar mine. It is essentially based on a ground scheme that is easy to perform and that gives good results for a minimum of design effort. However, it is also possible to have an analytical approach that is based on failure mechanisms of the rock mass. In some cases, such an approach can be more appropriate to use as it comes from a more objective perspective. Finally, it is possible to use numerical models to perform a thorough evaluation of a specific situation. This approach is generally more tedious and time consuming than the other ones. Thomas [17] explains that:

> ‘’In terms of approaches to design, in theory, there is a spectrum from a reliance on pure empiricism to total faith in prediction. In practice neither extremes are used.’’

In all of the approaches, instrumentation and monitoring can help in the design and control of the ground support. Thomas [17] outlines that, in the case of hard rock, instrumentation is used in the continuous design process as in the case of soft ground, it is there to validate that the support is behaving as designed.

Shotcrete in underground openings gained a lot of interest with the introduction of the *New Austrian Tunneling Method* (NATM) in the 1960s [1] (often referred to as the Sequential Excavation Method in North America). Instead of trying to resist directly the deformation of the ground, this method uses the strength of the ground by controlling the deformation until it reaches an equilibrium [17],[21]. While the use of shotcrete in this popular method is not essential to the approach, it is almost always present.

On the introduction of shotcrete in ground support, Kovári [1] outlines that:

> ''The replacement of timber supports by steel arches, rock bolts and sprayed concrete is one of the greatest achievements in the history of tunnelling. The combined use of these three means of support led to methods of excavation, which already in the 1950s were labeled the 'sprayed concrete' or 'shotcrete' construction methods. This is quite understandable because sprayed concrete (in contrast to timbering) has influenced the appearance of tunnelling most of all. Thus, the sprayed concrete lining method is the result of a long development on a broad international front, which in the beginning moved forward, partly in stages and partly with continuity experiencing unavoidable setbacks.''

The most common empirical approach for ground support is probably based on the Q-system initially developed by Barton, Lien & Lunde [22]. It was later updated by Grimstad and Barton [23] and used again by Palmstrom and Broch [24]. It is sometimes referred to as the *Barton Chart* for its famous design chart (Fig.4). This system allows to select the bolt spacing and the fibre-reinforced shotcrete thickness to apply depending on the rock mass quality and the geometry of the excavation. This approach works in various situations but does not directly take into account the strength and behaviour of the fibre-reinforced shotcrete. Nevertheless, some authors [25][26] have added energy absorption values to complement the original diagram despite difficulties in establishing a clear relationship between the behaviour of the opening and the energy absorption value form a test panel or even a clear correlation between the various energy absorption obtained from different test panels.

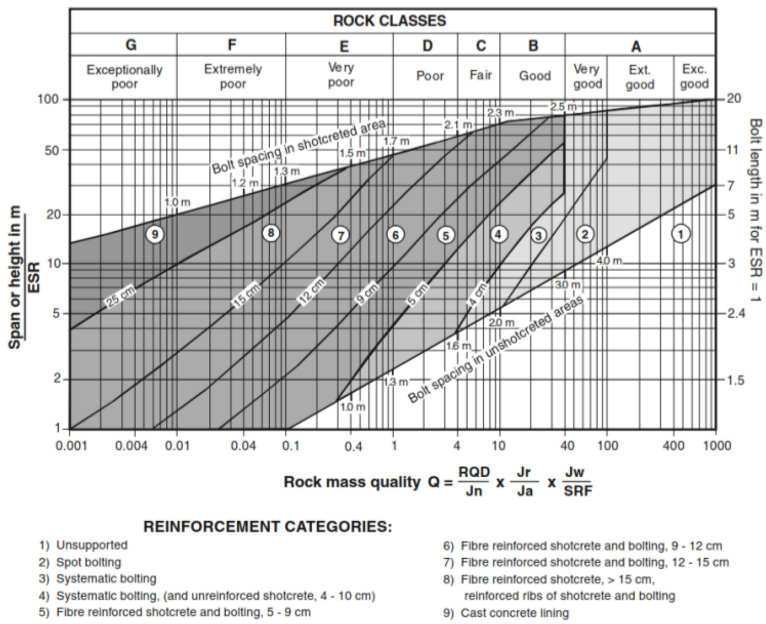


Figure 4: The *"Barton Chart"* from [22].

The excavation of the rock in ground openings can be done using roadheaders or with the drill and blast technique [17]. The choice of technique depends mainly on the quality of the rock. Low strength soft grounds can also be excavated using bucket excavators. Regardless of the technique used for the excavation, fibre-reinforced shotcrete often remains an effective tool for the immediate support of the opening. FRS can indeed be applied quickly and easily which contrasts with the time-consuming application of wire mesh [27]. It can follow the shape of the excavation, regardless of its roughness, therefore supporting loads more effectively [28]. Installing ground support rapidly and effectively is indeed an essential aspect of the mining operation as the unsupported ground has a finite ''stand-up time'' [17] and the productivity relies on the progress in the ground opening.

Rock bolts as reinforcement and wire mesh as support is probably the ground support scheme that is the most used worldwide. However, it is sometimes not the most effective as mesh is only a passive ground support – it only acts when the ground deforms significantly– and corrosion of these elements can become an issue. Shotcrete had been applied without reinforcement and with mesh reinforcement, but the introduction of fibre-reinforced shotcrete gave a response to most of the drawbacks of these other methods. Nevertheless, the use of rock bolts remains an essential aspect of ground support in many mines and often cannot be replaced by fibre-reinforced shotcrete. The rock bolts provide an internal reinforcement to the rock mass which FRS cannot provide directly. FRS can be expected to act differently as an element of the support system depending on the ground support scheme implemented by the engineer. In blocky rock for example, FRS is used to hold loose blocks in place to maintain the integrity of the rock mass and to prevent rockfalls. In the case of soft ground, FRS can be used as a complete stiff ring around the excavation. FRS is also used to build stiff arches in order to control the deformations of the rock mass and prevent rockfalls. When used in interaction with rock bolts, Yield-Line Theory (YLT) is often used to define the requirements and performance of FRS holding the rock between adjacent bolts. Nevertheless, the most effective ground support scheme is often a combination of different tools. Kovári [1] explains that:

> ''On a wave of enthusiasm, sprayed concrete achieved the same or even a higher importance in many places than rock bolts and steel sets. Very soon, however, it was realized that in many cases, a combination of these support elements provides the most efficient method both structurally and economically for controlling rock pressures and ground response.''

4.6. Conclusion

This chapter describes the general principles of ground support in underground mines. Although often comprehensively influenced by local history and practices, the design of a ground support scheme relies on some fundamental principles that can be summarized as *reinforcing* the ground (arch), *holding up* the opening and *retaining* all of the blocks. With this approach, it is clear that the use of fibre-reinforced shotcrete can bring unique benefits to this complex system.

5. FRS for Ground Support

5.1. Introduction

This chapter spends time examining some of the testing methods available in the industry to evaluate the behaviour of fibre-reinforced shotcrete. Although non-exhaustive, it tries to discern between tests methods more fitted for *design* and those more often used for *quality control*. Typical results obtained, typical interpretation and analysis as well as the engineering value of each methods are considered.

5.2. Performance requirements

Fibres are uniformly distributed discrete element of reinforcement in concrete, and the average distance between fibres is usually much smaller than that of reinforcing bars. The result is that fibres are mobilized earlier in the cracking process and will greatly influence the crack pattern and its evolution under load. Because the performances of fibre reinforced concrete or shotcrete vary with the type of fibre and their dosage, *and* with the properties of the concrete they are added to, it is essential to evaluate the performances of FRS, and also specify these performances, using standard test methods.

The difficulty arises when time comes to select an appropriate test method to work with. Before doing so, the engineer must not only reflect on the objective(s) of the test (design, QA, QC, R&D, etc.), but also identify a test method that will allow to truly discriminate successful or meaningful results. This is not a situation unique to FRS, however it is critical since it is the *post-cracking* behaviour that we sought to characterize; a portion of the *P-Δ* curve that is well known to be experimentally difficult to reliably capture. Indeed, the fibres reinforcement can change the *post-crack* response of concrete from brittle to ductile under various type of loads. The most obvious improvements come to the *tensile strength* of concrete. Unfortunately, testing for post-cracking behaviour in pure tension is difficult and is usually reserved for academia and research. This is why most of the test methods presented in the next section rather focus on evaluating the improvement in *flexural* performances.

Imagining a generic flexural test, the response of a specimen is followed and a graph presenting the applied load (P) against the displacement (*Δ*) is plotted. As said, the interest is in the *post-cracking* behaviour which is why the various test methods will concentrate on the right-hand side of the peak to propose some measurements of the performance. This can be done using the *toughness* -the area under the curve- or some values of residual loads (or stresses) carried by the FRS after cracking at different displacement or, often more relevant, at some *crack opening*. The particularities of the various test methods arise when different

geometries of specimen and/or different load schemes are used. The amplitude of the imposed displacement in the test, as well as the performance criteria derived, are also critical as it will influence how the fibres effect manifests and therefore the observed post-crack response, i.e. the shape of the curve.
In fact, the *stress* vs *crack width* curves are the most relevant characteristics of FRS in a flexural design. These curves represent the true behaviour of the material regardless of the size of the structural member or the loading conditions. However, as useful these relationships can be, it is crucial to understand that failure mechanism of FRS is not always in pure flexure and that shear loads are also present.

5.3. Test Methods

There are a number of test methods relating to FRS available around the world. The goal here is to present a few of them to illustrate what type of testing can typically be conducted and especially what results are obtained. The test methods presented in the following section are specific to tests aimed at characterizing the *post-crack* performance of FRS, and as such do not cover tests that would be dedicated to evaluating the cracking potential or to measuring improvements in fire protection for example. An overview of these test methods is presented in Table 3.

5.3.1 Tests on beams

EN 14651 - Test method for metallic fibered concrete – Measuring the flexural tensile strength (limit of proportionality (LOP), residual)

Usefulness

The *EN 14651* test method is a European standard designed to measure the post cracking flexural tensile strength of fibre-reinforced concrete (FRC) [29]. It can be used to evaluate fibre-reinforced shotcrete (FRS) samples if the sampling procedure is adequate (i.e. it is representative of the actual structure). It is initially intended for testing concrete with metallic fibres but can also be used with synthetic fibres.

The advantage of the notch in the beam is a more controlled crack growth which generally leads to less noise in the results. This standard test method is often preferred in many countries as it provides information that can be directly used for structural design with *fib*'s *Model Code 2010* [30]. However, as any beam test with a relatively small crack section, the variability in the results can be higher than in tests on panels.

Using the results from this test method, it is easy to calculate the stress-crack width relationship of FRS. This is particularly useful as it can be used in the design regardless of the specific loading conditions. However, the maximum crack width is somewhat limited compared to what can be seen in ground support for mine openings.

Execution

In this procedure, a simply supported notched prism is loaded in its centre (Fig. 6) to produce a load-*crack mouth opening displacement* (CMOD) curve up to 4 mm (Fig. 7). The test specimen is a beam of 150 mm width, 150 mm depth and length between 550 and 700 mm. The beam is supported on two rollers on a 500 mm span.

The test specimen to be used in this standard needs to be sawn from a shotcrete material test panel. This material test panel must be large enough to allow the production of a representative shotcrete sample. The influence of rebound in the corners and the sides of the panel must be eliminated. Therefore, it is not adequate to spray shotcrete directly in a mould of the exact size of the test specimen. The production of the samples should follow a standard practice such as *EN 14488-1 Testing sprayed concrete – Sampling fresh and hardened concrete* or *ASTM C1140/C1140M Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels* [31],[32]. If multiple beams need to be taken from the same spraying panel, the panel size required to produce a sample representative of the actual structure can become large. This should be considered as the handling of this panel can affect the integrity of the sample and be a safety hazard for workers.

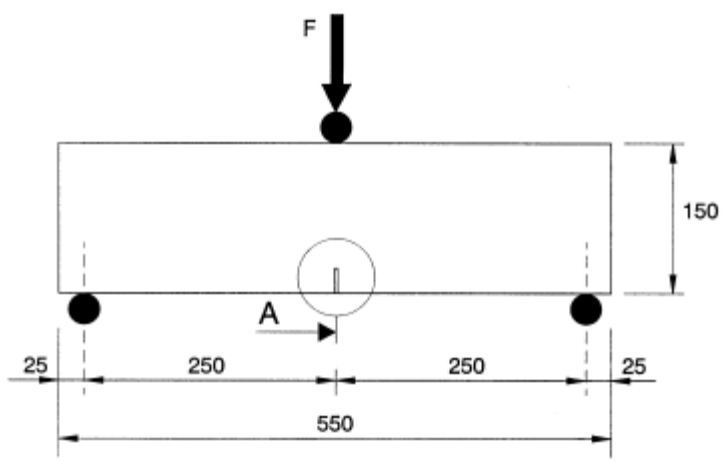


Figure 6: Schematics of the EN 14651 test specimen under load (from [29])

When testing FRS with *EN 14651*, the test specimen should not be rotated like it is with regular FRC. The test specimen needs to be loaded along the spraying axis from the nozzle side. This means that the side of the beam that was at the bottom of the material test panel is the side that is to be notched.

This test is performed under *closed-loop control* of either the CMOD or the net deflection. As for any other closed-loop control test, precautions should be taken regarding the tuning of the procedure. The test procedure should be able to deal with materials with different behaviours without affecting the results.

Results

This standard gives a load-CMOD or load-deflection curve that represents the behaviour of the FRS under flexural load. From this curve, much information can be retrieved. However, the most relevant values are generally the *Limit of Proportionality* (LOP) and the *residual flexural tensile strengths* given at four (4) different values of CMOD (fig.7). The order of magnitude of these values is one MPa and they typically range from 2 to 5 MPa.

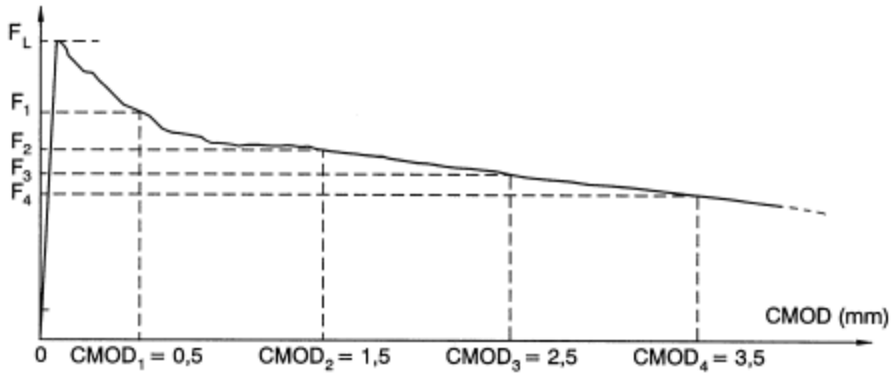


Figure 7: Example of a *Load-Deflection curve* in an EN 14651 test (from [29]).

Normative Interpretation

The *fib* (International Federation for Structural Concrete) uses these values of average stress on the cracked section at different crack mouth opening displacements in the *EN 14651* for structural design in its *Model Code 2010* [30]. Those values are used to simplify the *stress* vs *crack width* curve in order to have an easily applicable relationship for design purposes. Noteworthy, the *Model Code 2010* recognizes that conventional reinforcement can be (partially or completely) substituted with fibre reinforcement in ultimate limit state design when the post-peak behaviour in fig.7 displays a sufficiently efficient uptake on the load bearing; this is expressed in terms of minimum proportional values on f_{R1} and f_{R3} (i.e. $f_{R1}/f_L > 0.4$ and $f_{R3}/f_L > 0.5$)

Engineering Value

In the design of FRS as ground support, the stress-crack width relationship obtained from this test method can be used to determine the bearing capacity and energy absorption of the deformed lining through Yield-Line Theory (YLT). However, since the maximum crack width in this test is relatively small compared to real cracks in FRS in mines, it can be difficult to evaluate the behaviour of the lining at large displacements.

ASTM C1609/C1609M Standard Test Method for Flexural Performance of Fibre-Reinforced Concrete (Using Beam With Third-Point Loading)

Usefulness

The *ASTM C1609/C1609M* test method is an ASTM standard intended for the evaluation of the post cracking flexural performance of FRC [33]. It can be used to test shotcrete samples as long as the specimens from shotcrete material test panels are prepared in accordance with standard practice (see below). It is designed to test concrete with any type of fibres.

This test method is popular with structural designers that use the *ACI 318M* code because the equations in this document are based on results from this test method. In theory, it is also possible to calculate the stress-crack width behaviour of FRS with this test method. However, since the crack is not necessarily in the middle of the beam it is not as simple as in the EN 14651 to derive this relationship. As any beam test with a relatively small crack section, the variability in the results can be higher than in tests on panels.

Execution

In this setup, a simply supported beam is tested under a third-point loading setup (Fig. 8) to produce a load-deflection curve (Fig. 9). There are two options for the size of the test specimen depending on the maximum fibre length: the beam can be 100 mm in width, 100 mm in depth and 350 mm in length or 150 mm in width, 150 mm in depth and 500 mm in length (the beam dimensions should be at least 3 times the length of the fibre). The beam is supported on two rollers on a span that is 3 times the depth of the beam. Thus, the span must be 300 mm or 450 mm depending on the beam size.

The specimens for this test method must be obtain following *ASTM C1140/C1140M.* This last standard refers to *ASTM C42/C42M Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete* which gives guidance on how to prepare sawed concrete beams [34]. In general, the idea in these standard practices is to create shotcrete sample that is representative of the actual structure. Directly filling a mould of the exact size of the test specimen is not adequate. As for the *EN 14651* test method, the preparation of larger beams can lead to the use of large panels. This aspect should be considered as the safe and correct handling of such panels can become a challenge.

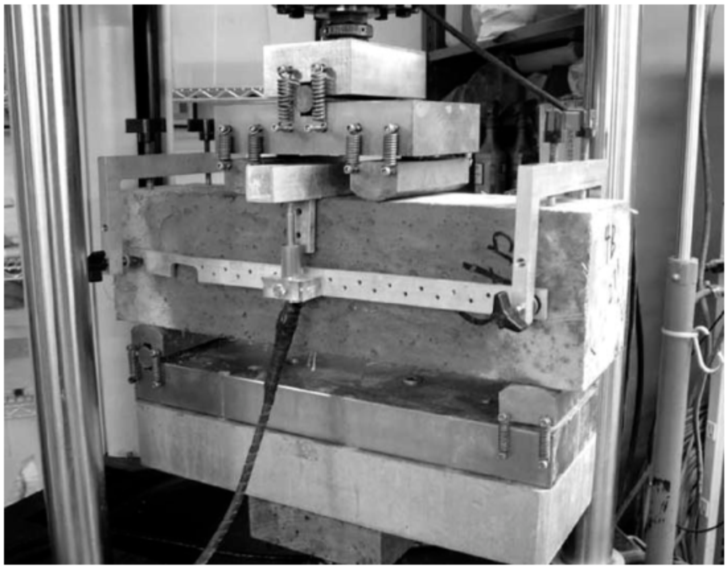


Figure 8: Schematics of the ASTM C1609 test specimen under load (from [33])

As for *EN 14651*, a FRS test specimen should not be rotated like it is with regular FRC when following *ASTM C1609/C1609M* (Fig. 8). The test specimen must be loaded along the spraying axis from the nozzle side.
This test is performed under *closed-loop control* of the net central deflection of the beam. The same precautions regarding tuning that apply to *EN 14651* should be followed in this procedure, especially since the crack growth is not controlled as it is in a notched beam. With certain mixtures, the beam specimen can “jump” immediately after cracking which can cause noise in the results or even terminate the testing prematurely. As with all close-loop tests, the care and meticulousness required in conducting this test cannot be overemphasized; many experimental set-ups have great difficulties in respecting all requirements of the standard, particularly with the acceptable maximum displacement rate immediately after cracking (*ref. Table 1 in* [33]).

Results
This standard gives a load-deflection curve that represents the flexural performance of the FRS. The most relevant values that are retrieved from this curve are generally the *First-peak strength*, the *Peak strength*, the *Residual strengths* at deflections of *L/600* and *L/150*, and the *Toughness* at a deflection of *L/150*. The order of magnitude for the peak and residual strengths is one MPa and they typically range between 2-5 MPa. The order of magnitude for the toughness is tens of joules and it typically ranges between 20-100 J.

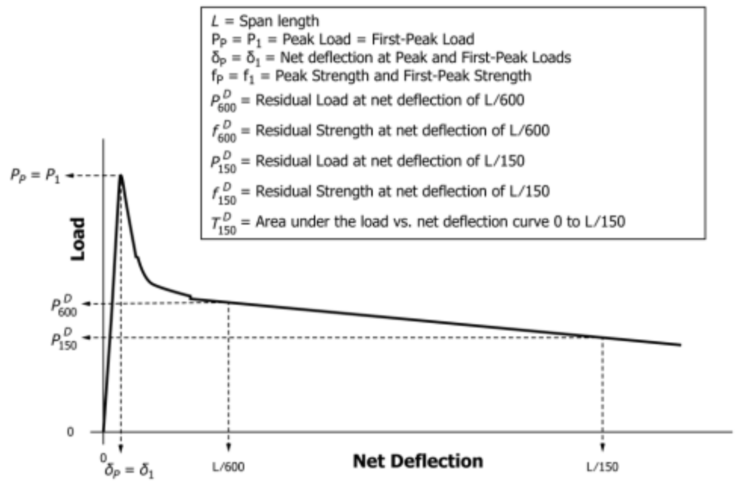


FIG. 3 Example of Parameter Calculations for First-Peak Load Equal to Peak Load (Not to Scale)

Figure 9: Example of a *Load-Deflection curve* in an ASTM C1609 test (from [33]).

Normative Interpretation
As in the notch beam, the residual strength at deflections of L/600 and L/150 can be used in the design of structures at service limit state (SLS) and ultimate limit state (ULS). The *American Concrete Institute* (ACI) uses these values of the *ASTM C1609/C1609M* in the *Building Code Requirements for Structural Concrete - ACI 318M* [35]. Those values are used as an average stress on the cracked section to simply determine the residual bearing capacity of a structure.
Engineering Value
The test gives a good representation of the flexural behaviour of FRS. As for the previous beam test, the maximum crack width in this test is relatively small for FRS in mines; it is not representative of the overall behaviour of the lining at large displacement. Moreover, recent testing has validated that when the fibres provide bending hardening characteristics, the C1609 test can significantly understate the load carrying capacity at higher deflections (L/150 value). This is due to the fibres providing for increased load capacity resulting in a structural response in the beam and multiple cracks to form. In the notched beam test (EN 14651 test), the notch dictates that only a single crack will occur even when hardening characteristics are achieved. For higher performance fibre, it appears that performance characterization using a notched beam is more appropriate[36].

ASTM C1399/C1399M Standard Test Method for Obtaining Average Residual-Strength of Fibre-Reinforced Concrete

Usefulness
The *ASTM C1399/C1399M* test method is an ASTM standard that is used to characterise the post cracking flexural performance of FRC [37]. As for

ASTM C1609/C1609M, it can be used with FRS if the proper practices are followed.

This test method is not as popular as other beam tests because it does not give as much information. However, it is simpler to perform as it is not under a *closed-loop control*. As any beam test with a relatively small crack section, the variability in the results can be higher than in tests on panels.

Execution
The setup used in this standard is similar to the one in *ASTM C1609/C1609M*, but the concrete beam is pre-cracked while being supported by a steel plate; the actual test is therefore performed on a precracked specimen.

Results
This standard gives a reloading curve that represents the postcracking flexural performance of the FRS. From that curve, *Residual strengths* at four (4) deflections are retrieved to calculate the *Average Residual Strength* (ARS). The order of magnitude for the ARS is one MPa and it typically ranges between 2-5 MPa.

Normative Interpretation
The ARS can be used in a structural design for FRS after cracking. This stress represents the average stress in the cracked section of the lining. This average value can however be seen as an oversimplification of the behaviour of FRS.

Engineering Value
This test is most often used in quality control given its simple set-up in the lab.

5.3.2 Tests on panels

EN 14488-5 Testing sprayed concrete – Part 5: Determination of energy absorption capacity of fibre reinforced slab specimens

Usefulness
The *EN 14488-5* test method is a European standard meant for the determination of the energy absorption capacity of FRS [38]. It is sometimes referred to as the *"EFNARC Square Panel Test"* because of its origin. This test is used in the empirical ground support design method *Q-system* [39] and for quality control of FRS.

Since the square slab is placed on a *continuous support*, it is statically indeterminate and allows for stress/load redistribution in the panel during the test.

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 allows for the FRS to better express its true behaviour. Indeed, it has been shown that a specimen will evolve from a pure shear failure to a combined shear/flexural failure as the fibre content increases [40].

The loading in this standard is not done under *closed-loop control* which makes it simpler to run. Since the cracking pattern is not determinate and because of the punching shear effect, it can be difficult – almost impossible – to obtain a postcracking flexural strength as it possible with other test methods.

Execution
In this procedure, a FRS square slab specimen is loaded in its centre with a square steel head and continuously supported by a rigid steel frame on its entire perimeter (Fig. 10). The slab is loaded, and the central deflection measured to produce a load-deflection curve (Fig. 11a) which is analysed and converted into an energy absorption-deflection curve (Fig. 11b). The square slab is 600 mm in width and 100 mm in thickness. The rigid square frame has 500 mm internal sides.

Since the size of the test specimen is large enough and better represents the actual structure, it can be prepared by spraying shotcrete directly in a panel. As always, the spraying technique should allow the rebound to be eliminated from the panel. It should be done in accordance with *EN 14488-1.* Attention should be paid to the trimming of the panel as the thickness and the angle of the surface can affect the results.

The moulded face of the test specimen must be placed on the rigid frame and the loading head must be facing the sprayed surface. It can be difficult to obtain an even surface and a true continuous support when the mould used is not rigid enough or bent. Depending on the FRS mixture, it can also be challenging to obtain a top surface that is parallel to the loading head. A stiff bedding material such as mortar or plaster can be applied between the square panel and the equipment to ensure that all points of contact are continuous.

Results
This standard gives a load-deflection curve and an energy absorption-deflection curve that represent the behaviour of FRS under a combination of flexural load and punching shear load. The most relevant values that are retrieved from the previous curves are the *maximum load* and the *energy absorption* at a 25 mm deflection. It is important to note that it is a common practice in some areas (particularly in Norway) to apply a reduction factor to the value of energy absorption to consider the effect of friction between the steel frame support and

the FRS panel. The order of magnitude for the energy absorption is hundreds and thousands of Joules and it typically ranges between 500-3000 MPa.

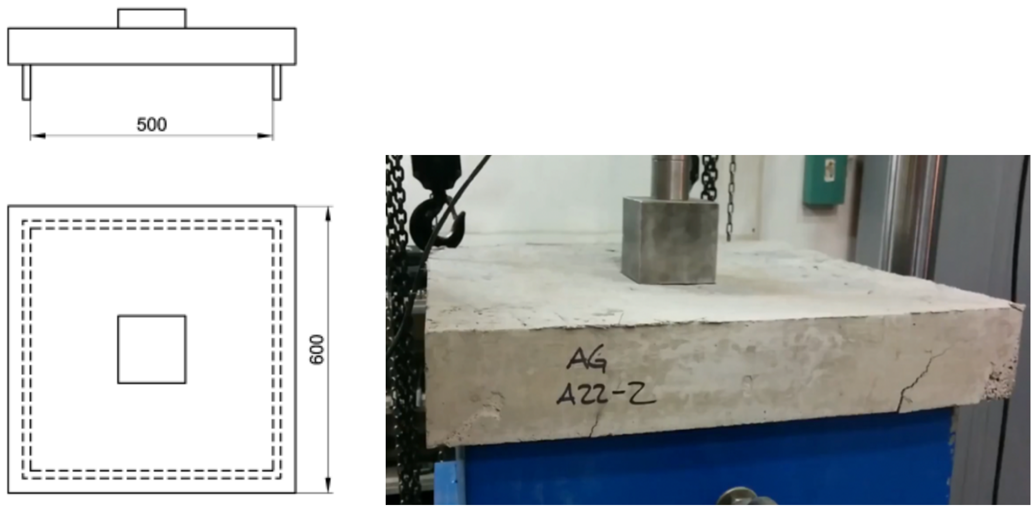


Figure 10: Schematics of the EN 14488-5 test specimen under load (from [38])

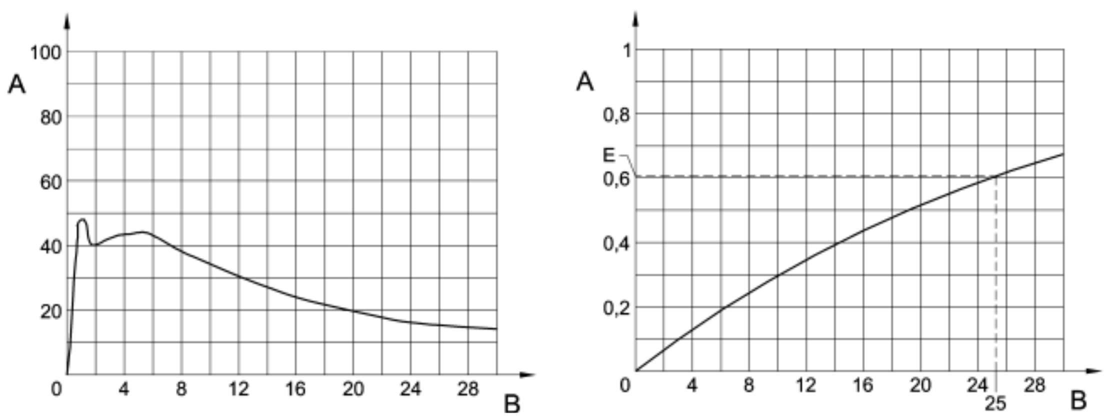


Figure 11: Example of a *(a) Load-Deflection curve* and *(b) Energy-Deflection curve* in an EN 14488-5 test (from [38])

Normative Interpretation

The energy absorption at a 25 mm deflection can be used to classify FRS in different energy absorption classes such as E500 (500 J) or E700 (700 J) for example. Ultimately, this value can be used as a parameter in the empirical ground support design method *Q-system* [39] and for quality control of FRS. ASQUAPRO, the French Association for Quality of the Projection of Concretes, offers additional recommendations on the EN 14888-5 test [41]. First, it recommends that the value of absorbed energy exceeds 500 J. Secondly, it gives recommendations on the behaviour of the FRS to verify the ductility of the composite material using criteria that describe the shape of each curve obtained and are meant to reject brittle composites behaviour. These criteria state that the maximum load in the elastic zone (F_{max-el}) must be reached at a deflection of less than 2 mm and that the minimum load after cracking and up to a 5 mm deflection must be of at least 70% of this F_{max-el}.

Engineering Value

This test method is probably what is the closest from the actual loading conditions in a ground support scheme with bolts. It is a statically indeterminate setup which allows for load redistribution and it creates both flexural and punching shear stresses leading to more realistic, albeit complex, failure modes - the *Barton Chart* (fig 4) initially included a reference on the energy absorption obtained with this test. The complex failure modes and the variable crack pattern make it more difficult to understand how the material performs when analysing the results.

Because the loading conditions and the test setup are fundamentally different than most of the other test method for FRS, the results from the EN 14488-5 should not be compared directly with results from other test methods. Even though conversion factors have been proposed in the past, the performance results of FRS should not be compared between different test methods.
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 be seen underground. For example, if we consider a span of 1.5 m between rock bolts, the equivalent deflection would be 75 mm for the same approximated crack rotation. Some testing laboratory run the test to a central deflection of up to 40 mm, with success, to generate more useful results.

Norwegian Round Panel

Usefulness

This test method comes from the *Norwegian Concrete Association* document *Sprayed Concrete for Rock Support* and is designed to measure the energy absorption capacity of FRS [42]. It is a Norwegian standard that is very similar to the *EN 14488-5*; the shape of the panel is the main difference.
It can be used in the empirical ground support design method in Norway and for quality control of FRS. Because this test method also represents the behaviour of FRS under a combination of flexural load and punching shear load it can be difficult to calculate a postcracking flexural strength.

Execution

The setup is essentially the same, a rigid frame supports the *circular* panel on its perimeter as a circular piston applies the load at the centre of the panel. A load-deflection curve and an energy absorption-deflection curve are produced. The test specimen is a circular slab of 600 mm in diameter and 100 mm in thickness on a 500 mm diametral span.

Results

The same precautions that apply to *EN 14488-5* regarding the preparation of the panels, the trimming of the surface and the setup of the panel on the testing equipment should be followed. The most relevant values that are retrieved from the previous curves are the *maximum load* and the *energy absorption* at a 25 mm deflection. The Norwegian approach is now to apply a reduction factor to the energy absorption to take into account the friction effect during the test. The order of magnitude for the energy absorption is hundreds and thousands of Joules and it typically ranges between 500-3000 J.

Normative interpretation

As in the square panel version of the test, the only value that is used from this test method is the energy absorption at 25 mm deflection. This value is used as a parameter in the empirical ground support design method in Norway and for quality control.

Engineering interpretation

The same engineering interpretation of the EN 14488-5 applies to this test method.

ASTM C1550 Standard Test Method for Flexural Toughness of Fibre Reinforced Concrete (Using Centrally Loaded Round Panel)

Usefulness

The *ASTM C1550* test method is an ASTM standard that is used to evaluate the flexural toughness (or energy absorption) of FRC and particularly FRS [43]. It was originally designed for use with FRS to reduce the variability in results when compared to other methods on beams. It is well known as the *RDP -Round Determinate Panel- test.*

Because the crack pattern is determinate (three cracks or the test is deemed invalid), it is possible to determine the postcracking moment capacity, flexural strength and therefore the stress-crack width relationship of FRS using yield-line theory [44],[45]. This is particularly useful as it can be used in the design regardless of the specific loading conditions.

The energy absorption from this test method can be used in the *Q-system* design method [26]. It is also a test frequently used for quality control of FRS.

Execution

In this test, a FRS round panel specimen is loaded in its centre with a rounded steel head and supported on three articulated points placed 120° apart on the perimeter (Fig. 12). The round panel is loaded, and the central deflection is measured to produce a load-deflection curve (Fig. 13). The round panel has a diameter of 800 mm and a thickness of 75 mm. The transfer plates that support the panel are placed on a pivot that is at a radius of 375 mm from the its centre.

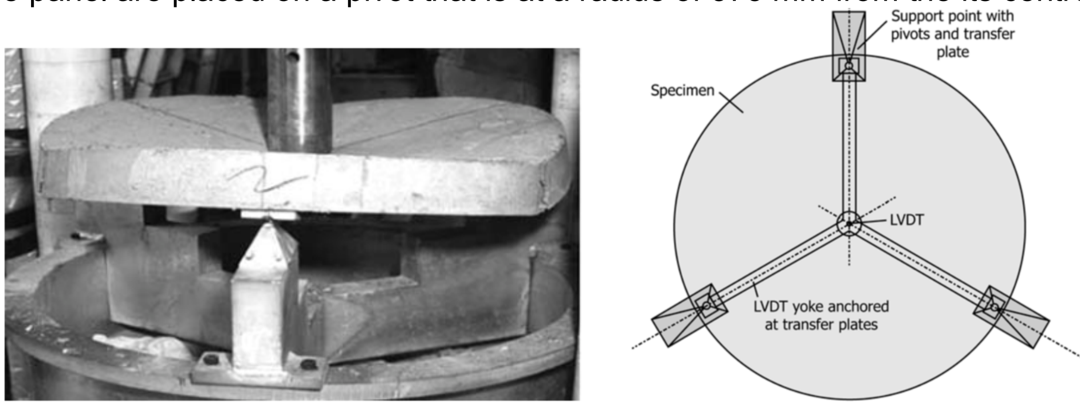


Figure 12: Illustration and schematics of the ASTM C1550 test specimen under load (from [43])

As for the *EN 14488-5,* the size of the test specimen allows it to be prepared by spraying shotcrete directly in the mould. The preparation of the sample should be done in accordance with *ASTM C1140/C1140M.* Finishing or cutting the panel at the required constant thickness is also critical. However, the rounded loading head is not as sensitive to the quality of the surface as it is in other test methods. Also, the equations in this standard allow to correct the results with the actual dimensions of the round panel.

The moulded face of the test specimen must be placed on the three transfer plates that support the panel. Since there is no continuous support in this test method and because the loading head is hemispherical, it is less sensitive to the evenness of the panel. It also allows to perform this test method in a fast and reliable way.

Results

The result that is given in this standard is a load-deflection curve that represents the postcraking flexural behaviour of FRS. From the results, the uncorrected and corrected *peak load* and *energy absorptions* are calculated. The values of energy absorption are typically reported at central deflections of 5, 10, 20 and 40 mm. The order of magnitude for the energy absorption at 40 mm deflection is hundreds of Joules and it typically ranges between 300-1500 J.

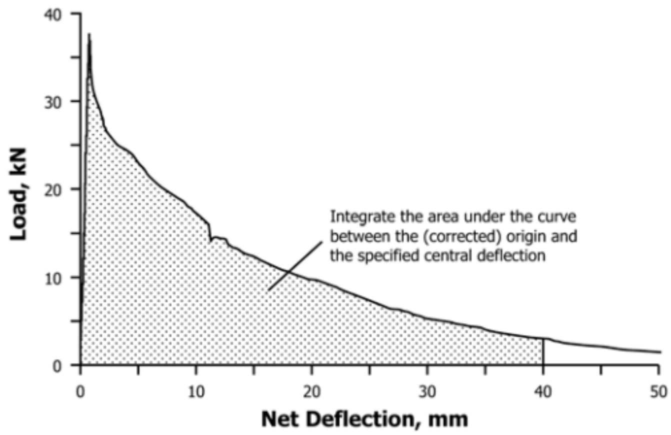


Figure 13: Example of a *Load-Deflection curve* in an ASTM C1550 test; the *area* under the curve -or energy absorption- @ 40 mm central deflection is represented by the shaded area (from [43]).

Normative Interpretation

The distinction between the values of energy absorption at different central deflections is essential as the interpretation of these results depend on the intended use of the FRS. In fact, different deflections lead to different crack rotations and, thus, different crack openings. This test method is frequently used for quality control, and the energy absorption at a 40 mm deflection is used as a parameter in the *Q-system* design method[26]. In the past, a correlation between the energy absorption (at 40 mm deflection) obtained with this test and the one obtained with the square plate describe before (EN 14488) has been proposed[46] and even included in the *modified Barton Chart*. Recent testing on a broader range of fibre types and concrete strengths unfortunately shows that this correlation does not exists and that using a direct relationship between the results of both tests can lead to unsafe ground support assessment[47].

Engineering Value

Using Yield-Line Theory (YLT), 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 span between rock bolts, the equivalent deflection could be almost 140 mm for the same approximated crack rotation.

This test method does not allow for load redistribution between different cracks as it is statically determinate. It is not a substitute for an inderterminate test set-up (such as the EN 14488-5 above) that allows for mobilizing the FRS in hyperstatic conditions and generating a multicracking response. However, it has the advantage of giving a lower variability in the results and the material behaviour can easily be analysed from the results.

5.3.3 Compressive strength tests

Usefulness

The compressive strength of mature FRS can be used for many different purposes in the design process and for quality control. It can be measured with different test methods, but it is typically measured on cored or cubic specimens. The American standard that is specifically designed for shotcrete is *ASTM C1604/C1604M Standard Test Method for Obtaining and Testing Drilled Cores of Shotcrete* [48],[49].

Execution

The specimens must be taken from a shotcrete material panel or directly from the structure to be representative of the effects of the spraying process. This should be done following a standard practice such as *ASTM C1140* or *EN 14488-1*. Once FRS has hardened and reached at least 10 MPa, cylinders can be cored and cubes can be sawn from the sample or structure without affecting the integrity of the material.

Results

The results from these test methods are the compressive strength of FRS expressed as a stress, usually in MPa. It is important that this value is accompanied by details on the type of sample used (cube or cylinder) and the time (FRS age) at which the test was performed. The order of magnitude for the compressive strength is tens of MPa and it typically ranges between 30-60 MPa.

Engineering Value

Even though the compressive strength of shotcrete is generally a good indicator of the quality of the material and the application process, it cannot be used as an indicator of the performance of FRS since it does not provide information on the postcracking flexural performance. In general, at common dosages, fibres do not affect the compressive strength of FRS. Also, as the compression strength changes through time, the mode of failure of the fibres can change which can modify the composite behaviour of FRS.

5.3.4 Proposed upcoming tests

Double Punch-Barcelona Test

The *Double Punch-Barcelona Test* is a Spanish test method designed to measure the residual tensile strength and toughness of FRC [50],[51]. The biggest advantage of this test method is the small size of the test specimen and the simplicity of the testing procedure. It has recently gained attention in the tunneling and mining industry by being used to evaluate the toughness of FRS.

It is still not clear how reliable and robust this test method is to evaluate the flexural performance of FRS. Therefore, the results from this test method should not be used as the only mean of assessing the performance of FRS. However, if this test method was to gain recognition for testing FRS, it could greatly simplify the sampling, handling and testing of FRS. Since it is not complex nor expansive, running this test in parallel as a supplementary evaluation method could help generate relevant data and eventually lead to its adequate use.
In this procedure, a FRC cylinder specimen is compressed vertically between two steel circular punches (Fig. 14). Typically, a 150 mm diameter cylinder would be used with a punch of a diameter four (4) times smaller. During the test, the load, the *total circumferential opening displacement* (TCOD) and the vertical displacement are measured. An energy absorption-TCOD can be calculated from the results of this test method.

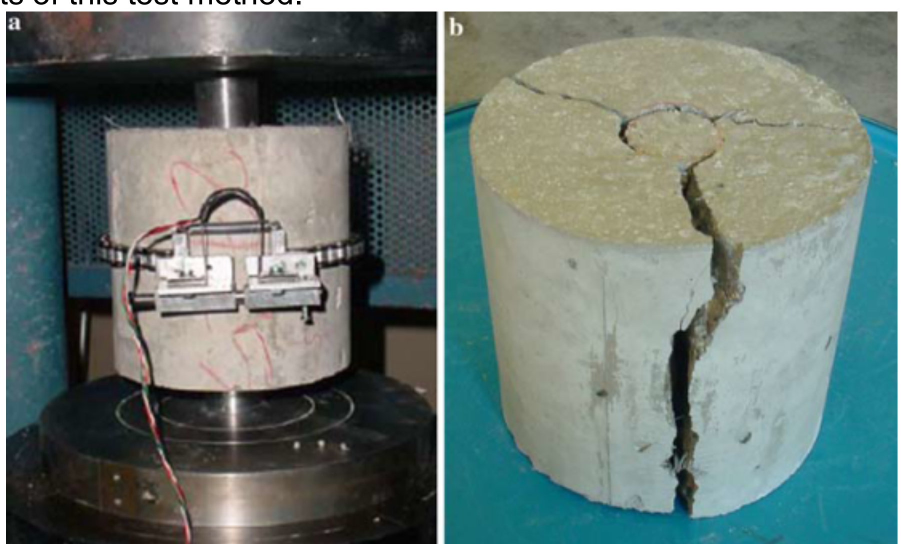


Figure 14: Example of the *Double punch-Barcelona* test specimen (a) under load and (b) after the test (from [51])

EFNARC Three Point Bending Test on Square Panel with Notch

The *EFNARC Three Point Bending Test on Square Panel with Notch* is a European proposed test method designed to measure the flexural tensile strength of FRS [52]. It can also be used to evaluate cast-in-place FRC samples although it was initially intended for FRS.

This test method is essentially the same as the EN 14651, but on a larger and thinner beam (panel). This test method was proposed to reduce the variability in the results from the notched beam while using a specimen that is closer from the actual conditions of the structure. For that reason, it uses the same specimen dimensions than in the EN 14488-5, a 100 mm thick and 600 mm sided square panel (fig.15). As for the EN 14651, the results from this test method could be used for structural design with *fib*'s *Model Code 2010.* The results from this test method can also be used to calculate the stress-crack width relationship of FRS.

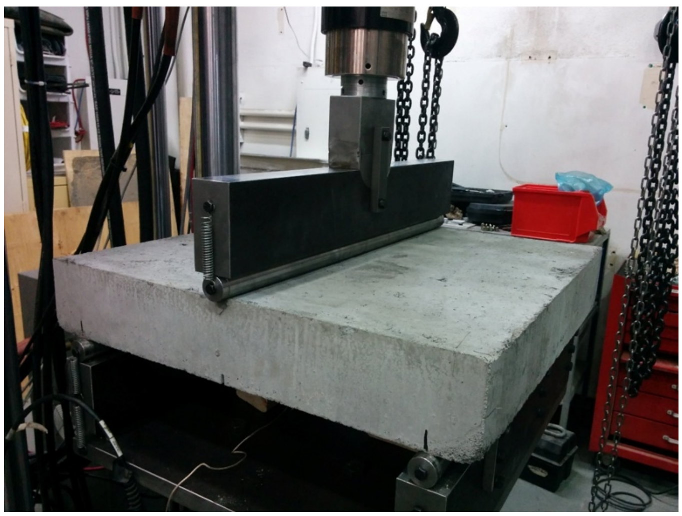


Figure 15: Example of the *EFNARC Three Point Bending Test on Square Panel with Notch.*

This test method has been investigated in recent research projects and showed good repeatability and reproducibility. However, the length on which the loading roller must be in continuous contact and its degrees of freedom can be an issue for FRS (fig.15). Indeed, it is difficult in some cases (e.g. when using set-accelerating admixtures) to produce completely flat specimens. Recent results from early investigation in different laboratories indicate that this is a suitable test for characterizing FRS. Given the distinct advantage that the specimen is produced using similar tests panels as the EN Plate (EN 14488-5) and requires minimum saw cutting, it should not be surprising to see more of this test method in replacement of the EN Beam test (EN-14651). In fact, the early results show results comparable to those obtained with this beam tests, particularly for fibre content usually encountered in FRS for ground support.

Table 3: Overview of the different test methods for FRS

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 (MPa) - Residual strengths (MPa)	- 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 (MPa) - Residual strengths (MPa) - 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 (MPa) - Average residual strength (MPa)	- No need for closed-loop control	- Necessity to saw beams - Incomplete loading curve - Small crack opening	
EN 14488-5	Energy absorption capacity on a square panel	- Energy absorption-deflection curve - Maximum load (N) - 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 (N) - 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 (N) - 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	
Compressive strength tests	Compressive strength on cylinders or cubes	- Compressive strength (MPa)	- Simple procedure - Small specimen size	- No information on postcracking behaviour	

5.4. Conclusion

The performances of FRS vary with the type of fibre and their dosage, *and* with the properties of the concrete they are added to, making it is essential to evaluate *and* specify them using standard test methods. This chapter examines some testing methods available in the industry; while some tests methods are more fitted for *design* and others for *quality control*, the typical results obtained, and their interpretation are discussed (see Table 3 for an overview).

Selecting the right test and using the right comparison criteria can be challenging. In that regards, specifying agencies are trying to orient the engineer in this manner. Indeed, the ASTM has included guidelines on the selection of the deflection at which the energy absorption is reported (*ref.* ASTM C1550). They state that"

> *"The energy absorbed up to 5 mm central deflection is applicable to situations in which the material is required to hold cracks tightly closed at low levels of deformation. Examples include final linings in underground civil structures such as railway tunnels that may be required to remain water-tight. The energy absorbed up to 40 mm is more applicable to situations in that the material is expected to suffer severe deformation in situ (for example, shotcrete linings in mine tunnels and temporary linings in swelling ground). Energy absorption up to intermediate values of central deflection can be specified in situations requiring performance at intermediate levels of deformation."*

Similarly, the European standard EN 14487-1 offers different ways of specifying the ductility of FRS in terms of residual strength and energy absorption capacity. It also reports that both approaches are not exactly comparable and even recommends typical cases:

- The energy absorption value measured on a panel can be prescribed when - in case of rock bolting - emphasis is put on energy which has to be absorbed during the deformation of the rock. This is especially useful for primary sprayed concrete linings
- The residual strength can be prescribed when the concrete characteristics are used in a structural design model

Obviously, it can be challenging to select an appropriate test method to work with. Before doing so, the engineer must not only reflect on the objective(s) of the test (design, QA, QC, R&D, etc.), but also identify a test method that will allow to truly discriminate successful or meaningful results.

6. FRS around the World

This chapter's intent is to give an overview of the current situation of FRS in the world and to highlight common practices in the mining industry as well as special situations. The authors have gathered information from their own experiences, informal communications with collaborators worldwide and through a survey that has been specifically shared for the purpose of this document. This chapter is a complement to the previous sections; it serves to highlight and to better define some the challenges encountered in using FRS in ground support in mines.

FRS Practices

On an international scale, it is easy to see that FRS is used very differently from one region to another. Examples of such differences are:

- The amount of FRS used in ground support
- The choice of placement process
- The type of fibre used
- The use of admixtures
- The test methods used

However, engineers usually manage to find adequate support scheme combination(s) to make FRS work for their specific situation(s). In fact, many combinations can lead to good performance of FRS. In many cases, however, the use of a given placement process or a certain type of fibre appears to be a default parameter rather than the result of a rational design choice. Selection of a support scheme appears to be mainly based on past experiences of the users and to a lesser extent on an engineered approach.

Regardless, it is important to recognise that some decisions around the use of FRS are influenced by factors outside the control of engineers. The result is that certain trends, or even habits, appear to stifle innovation in techniques and products used in FRS. It is believed that in some cases, different approaches would most certainly lead to a more optimal use of FRS, reducing costs without sacrificing safety.

Rockbursts and Dynamic Loads

For some mining operations, rockbursts and dynamic loads are an important aspect of their ground support design efforts, and the impact of FRS are most interesting. A literature review on the subject seem to indicate a level of understanding sufficient for the design of appropriate ground support with FRS. However, discussions with researchers and users in this field showed that, in reality, it might be far from that. Although FRS is generally accepted as an efficient ground support method for low to medium energy level events, it is sometimes reported that it cannot be used to prevent violent events in mines [13],[53].

It has been shown that FRS can absorb as much and even more energy as traditional methods [54],[55]. Thomas [17] explains that FRS in combination with rockbolts performs particularly well in extreme loading conditions; it can absorb more energy than wire mesh alone or wire mesh inside a shotcrete layer. Also, the potential of FRS under dynamic loading has been shown through mass drop test methods [56],[57]. However, the fact remains that, in severe bursting conditions, FRS alone is not sufficient and may even become part of the flying debris. This observation is supported by the experience of collaborators in the international survey.

It is important to question the standard ground support approach where rockbursts can occur. The contribution of FRS in controlling them might not solely come from its shear or flexural strength nor its toughness, but may also be from its ability to modify the behaviour of the rock to the incoming energy wave. Attention should also be given to the different behaviour encountered or expected from the ground support system: a wire mesh attached to the bolts will offer a large *displacement* capacity while an effective FRS lining will *resist* or *contain* a rockburst, albeit with a limited displacement capacity. FRS and other support scheme have been used with varying degrees of success; their performances might not be exactly understood. What is clear is that the current level of understanding of dynamic events does not allow for a strict design approach of FRS against rockbursts, even though it is strongly believed it has unexploited potential.

FRS in the support installation sequence
Another interesting aspect that was found from the experience of collaborators worldwide has to do with the position of FRS in the ground support installation sequence. It was found that FRS is used quite differently in combination with wire mesh and bolts from one mine to another.

In general, when FRS is used, it represents the initial ground support applied in the excavation. This actually makes sense as it is probably the simplest support to apply compared to the installation of bolts or mesh. Some mines will use this FRS lining alone with bolts to reinforce and retain the rock underneath. Other mines will add a layer of mesh on top of the FRS lining to retain the rock in case the displacements exceed the deformation capacity of FRS. Although relatively expensive, this combination seems to offer the best performance, especially in dynamic loading conditions. It allows to take advantage of both the locking capacity and energy absorption of FRS and the large deformation of wire mesh (i.e. basket effect).
The issue reported with FRS in the support installation sequence is when it is applied over mesh. In that case, the wire mesh is encapsulated in the FRS lining. This is apparently not the optimal way to use the combination of these layers because the deformation capacity of mesh is greatly reduced even though the flexural capacity of the composite layer is improved. Indeed, the mesh can freely deform only where the FRS cracks which lead to rapid yielding of the wires rather than allowing for an overall deformation of the mesh. This is a potential issue that should be taken into account as it seems to be a common practice in the industry.

Minimum compressive strength as a performance criterion
From the information gathered in the international survey, it appears that a minimum compressive strength of FRS is often used as a performance criterion. This minimum requirement implies that having a higher compressive strength is not an issue and should not impact the other properties of FRS.

The compressive strength is a common characteristic of concrete and is often used for controlling the quality of shotcrete. In general, it is a good indicator of the quality of the placement of shotcrete and the quality of its ingredients. However, it is not a good indicator of the performance of FRS as it does not provide information on the postcracking performance. In fact, a higher compressive strength does not necessarily lead to a higher postcracking flexural strength or a higher energy absorption: the matrix can become so strong that fibres will break instead of pulling-out (*ref.:* Section 3.2).

FRS to highlight ongoing deformation

One advantage of FRS that is not often presented is the fact that this support lining allows for a better representation of the ongoing deformation of the ground. This is something emphasised as important for many collaborators in their everyday inspection tasks underground.

In this perspective, FRS not only acts as a part of the ground support system, but also helps in the continuous assessment of the ground conditions and in the subsequent design process. It becomes an evaluation tool as well as a ground support tool.

7. Complexity of the system & knowledge gaps

Ground and FRS interactions

So far, this document has covered many elements of fibre-reinforced shotcrete, covering aspects such as the working of a fibre in a cement matrix or the testing of FRS specimens. Upon reflection however, there seems to be an important aspect that is somehow missing in the text and that certainly deserves more attention and discussion. Indeed, the interaction between the FRS and the ground is only *described* in various places (section 4.3 for example) without ever being able to exactly state or *quantify* how the FRS is actually solicited by the ground or, inversely, how exactly the FRS is acting upon the ground it helps to support. The fact is that the challenge here is threefold. First, there is a (large) number of different ground conditions that can be encountered, sometimes even on the same site, leading to different types of *solicitations* of the reinforcement and the support systems. Second, FRS can be designed to offer a wide range of behaviours depending on the level of deformations encountered; from a crack opening control approach and rigid response at smaller deformation to a significant energy absorption in displacement capacity driven ground conditions for example. Finally, the ground support system selected, including FRS, bolts, mesh, etc., creates a number of interactions that, between the movement of the ground and the response of the FRS, only complicates the overall picture of this hyperstastic/nonlinear response system.

Needless to say, the selection and design of a ground *reinforcement and support system* is a complex task that requires the full and continuous attention of the engineering team in charge. Identifying solicitations (direction and magnitude of loads and/or displacements) and selecting the most efficient, safe and economic means to resist them is truly the centre of the engineering work.

Performance and Failure Modes of FRS

An intersecting aspect that stands out from the information gathered in the literature and from surveys is the duality between FRS's apparent modes of failure and the way its performance is assessed. Indeed, many reports that the most common mode of failure of FRS is one that is predominantly in *(punching) shear*. At first, this is somewhat of an important contrast with the loading conditions and failure mode found in most test methods used to measure the performance of FRS as seen in Chap.5.

In fact, most popular test methods are either testing a beam in flexure or a larger panel in flexure. In these test methods, shear failure is only rarely, and arguably erroneously, observed. One could argue that the EN 14488-5 test method on square panel with continuous support actually evaluates punching shear performance of FRS. This is partially true because a punching shear failure or a hybrid (shear-flexure) failure is sometimes seen. However, the most common type of failure in this test remains a flexural failure.

Two questions arise from this duality:

1) Is it true to say that the most common mode of failure of FRS in mines is from punching shear?
2) Are common test methods a good indicator of the performance of FRS in mines?

Indeed, the mode of failure depends on various factors such as the roughness of the excavation, the adhesion between FRS and the rock and the loading conditions. In the simplified case of a perfectly smooth surface, the better the adhesion between FRS and the rock, the better the chances of a shear failure. In the case of early-age shotcrete, when the cementitious composite matrix has not yet fully hardened, punching shear is generally the predominant mode of failure [58]. Similarly, if the mature FRS surrounding a loose block is perfectly bonded to the ground, the failure of the lining will most likely be punching shear [20]. However, many practitioners argue that given the reality of uneven surfaces, varying thicknesses or properties of shotcrete, or small ground movements, it is hard to believe that a perfect and constant adhesion is present and wholly maintained throughout the service life of the lining. Where adhesion is reduced or lost, flexure will most likely be the predominant observed mode of failure. The case could also be made that with the complex geometries and loading conditions found in many mines, it would be difficult for an engineer to isolate and identify a unique failure mechanism of the lining. Indeed, observations are usually made *after* the failure is completed, yielding little information on the behaviour of the lining prior to failure as the loads and deformations increased.

Nonetheless, how can the test methods we use help us evaluate the in-situ performances of FRS? A part of the answer can be found in Ding and Kusterle [40] where it was shown that incorporating fibres in shotcrete will transition the failure mode of an EN 14488-5 plate from a punching shear failure to a flexural failure [40],[59]. Moreover, all test methods that evaluate the flexural performance of FRS provide, to various extent, information about the *stress-crack width* response; a response that allows to directly assess the fibre contribution to the punching shear strength of FRC [60]. In fact, the evaluation of the post-cracking flexural performance of FRS might be very similar to the evaluation of its post-cracking shear performance. A linear correlation between the shear strength and flexural strength of FRC has already been found [61]. Therefore, the current test methods can provide enough information for a basic design of FRS lining as ground support.

In view of the apparent difficulty in bringing together the loads cases found in a mine and the testing conducted to evaluate performances of FRS, it is interesting to recall an enlightening comment by Tannant [62]. Indeed, he reminds us that although most support design focuses on the *load capacity* of the support, it is equally important to consider the support's *displacement capacity*, especially in situations where large relative displacements are expected (such as in high convergence ground or rockbursts conditions).

Testing
A complete chapter has been dedicated to the presentation of a number of test methods available in the industry worldwide to test FRS. All the efforts were made to distinguish between tests better suited for QA/QC or for design, as well as outlining the various advantages of one or another depending on various parameters such as specimen production to availability and reliability of testing equipment. Nonetheless, the entire presentation on the different test methods only strengthens the key role of the engineer(s) in the process. Indeed, it is up to them to capture and understand the ground conditions and select an appropriate ground support scheme. From there, and specifically for shotcrete and fibre-reinforced shotcrete, the important task is to translate the *ground support system requirements* into minimum *material properties*. This is where the selection of the appropriate test method (and its interpretation) is paramount, as it must allow for measuring and reporting material properties that are compatible with said requirements.

Given the discussion of the sections above on our comprehension of the exact behaviour or interactions between the FRS and the ground it is helping to support, it should not come as a surprise that many of the specifications found rarely correctly correspond to the needed property. In that regards, a typical specification framework is proposed in Appendix 1.

Limitations and Shortcomings
Despite the incredible progress and advances in the field of FRS over the last decades, there are still a number of issues that limit our understanding and use of FRS. Although many have already been mentioned in the text, it seems essential to articulate them in terms of future R&D and documentation. The common source of the shortcomings and limitations is simple: *the various type of ground conditions encountered combined to the different FRS behaviours available lead to a complex response of the ground and FRS interaction*. This leads to:

1. *Difficulties in offering a uniform design method* – Before anything, a design approach implies that common *failure criteria* have been identified; often challenging by itself. The basic approach of design for all engineers is then to make sure the *capacity* is larger the *solicitation*. Identifying these solicitations (shear, flexure, deformation, etc.) and their magnitudes is already a vast and complex field; evaluating the capacity of the support scheme, not only the FRS, is also quite the challenge.
2. *Dynamic loads* – A special case of the *capacity* ≥ *solicitation* relationship, the presence of dynamic loads such as micro-seismic events or rockburts opens entirely different fields in strength of materials and structural behaviour. The particular case of rockbursts seems to especially require the early attention of engineers as their occurrence will grow with increasing mining depths and methods to counter them are not fully understood and often the source of many misunderstanding or misinterpretation in the ground support behaviour at failure.
3. *Large deformations* – Also a special case of the *capacity* ≥ *solicitation* relationship, the large deformations found both in service and at failure of many underground openings lead to changes in our definition of failure. The expected behaviour of the ground support scheme, and especially of the FRS, are changing accordingly. Designs using

a *deformation capacity approach* of the ground support system will be more and more present, putting emphasis on the importance of the *interactions* between the ground and the support system (FRS, bolts, mesh, etc.). Topics such as membrane behaviour, strain hardening or strain softening response, and testing methods all have to be further explored to address this.

4. *Case studies* – An indirect result of the shortcomings and R&D needs described above is the difficulty in assembling complete and relatable case studies to illustrate how various ground support challenges have been addressed in the world using FRS. Indeed, most if not all of the information found through literature review and discussions with collaborators relates more to correction methods applied in the case of observed local failures than a thorough design approach. As such, it is important to try and normalise the collection of information and report of case studies in order to draw a clearer picture of the R&D needs in the industry.

As can be seen, a better understanding of the interactions between the ground and the support system (FRS, bolts, mesh, etc.) throughout its deformation and loading history (service and failure) appears to be the keystone of further developments and better optimal use of fibre-reinforced shotcrete.

8. Conclusions

The present guide explores the situation of fibre-reinforced shotcrete and offers guidelines on its applicability for ground support in mines. It provides insights to help mine owners, mining engineers, material suppliers and key players in making the most out of FRS in their ground support programs.

The different mechanisms of fibre reinforcement and shotcrete are first described, ***introducing the types of fibres available and their properties (objective 3)***. Most fibres can be categorized as either macrofibres or microfibres depending on their diameter, and steel fibres or synthetic/polymer fibres. Then, an overview of the general principles of ground support in underground mines is presented. Regardless of the local history and practices, FRS can usually bring benefits to a ground support scheme that typically reinforces the ground, holds up the opening and retains blocks. This overview of ground support in mines allows to identify the position of FRS in this field and ***explain the basic mechanisms through which this composite can function as a support component (objective 2)***. Even though potential modes of failure of the FRS lining have been defined, interpreting the true nature of the actual failure from an observed failure remains a challenge. Therefore, ***specifying performance requirements of FRS (objective 1)*** depends on the specific conditions of a mine's ground support system and the preferred local practices. This guide also examines and ***provides a description of the common testing methods used for FRS and how to interpret the information generated (objective 4)***. Engineers must not only reflect on the objective(s) of the test (design, QA, QC, R&D, etc.), but also identify a test method that will allow to truly discriminate successful or meaningful results. Unfortunately, it turns out gathering ***case studies and examples of best practices in mining (objective 5)*** represent a bigger challenge than expected, to the point where they have become the focus of future work. Finally, some of the current challenges encountered in using FRS in ground support in mines as well as special situations are defined to ***identify gaps in knowledge and capabilities of FRS in meeting desired requirements (objective 6)***. The disconnect between FRS's apparent modes of failure and the way its performance is assessed appears to be an essential question to resolve, as well as ground – support system interaction throughout the load/displacement history.

9. References

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Appendix 1

This appendix is proposed as a starting point for assembling a *Specification* document for fibre-reinforced shotcrete for ground support. It concentrates *only* on aspects related to the presence of fibres in shotcrete and as such does not address all aspects of shotcrete specification and quality control.

General
In North-America, specifiers find general guidance for specification of FRS in *ACI 506.2 - Specifications for Shotcrete*, *ACI 506.5 - Guide for Specifying Underground Shotcrete*, and *ACI 544.3 - Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete*.

In Europe, specifiers will find general guidance for specification for FRS in *EN 14487-1 Sprayed concrete - Part 1: Definitions, specifications and conformity.*
Additional requirements should be added to specify the type and material of fibers allowed, and either the *performance criteria required*, or the *type and quantity of fibres required*. The user is cautioned that specification of a minimum dosage rate is not a guarantee of a minimum performance level. As it has been abundantly expressed in the present document, specification of a *performance level* includes the synergistic effects of concrete strength and fibre material, type and dosage rate at a minimum. In the cases where the *type and quantity of fibres* are specified, they should be based on a properly designed conformity testing scheme based on *shotcrete* sprayed in conditions similar to that of production, including but not limited to equipment type, mix design including all admixtures and spraying orientation.

Assessing Performance
At some point, the performances of FRS need to be evaluated, whether to determine the type and quantity of fibres required or to validate the conformity to the performance criteria. The role of the engineer in defining the performance requirements cannot be overstated; the discussions in Chapters 5, 6 and 7 clearly illustrate the need to define the expected ground support system behaviour from which to derive FRS performance criteria (energy absorption, crack width, toughness performance levels, etc.). From there, selecting the proper test methods should prove more natural.

ASTM C1609 beams and ASTM C1550 round panels are currently the preferred methods in North America to test fibre-reinforced shotcrete toughness for both the wet and dry mix shotcrete processes. Beam tests are used in normal practice to determine the residual strengths available from given fibres and dosages, while the round panel tests are used for quality control and assurance during construction. However, a correlation can be developed between ASTM C1609 and ASTM C1550 at 40mm to ensure that the flexural strength required is achieved (Barsby, 2011).
A similar approach is used in Europe where the EN 14651 beam test and the EN 14488-5 square slab test are used in combination, the beam being used primarily for design purposes and the square slab test for quality control and assurance during construction.

Laboratory and large-scale tests confirm that fiber types, materials and shotcrete processes have a considerable effect upon the performance of the FRS. One must consider how the sampling and the testing will change what is actually sprayed on the supported opening. As a rule, testing is always performed on sprayed shotcrete. All standards must be carefully followed as changing sampling or testing conditions can have a significant impact on the reported values.