Best Practice for Testing Fibre Reinforced Shotcrete

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Fibre reinforced shotcrete (FRS) is used in many underground applications from low stress friable ground to deep level hard rock mines. It can be subjected to harsh conditions, including very high static stresses, high temperatures, dynamic loading and a very corrosive environment. When designing a surface support system, such as a fibre reinforced shotcrete lining, it is important to understand how the system behaves and the mechanism of loading to which that shotcrete lining support may be subjected.

Shotcrete linings require a rotation capacity in order to follow ground movements while the arching effect in the surrounding rock mass develops. The fibre reinforcement within the shotcrete overcomes the brittleness of concrete and provides the necessary ductility after the shotcrete cracks, to prevent a sudden failure. Due to the load bearing capacity available after cracking, the failure mechanism is transformed from a brittle mode characteristic of unreinforced concrete to a nearly elasto-plastic mode. Therefore, energy absorption or residual strength performance criteria (post crack performance) are generally required to specify and rate FRS performance.

When evaluating fibre reinforced shotcrete it is very important to use a test methodology that is well representative of the loading mechanism and reflects the full capabilities of the fibre. Since primary shotcrete linings in hard rock tunnelling and mining are typically relatively thin, and the lining follows the naturally irregular rock surface, the shotcrete lining on an excavation cross-section scale does not provide a structural bearing arch. Because of this, rather than failing due to a combined thrust/bending load like in thick-shell lining, any failure mode is most likely governed by bending induced by a more or less concentrated load, sometimes referred to as a ‘punching load’. Based on this failure mode, structural tests to evaluate the post-crack performance of the lining are typically conducted on different types of panels rather than on classical beams.

Image 1: Typical applications of FRS linings are subject to both internal and external forces that are statically indeterminate, which cannot be represented in a beam test. (NIOSH 2015)
At normal dosages (< 1% vol.) fibres have no effect on the properties of uncracked concrete such as compressive or flexural (first crack) strength. Once the concrete has cracked, the fibres are activated and start bridging the crack instantly as with conventional mesh reinforcement.

This is where the fibres act to overcome the inherent brittleness of concrete and impart post-cracking load bearing capacity to the concrete. High performance fibres are designed to “pull-out” of the concrete matrix, which provides the required ductility (or toughness) of the matrix.

Fibres, evenly distributed in the shotcrete matrix, result in a composite material that is ductile, tough and impact resistant. These are important properties for ground support applications. Toughness of shotcrete is a very important criterion because it may prevent an uncontrolled failure after initial cracking of the shotcrete lining associated with deformation of the rock.

To assess fibre performance, the concrete must be cracked, hence, it is suggested to implement a test method where cracks can develop over a large area, to more reliably measure the performance of the fibres. This is why panel testing is preferred over beam testing when measuring the capacity of fibre reinforced shotcrete.

*Image 2: Typical failure mechanisms of FRS linings which are not reflected with classical beam tests. (Adopted from NIOSH 2015).*
Steel fibres

Steel fibres have been used as reinforcement for concrete and shotcrete since the late 1960’s, although more commonly in underground construction only from the early 1990’s. Since then they have gained considerable acceptance in the engineering community as a means of reinforcing concrete. However, there are some significant limitations when using steel fibre reinforced shotcrete (SFRS). These limitations are primarily related to durability, i.e. corrosion and embrittlement, and progressive performance loss with age.

For more information see BarChip Technical Note ‘Durability & Long Term Performance of FRC’.

Macro synthetic fibres

Macro Synthetic Fibres (MSF) are a more recent development, with their initial introduction to the market occurring in the late 1990’s. High performance macro synthetic fibres are typically made of polypropylene and are able to be manufactured with a high tensile strength of more than 650 MPa. The base material, polypropylene, makes them inert to chemical attack such as corrosion caused by chloride ions. Thus, they are an excellent choice for shotcrete reinforcement, as shotcrete is often used in very aggressive environments such as deep mines, tunnels below the water table or in slope protection along traffic ways using salt for de-icing.

Image 3: The effects of corrosion and embrittlement on the long term durability of SFRS are severe.

Image 4: MSF will never suffer from corrosion and is the preferred fibre in aggressive environments or where long service life is required.
BarChip high performance MSF are engineered to produce a ductile fibre pull out in the post-crack phase. As such, the failure mode is similar to shotcrete reinforced with steel mesh or quality steel fibre. That means that comparative tests are appropriate to distinguish the performance of each fibre type and no additional test methodology needs to be undertaken for MSFRS (EN 14487-1).

BarChip MSFRS yields outstanding residual strength and energy absorption capacity, which often outperforms SFRS, especially at larger displacements, due to the lower Young’s Modulus compared to steel fibre.

It performs extremely well at both small and large crack widths but their ability to resist corrosion means that MSF are able to withstand higher deformations and larger crack widths without detrimental loss of performance. This is also achieved by using longer fibres up to 65 mm, which is possible because the length of macro synthetic fibres is not limited by the hose or nozzle diameter.

Steel fibres, due to their inherent stiffness are limited in length, typically to 30-35 mm to avoid line blockage, which in turn leads to a rapid performance loss through pull-out with increasing crack widths. In contrast, high performance macro synthetic fibres show a high post-crack performance level even at very large displacements.
Since the mid-1990s, multiple bodies have developed guidelines or standards for the use of fibre reinforced shotcrete, e.g., in Europe (EFNARC 1996 and NB7 2011, EN 14487 and EN 14488), in the USA by the American Concrete Institute (ACI 506.1R 2008) and the American Shotcrete Association, or in Australia by the Concrete Institute of Australia and the Australian Shotcrete Society (2010). These documents provide guidance that is generally independent of the fibre material, whether it is steel or synthetic.

The design of fibre reinforced shotcrete linings herein is largely based on energy absorption capacity in ultimate limit state (ULS) obtained from panel test results. The panel tests were specifically developed to assess the performance of FRS in larger deflections that need to occur to enable the ground to stabilize and take the stresses by creating the arching effect in the surrounding rock mass itself, typically for NATM tunnelling methods. The following table shows typical performance levels of energy absorption capacity required for given ground support conditions, which can be found in the before mentioned guidelines.

Internationally the most common design approach is based on the Q-System developed and expanded upon by Barton and co-workers over many years (Barton et al. 1974, Barton & Grimstad 1994, Barton & Grimstad 2004, NGI 2015). In this widely recognized empirical rock stability classification a minimum thickness and toughness performance of FRS is selected according to the so-called Q-chart or Barton chart. The required toughness performance herein was classified according to the EFNARC panel test-based energy absorption requirements (EFNARC 1996) for different rock mass qualities. Using the correlation to EFNARC panel test results from Bernard (2002), Papworth (2002) correlated the energy absorption criteria used in the Barton chart to the round determinate panel (RDP) test.

<table>
<thead>
<tr>
<th>Level of Ground Support</th>
<th>Continuously Supported Panel e.g. EN 14488-5</th>
<th>Round Determinate Panel ASTM C 1550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>500 J</td>
<td>280 J</td>
</tr>
<tr>
<td>Moderate</td>
<td>700 J</td>
<td>360 J</td>
</tr>
<tr>
<td>High</td>
<td>1000 J</td>
<td>450 J</td>
</tr>
</tbody>
</table>

*Table 1: Energy (in Joules) in EN 14488-5 square panel test measured at 25 mm deflection, energy in ASTM C 1550 round panel test measured at 40 mm central deflection. More details on these test methods can be found in chapter 4.*
**Support categories**

1. Unsupported or spot bolting
2. Spot bolting, SB
3. Systematic bolting, fibre reinforced sprayed concrete, 5 - 6 cm, B+Sfr
4. Fibre reinforced sprayed concrete and bolting, 6 - 9 cm Sfr (E500) + B
5. Fibre reinforced sprayed concrete and bolting, 9 - 12 cm Sfr (E700) + B
6. Fibre reinforced sprayed concrete and bolting, 12 - 15 cm + reinforced ribs of sprayed concrete and bolting, Sfr (E700) + RRS I + B
7. Fibre reinforced sprayed concrete > 15 cm + reinforced ribs of sprayed concrete and bolting, Sfr (E1000) + RRS II + B
8. Cast concrete lining, CCA or Sfr (E1000) + RRS III + B
9. Special evaluation

Bolts spacing is mainly based on Ø20 mm
E = Energy absorption in fibre reinforced sprayed concrete
ESR = Excavation Support Ratio
Areas with dashed lines have no empirical data

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**Image 7:** Permanent support recommendations based on Q-values and span/ESR with correlating energy absorption requirements as based on panel testing.
The simply supported beam test has serious limitations. A beam test is not representative of a shotcrete lining, as it does not correctly reflect the behaviour and performance of a lining with increasing deformation due to ground movements. Further, the beam test setup is statically determinate, whereas a fibre reinforced shotcrete lining is internally and externally statically indeterminate. Such hyperstatic structures allow for moment or stress redistribution, which provides redundant structural capacity, whereas in a beam test, only one single crack will develop and eventually lead to failure. The failure mode of a linear structure like a simply supported beam is a cross-sectional failure, which is in complete contrast to the multiple cracking and system redundancy of a shotcrete lining, and thus, does not represent the biaxial bending occurring in ground support.

Beam tests produce very conservative results compared to in situ behaviour of FRS in linings because in-plane compression almost always co-exists with bending moments and these stresses act to enhance ductility compared to what is observed in simply supported beams. It is for this reason that strain-hardening behaviour is not required in a beam test even if deflection-hardening behaviour is desired in a tunnel lining. Beam tests do not provide information for larger displacements that can be found in underground environments. Due to the geometry of the specimens, a beam test focuses only on small crack widths in a very short crack length (125 to 150 mm, depending on the specimen width).

These limitations make it unrepresentative for shotcrete linings, where stress redistribution is possible and larger deformations occur. One should be careful of extrapolating the results of standard beam tests - where there is limited opportunity for load redistribution - to tunnel linings, which, in static terms, are highly redundant shells which can redistribute loads very effectively (Picket & Thomas 2013).

The difficulty in determining net deflections and using the required closed-loop, servo-controlled testing machines, and the inherent variability of beam flexural testing are further disadvantages of beam tests. They have a high variability due to the limitation in measuring only a single crack in a statically determinate system. Coefficients of variation (COV) of up to 35% are not uncommon in post-crack beam results. This makes it very difficult to manage on-site QA testing against approved project performance specifications. Panel test methods have the advantage of low variability, and due to the fact that the test specimens are the sprayed panels, the specimens do not have to be prepared (sawn) from it, which eliminates additional labour, costs and potential influences on the test results.
Toughness, or energy absorption capacity, is the first and most basic requirement for fibre reinforced shotcrete in order to provide sufficient performance data at larger deformations. For sprayed concrete linings, a panel test which measures energy absorption is the more relevant test method to represent a FRS lining working and failure mechanism. Panel tests are statically indeterminate (hyperstatic), just as the lining itself is, allowing stress redistribution and multiple cracking and thus, represent the structural behaviour of the FRS lining significantly better than a simply supported beam.

These panel tests involve the application of a central load to a square or round panel, which is continuously supported along all four edges or along the perimeter. This models the typical punching effect of a rock bolt on the shotcrete lining. The hyperstatic test setup allows for stress redistribution so that, depending on the performance of the fibres, multiple cracks can develop. Further, the panel tests measures significantly larger deformation (out to 25 mm), and thus provides a much more accurate model of a real shotcrete lining behaviour than a beam test.

Panel tests have a significantly lower variability than beam tests because a much larger (cumulative) crack length develops due to multiple cracking, meaning COV’s of less than 15% can be achieved in these panel tests. Thus, the meaningfulness and the reliability of panel testing is much higher. Consequently, panel testing requires fewer specimens per set than beams in order to yield stable average numbers, i.e. project costs can be reduced using fewer panel tests than beam tests.

It must be noted that panel tests such as EN14488-5 suffer a limitation due to friction effects. By supporting the panels continuously, a high level of friction is induced between the panel and the support frame in the test setup. This occurs because as the deflection increases the panel tends to move over and subsequently rotate around the support. The free movement is impeded, however, as a result of friction at the support surface, which induces an axial stress in the panel. This effect can considerably increase the apparent performance of the panel (Bjøntegaard and Myren 2009). This makes it more difficult to assess the effective fibre performance for comparison.

“Panel tests...represent the structural behaviour of the lining significantly better than a simply supported beam.”
Round determinate panel (RDP) test

ASTM C 1550

The Round Determinate Panel test (RDP test) was developed in Australia in the early 2000’s, as a means of more accurately determining the performance criteria for fibre reinforced shotcrete for underground mining and tunnelling. In contrast to the continuously supported panels this test setup is statically determinate, as the round panel sits on three pivoted support points. Thus, a predefined crack pattern with three radial cracks between the support points will develop independent of fibre type or performance. This yields significantly reduced variability in the results, thus COV’s of 10% or lower can be achieved.

This test specimen has the same depth as an EFNARC beam (75 mm), but involves 1200 mm of crack length out to 40 mm central displacement, which is far more representative of deformations experienced by a ground support system, especially with regards to larger ground deformation in situ. The small depth of the panel further ensures that bending is the primary mode of failure, excluding shear influences and arching effects, just as happens in a typical thin FRS lining.

The introduction of a second deflection criteria at 10mm in the RDP test accounts for in-service considerations (SLS) for situations where crack widths must be limited. This was first proposed by Papworth (2002) in order to overcome the need for beam testing.

The RDP test also involves a lower level of inherent friction at the supports compared to the EFNARC test. The contribution of friction to energy absorption capacity in this test is significantly lower compared to continuously supported panel tests (Bernard 2005) so the effect of axial stress on the panel is reduced, providing a much more accurate comparison between the performance of different fibre types, which is the primary aim of these tests.

In addition, RDP panel test results can be correlated to EFNARC panel results. Bernard (2002) found a correlation of;

\[ R^2 = 0.88 \text{ for EFNARC}_{25mm} = 2.5 \times \text{RDP}_{40mm} \]

(both in Joules). This allows for comparison between results that are obtained using regionally different standards.
In summary, when choosing a test for fibre reinforced shotcrete, it is necessary to nominate a test methodology that reflects what is actually occurring in the field, i.e. how FRS linings work under site conditions. Because the mode of failure experienced in the specimen is more representative of in situ lining behaviour, a panel test should be nominated in preference to simply-supported beam tests for the performance evaluation of a fibre reinforced shotcrete.

There are similarities and differences between the panel test methods discussed above, but if the aim of the testing is to determine the best fibre for a project, then the ASTM C 1550 Round Determinate Panel test is arguably the most suitable methodology to use. This is because it involves a large crack area and significantly reduced friction, aiming at measuring the performance of the fibre as the main outcome of the test. The RDP test overcomes problems related to cost, reliability and repeatability, which are short-comings of the other standardized test methods.

Due to potential corrosion effects and performance loss with age associated with steel fibres, standard testing at 28 days does not adequately describe the long-term performance of a fibre reinforced shotcrete lining. It is advisable that designers also request testing at a later age, e.g. at 90 days, to better assess the long-term performance of fibre reinforced shotcrete.

For more information see BarChip Technical Note, ‘Durability & Long Term Performance of FRC’.

References

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BarChip has a simple vision - revolutionise the world of concrete reinforcement. For over 100 years the technology of concrete reinforcement has barely changed. We set out to create a new reinforcement for the 21st century. We created BarChip synthetic fibre reinforcement.

Our vision

We believe that long term business relationships can only be sustained by a commitment to provide the highest quality products and services. We make sure to understand your concrete, know the performance requirements and work with you to get the right design and the right performance outcomes.

Our process

When you work with BarChip you know that your concrete asset has been reinforced to the latest engineering standards. It will never suffer from corrosion. It will be cheaper and quicker to build. It will be safer and it will keep performing throughout its entire design life.

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