Design Guidelines for the Use of Fiber-Reinforced Shotcrete in Ground Support

by F. Papworth

Editor's Comment: American Shotcrete Association Board members attended the International Conference on Engineering Developments in Shotcrete in Hobart, Tasmania, Australia in April 2001. One of the outstanding papers presented at the Conference was a paper by Grant, Ratcliffe and Papworth on "Design Guidelines for the use of SFRS in Ground Support". Frank Papworth was asked to submit an updated paper on the subject for publication in the ASA Shotcrete Magazine and so here it is. It is more technical than most of the papers published in the ASA Shotcrete Magazine, but was selected because it was considered that it would be of considerable value to designers of fiber-reinforced shotcrete linings for ground support in civil and mining applications.

Abstract: There are presently no design guidelines based on toughness for the use of fiber-reinforced shotcrete (FRS) in ground support for underground mine development. Typically, in the Australian mining environment, the approach to the use of FRS has been one of borrowing experiences from other mines and a "trial-and-error" method of design, installation, and assessment. There is a need for a ground support design guide that can be simply applied by "front-line" personnel.

This paper provides an overview of the performance characteristics of FRS and how the various shotcrete guides specify its use. Practical experiences with the use of FRS in Australia and Canada in various applications and ground conditions are combined with existing empirically based ground support-design methods to develop a ground support guideline that incorporates the concept of toughness. An assessment of structural synthetic fibers shows that their low modulus makes their performance characteristics different from those of steel fibers, and that they are not likely to be economical in linings where crack widths are limited, but that they are preferable where large deflections are permissible.

1. Introduction

Fiber-reinforced shotcrete (FRS) has been used successfully for ground support for more than 20 years. Although its use today is widespread globally, the understanding of how it works is limited and application assessment is subjective. The introduction of structural synthetic fibers introduces additional variables that are also not well understood.

The performance of FRS can be characterized using a variety of test methods taken from European, Japanese, and American standards, and more recently, by a method developed in Australia. These tests characterize the performance of FRS by measuring the ability of this composite material to carry load in flexure beyond the flexural capacity of the concrete itself—that is, ductility or "toughness." Extensive use of these tests to assess the ever-increasing range of fibers available and the author's development of FRS specifications for a range of applications show that:

- The performance of different fibers varies enormously;
- Many of the test methods give poor repeatability;
- Many tests are undertaken erroneously; and
- There are no criteria relating ground condition, in-situ performance requirements, and the physical properties of FRS.

Field experience has shown that FRS is a safe, efficient, and economical ground support method. To promote its adoption, a performance-based design guide that can be simply applied by "front-line" personnel is required. This paper reviews testing methods and application assessment in the industry to develop such a performance-based design guide.

2. Toughness measurement

The post-crack capacity of FRS can be determined through a variety of internationally recognized methods. Beam tests are generally used to give a post-crack residual flexural strength at a given deflection or an equivalent flexural strength over a deflection range. FRS performance criteria for deflections in the range of 2 to 3 mm on 300- to 450-mm-wide beams are common. This relates to crack widths of approximately 2 mm. All current standard test methods have poor repeatability and reproducibility. With the high variability, it is desirable to take the average results from at least five samples. The tests are also complex to set up, are not available in many laboratories, and do not represent how shotcrete fails under site conditions. The author's experience is that fiber manufacturers market their products using the best results from tests over the life of the product, which leads to unrealistic and dangerously high expectations. These results are sometimes from laboratories that undertake the test believing it to be similar to the standard flexural strength testing they are familiar with. The output is then wrong, but the testers do not have the expertise to recognize the errors introduced.

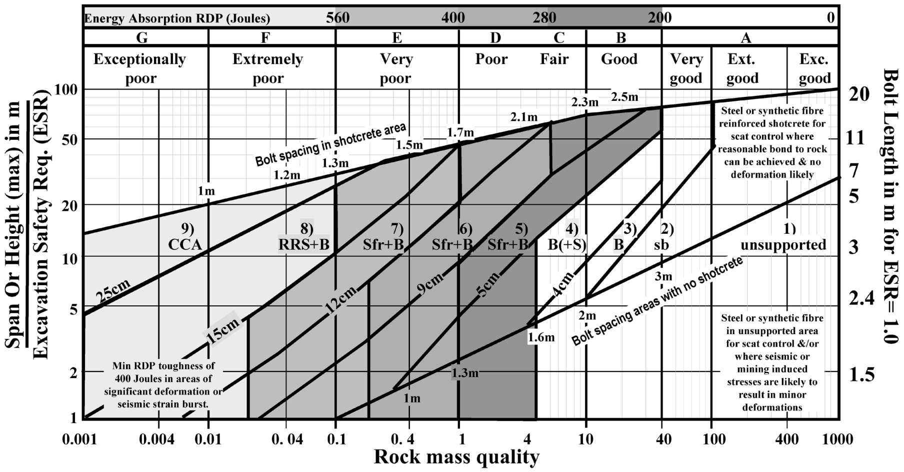

Figure 1: Modified Barton chart.

The EFNARC panel test comprises a 600-mm-square, 100-mm-thick panel supported on all edges. The center-point load versus deflection is measured, and the absorbed energy is calculated. The standard performance criterion used is energy absorbed, in joules, up to a deflection of 25 mm. This equates to a surface crack width of around 5 to 10 mm. The panel failure mechanism is representative of lining behavior, and the test is simpler to undertake than beam tests (although samples are heavy). Results are more consistent than beam tests, but inconsistencies can arise from nonuniform seating of samples. It was becoming the international method of assessing FRS until the introduction of the Round Determinate Panel (RDP) test.

In the RDP test, an 800-mm-diameter panel is supported on three points, and the central point load versus deflection is measured. The energy absorbed is calculated, and the result at a deflection of 40 mm is reported as the standard assessment. The developer, Bernard (2001), recognizes that the deflection value used is somewhat arbitrary and that other deflections might be more appropriate.

Bernard (2000) related EFNARC panel results to RDP results. An r^2 correlation of 0.88 was found for:

$$\text{EFNARC}_{25\text{mm}}\ (\text{J}) = 2.5 \text{ x } \text{RDP}_{40\text{mm}}\ (\text{J})$$

The correlation is not unexpected, as both results measure the integrated energy at high deflections. From the results in Bernard (2000), the author has calculated the relationship between JSCE SF4 F_{e3} values and RDP at 10 mm deflection. An r^2 correlation of 0.82 was found for:

$$F_{e3}\ (\text{MPa}) = (\text{RDP}_{10\text{mm J}} /92)1.33$$

The correlation is high, as both results measure the integrated energy at low deflections.

This test is rapidly becoming the internationally accepted standard. Its consistency means that certified results provide a reliable assessment of fiber performance in concrete. In all tests, the deflection criteria are somewhat arbitrary. The panel tests were specifically developed for shotcrete assessment. Typically, in NATM tunneling methods, it is accepted that large deflections need to occur to enable the ground to stabilize and take the load. This accounts for the large deflections quoted compared with the beam testing, where performance is primarily related to slabs on ground.

3. Existing guides relating ground condition to FRS performance

The major problem in designing support for underground openings is in determining the strength and deformation properties of the ground and matching them with the chosen support structure. Though a great deal of resources are utilized in trying to quantify the strength and deformation properties of the ground, and sophisticated modeling programs have been developed for analyzing ground behavior, there is presently no link between the behavior of the ground and the reaction of thin FRS linings. Because a decision regarding the FRS lining must be made as quickly as the ground is exposed, a design method that can be applied with relative ease by suitably qualified personnel at the development face is needed. While there are many standards and guidelines that discuss the measurement of shotcrete performance, only the Norwegian Concrete Association and Morgan, Chen, and Beaupré (1998) attempt to link FRS performance and ground condition.

The Norwegian Concrete Association's "Sprayed Concrete for Rock Support" (1993) acknowledges that no documented design models exist that incorporate the parameters of flexural tensile strength and toughness. Its general design approach is based on the widely recognized empirical rock stability classification, the Q-System developed by Barton et al. (1974) and updated in 1994. The relationship between rock mass quality Q and the associated rock reinforcement

Table 1: Correlating Morgan's TPLs to Q-system rock classes and FRS performance

Ground condition		Standard deflection criteria			High deflection criteria	
					Indicative dosage (kg/m^3) of high-performance fiber	
TPL	Rock class	EFNARC (Joules)	RDP$_{40mm}$ (Joules)	RDP$_{80mm}$ (Joules)	Structural Synthetic[*] Scanfibre CXO50/40SS	Steel[*] Scanfibre CHO65/35NB
IV	F	> 1400	> 560	> 840	11.5	55
	E	> 1000	> 400	> 600	9.0	40
III	D	> 700	> 280	> 420	7.5	27.5
II	C	> 500	> 200	> 300	6.5	20
I	B					
0	A	0	0	0	0	0

[*] Whether steel or synthetic, there is a large difference in performance depending on the precise fiber design.

measure is summarized in a single chart, which is often referred to as the "Barton chart." The Barton chart relates rock mass quality Q excavation dimensions and end use to recommend bolt length, spacing, and shotcrete thickness (plain or steel fiber-reinforced).

The Template Method by Morgan, Chen, and Beaupré (1990) does not provide any guide for the use of SFRS or toughness characteristics required for tunnel or mine drive linings. Morgan (1998) does provide some insight into the use of SFRS, however, according to his toughness performance template for certain applications using Toughness Performance Level (TPL), as follows:

- TPL IV–Appropriate for situations involving severe ground movement with an expectation of cracking of the SFRS lining, which squeezes ground in tunnels and mines, where additional support in the form of rock bolts, and/or cable bolts may be required;
- TPL III–Suitable for relatively stable rock in hard rock mines or tunnels where relatively low rock stress and movement is expected and the potential for cracking of the SFRS lining is expected to be minor; and
- TPL II–Should be used where the potential for stress- and movement-induced cracking is considered low (or the consequences of such cracking are not severe), and where the fiber is providing mainly thermal and shrinkage crack control and perhaps some enhanced impact resistance.

4. Linking Q values and FRS panel test results

The deficiency of the Norwegian design approach is that, although the thickness of the SFRS is given, there is no toughness requirement indicated. With the wide range in performance for different fibers (Clements 1996, Bernard 1999), the SFRS generically expressed in the Barton chart could range in toughness from 400 to 1400+ J of energy absorption based on the EFNARC panel test (1996). Given the structural requirements of the SFRS, this is not satisfactory.

Based on the description of the ground conditions applicable to the different TPLs given by Morgan (1998) and the author's own experience, a correlation between the description of ground conditions and the different rock classes was developed, as shown in Columns 1 and 2 of Table 1. Morgan's TPLs are based on ASTM C1018 beam tests but, as outlined in Section 2, results from panel tests are preferred for shotcrete assessment. For this reason, the EFNARC panel-based toughness performance recommendations were developed (Column 3, Table 1) based on Morgan's values of TPL and published performance data. For these EFNARC toughness ranges, the most suitable fiber type and dosage can be estimated by taking into account an appropriate fiber rebound of, say, a maximum of 20% for wet process and possibly 40% for dry process.

With the broad acceptance of the RDP test, the author used Bernard's correlation to EFNARC results to give the RDP values (Column 4, Table 1). The values from Column 4, Table 1 are shown directly on a modified Barton chart (Figure 1). It should be noted that the modifications evident on this chart are intended to provide guidance on the required toughness of FRS and do not alter the original format for support recommendations in any way.

5. Industry Specification of FRS

The established broad relationship between rock quality value Q and FRS toughness was checked by collecting data from 14 metalliferous mines in Australia regarding their use of FRS. All of the mines either presently or previously used shotcrete or FRS within their operations, with use varying from full production-cycle shotcrete to random campaigns.

The toughness of the FRS had not been specified in any of the cases analyzed. In operations where a large volume of FRS was used, the type (or general description) and dosage of the fiber were generally specified based on previous testing programs and/or experiences. The toughness of the FRS used was determined by relating the characteristics of the concrete mixture, fiber type, and dosage to test results in the public domain.

The estimated EFNARC energy absorption ranged from 500 J for minor weakness zones and for sealing of sound rock in areas unlikely to experience deformation to 1400+ J in rock subject to high stresses, potential strain bursting, and areas likely to experience large deformations.

Shotcrete thicknesses were generally specified for the various applications and ranged from a low of 30 mm up to 125 mm, with the typical range being from 50 to 75 mm. The thickness was normally deemed to be a "nominal" thickness. For less demanding, low-toughness shotcrete, the minimum thickness was usually 50 mm. For high-toughness shotcrete, 75 mm was typical, but in one case, a multilayer treatment of 75 mm plus 50 mm was used.

Of the 14 mines, all used some form of rock mass classification, ranging from the determination of RQD to estimate Q, intermittent determination of Q, formal determinations of Q, RMR (Bieniawski 1999), to MRMR (Laubscher 1990). Eleven of the 14 mines were able to provide some measure of Q or a range of Qs for their rock types.

Even though Q-values were commonly determined for the various rock masses, the Barton chart was rarely used for support determination. Some mines perceived that it inadequately catered for "mining-induced stresses," while, in contrast, others considered it too conservative.

In all cases, the span or height/ESR value on the left axis of the Barton chart was less than 3, and higher-toughness shotcrete was used as the value of rock mass Q reduced. Numerous FRS applications were in Area 1 of the chart; that is, no support was necessary.

These results verified the toughness levels in the "modified Barton chart" (Figure 1), but also led to the following conclusions:

- In areas of anticipated "significant" deformation, seismicity, or potential strain burst, a minimum energy absorption capacity of 1000 J should be used based on EFNARC panel tests (1996). In extreme cases, this should be 1400 J;
- Wherever possible, always bolt through the FRS;
- Shotcrete or FRS may be required in areas designated as "unsupported" in the Barton chart due to "mining-induced stresses"; and
- Unreinforced shotcrete is an effective measure for controlling scats and replacing mesh used for this purpose. However, the bond strength should be considered and, if likely to be very weak or if the ground is subject to minor deformation, post-bolted FRS should be used.

Table 2: Fiber properties

Property	Steel	SSF
Specific gravity	7.85	0.9 to 0.91
Strength (MPa)	300 to 1800	130 to 690
Elastic modulus (10^3 MPa)	200	3.4 to 4.8

6. Structural Synthetic Fibers

Large-diameter (0.5 to 1.0 mm) structural synthetic fibers (SSF) are typically manufactured from polypropylene and, while quite similar in size to steel fibers, tend to vary significantly in other regards (Table 2). As a crack in concrete opens, the strain is distributed over the length of the fiber between anchorages. Steel fiber has a high elastic modulus and hence, the extension and crack opening is small even though the load is carried along the fiber's entire length (approximately 50 mm).

The typical dosage rate of structural synthetic fibers to achieve similar deflection control to that of steel fiber is approximately 1:4 by weight or 2:1 by volume. With an e-modulus only 1/50th that of steel, the SSF must anchor over 1/25th of the length of a steel fiber to give the same deflection control. Hence, SSFs are deformed to give high mechanical bond and anchorage over approximately 2 mm. In effect, the better the anchorage, the higher the performance. Steel fiber anchored in the same way would lead to brittle failure at low deflections due to fiber breakage.

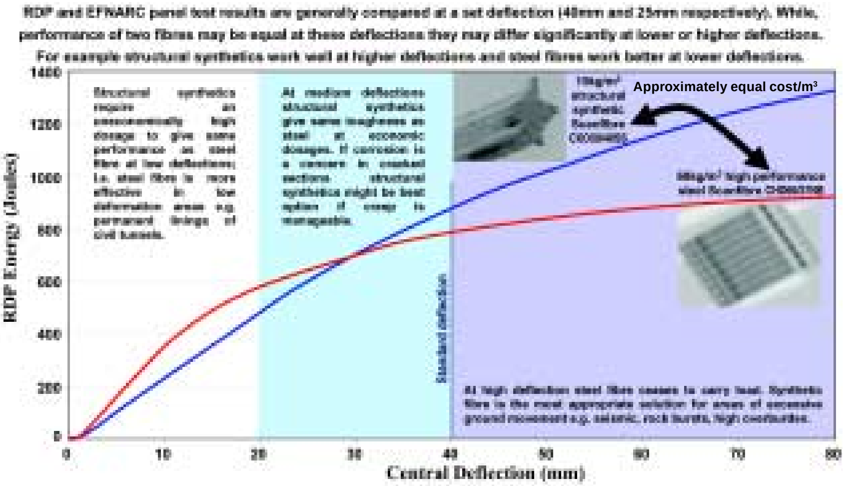

Figure 2: Performance as a function of deflection.

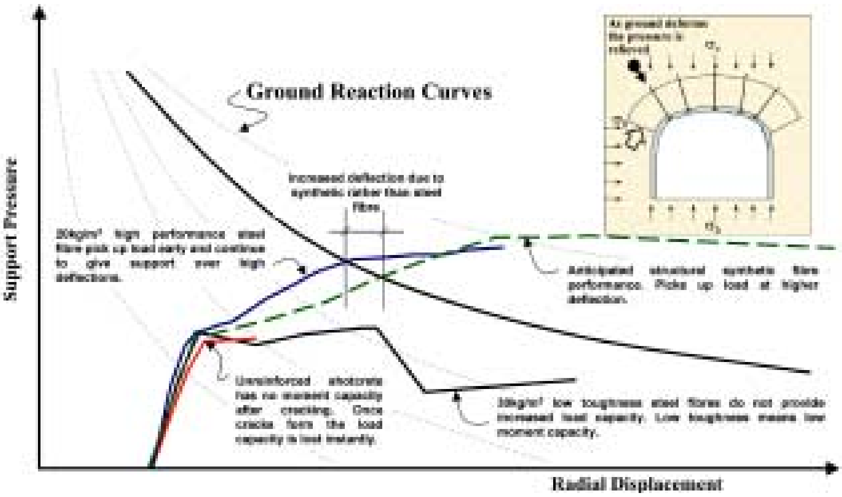

Figure 3: Interaction of the ground lining and support to show point of stability.

Table 3: RDP test results

RDP		Fiber dosage (kg/m^3)			Approximate
Deflection (mm)	Energy (Joules)	Steel		SSF	crack width (mm)
		HP$_{HD}$	HP$_{LD}$		
10	160	16	22	10	4
40	550	42	42	10	16
80	740	48	46	10	32

Table 4: Tests on 3 m x 3 m x 150-mm slabs

	Load (kN)	
	Maximum	1st crack
Plain concrete	200	180
6-mm bar @ 200 c/c top	320	200
6-mm bars @ 200 c/c top and bottom	380	280
20 kg HP$_{HD}$steel fiber	350	220
30 kg HP$_{HD}$steel fiber	> 345	290
20 kg LP$_{LC}$steel fiber	200	180

7. Performance Test on FRS

RDP energy absorbed-versus-deflection test results are shown in Figure 2 for fiber dosages of approximately equal cost per cubic meter of concrete. While the performance is similar at approximately the standard deflection, it is not similar across the entire deflection range. Table 3 compares the results for two "high performance at high deflection" (HPHD) steel fibers with a SSF dosed at 10 kg/m^3. Considering that the SSF fiber is around 4 times the cost/kg of these steel fibers, it is clearly uncompetitive in low-deflection situations and very competitive in high-deflection situations.

In Figure 2, energy absorption of the steel fiber shotcrete has stopped increasing at approximately 40 mm of deflection. It is important to recognize that this means that the load supported has dropped to zero. The SSFs, however, are continuing to carry load.

8. Ground/Support Interaction

Figure 3 shows a schematic of a load-displacement curve for ground moving in and a lining taking up the load in a tunnel. The lining resistance for low-toughness and high-toughness steel fibers are based on full-scale floor panel tests (Falkner 1993), which can be considered an upside-down tunnel. Additional results are shown in Table 4.

Stability occurs (Figure 3) when the ground pressure and the lining resistance meet. The "low-performance low-cost" (LPLC) fiber does not increase load capacity (also shown in Table 4), but it does increase the potential for stability in low-deflection situations, albeit at much higher deflections than the high-toughness steel fiber. Similarly, the theoretical support reaction for structural synthetic fiber shows a higher potential for stability than high-performance steel fiber. However, in low-ground movement situations, the deflection for stability would be higher. Table 3 shows that increasing toughness, by changing from a low-performance to a high-performance fiber at the same dosage or by increasing the dosage of high-performance fiber, has a major impact on load carrying capacity. This capacity comes at significant deflection due to moment redistribution in the system.

9. What RDP Criteria?

The performance of FRS must be specified by energy or residual strength at a given deflection. Deflection must be determined by the application.

Low deflection–Where cracking is of concern, RDP performance criteria should be stated for 10-mm deflection as:

- At this deflection, crack widths are becoming large (approximately 4 mm). A lower deflection might be recommended if sufficient supporting data becomes available; and
- There is excellent correlation with F_{e3} beam test results, and these are used for slab on ground criteria where crack control is also important.

Cracking is an issue in relation to waterproofing, corrosion of steel fibers, and aesthetics of civil structures. At such low deflections, SSF will be uneconomical compared to steel. It might also be that low-unit cost steel fibers perform better than steel fibers designed for high deflection.

For low-deflection situations, the required moment of resistance should be calculated and the moment capacity assessed using equivalent flexural strength (F_{e3}) for the cracked section and concrete flexural strength for the uncracked section. The relationship between RDP$_{10\ mm}$ results and JSCE F_{e3} strengths (Table 5) can be used for specification.

High deflection–Where high deflections are permitted, structural synthetic fiber can provide the load capacity without corrosion and at a lower cost/m^3 than steel fiber. As these fibers continue to carry increasing load at RDP$_{80mm}$, it would seem reasonable to use an 80-mm deflection criterion. Many laboratories are unable to test to such high deflections, however, and 40 mm may be the most appropriate criterion for some projects.

RDP energy absorption values given in Column 4, Figure 1, and Table 1 are for 40-mm deflection. It might be appropriate to increase the RDP$_{40mm}$ values by 50% for an 80-mm deflection criterion (this is consistent with the increase in SSF performance) for projects where high deflection criteria are more appropriate. These are shown in Column 5 of Table 1. Columns 6 and 7 give indicative dosages of high-performance fibers to achieve the given performance.

10. Conclusions

Toughness is the defining characteristic of fiber-reinforced shotcrete. There are many toughness test methods available internationally, but the Round Determinate Panel test overcomes the reliability problems found with other standardized panel tests and beam tests.

The Barton chart is widely used to assess ground conditions but its support recommendations do not include a toughness requirement. Guidance is provided to correct this deficiency.

Two deflection criteria are suggested for interpreting RDP results—that is, 10 and 80 mm—for situations where crack widths must be limited and areas where high deflections are allowed, respectively. Where deflection must be limited, calculated flexural strength requirements (F_{e3}) can be converted to 10-mm RDP values for specifications. Steel fibers will generally prove more economical than SSF at low deflections.

Where high deflection is allowable, the method suggested in this paper is proposed as a link between 80-mm RDP values and the Barton chart. SSFs will generally be more economical and, except for temporary works, are considered the only acceptable fiber due to the potential of corrosion of steel fibers in wide cracks.

Acknowledgments

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Table 5: Performance for low-deflection situations

F_{e3} (MPa)	RDP$_{10mm}$ (Joules)	Indicative dosage (kg/m^3) of high-performance fiber	
		CK050/40SS	CH065/35NB
2	150	9.5	15
3	200	13	25
4	250	18	37.5
5	300	—	50
6	350	—	60

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Measurement Conversions

1 in.	25.4 mm
1 MPa	145 psi
1 kg/m^3	1.685 lb/yd^3
1 kN	225 lbf