Design Guidelines For The Use Of Fibre Reinforced Shotcrete In Ground Support

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ABSTRACT: There are presently no design guidelines based on toughness for the use of Fibre 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 of the use of FRS in Australia and Canada, in various applications and ground conditions, are combined with existing empirically-based ground support design methods in order to develop a ground support guideline that incorporates the concept of toughness. An assessment of structural synthetic fibres shows that their low modulus makes their performance characteristics different to steel fibres such that they are not likely to be economic in linings where crack widths are limited but preferable where large deflections are permissible.

1 INTRODUCTION

Fibre Reinforced Shotcrete (FRS) has been used successfully for ground support for more than twenty years. However, 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 fibres introduces additional variables that are also not well understood.

The performance of FRS can be characterised using a variety of test methods taken from European, Japanese, and American Standards and, more recently, by a method developed in Australia. These tests characterise 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, i.e. ductility or "toughness". Extensive use of these tests to assess the ever increasing range of fibres available and the authors development of FRS specifications for a range of applications shows that:

- the performance of different fibres varies enormously
- many of the test methods give poor repeatability
- many tests are undertaken erroneously
- there are no criteria relating ground condition, insitu performance requirements and the physical properties of FRS

Field experience has shown that FRS is a safe, efficient, and economic 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 2-3mm on 300 to 450mm wide beams are common. This relates to crack widths of approximately 2mm. All current standard test methods have poor repeatability and reproducibility. With the high variability it is desirable to take the average result 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 authors experience is that fibre manufacturers market their products using the best results from tests over the life of the product leading to unrealistically and dangerously high expectations. These results are sometimes from laboratories that undertake the test believing it to be similar to 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.

The EFNARC panel test comprises a 600mm square 100mm thick panel supported on all edges. The centre point load vs deflection is measured and the energy absorbed is calculated. The standard performance criteria used is energy absorbed in Joules up to a deflection of 25mm. This equates to a surface crack width of around 5-10mm. The panel failure mechanism is representative of lining behaviour 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 non-uniform seating of samples. It was becoming the international method of assessing FRS until

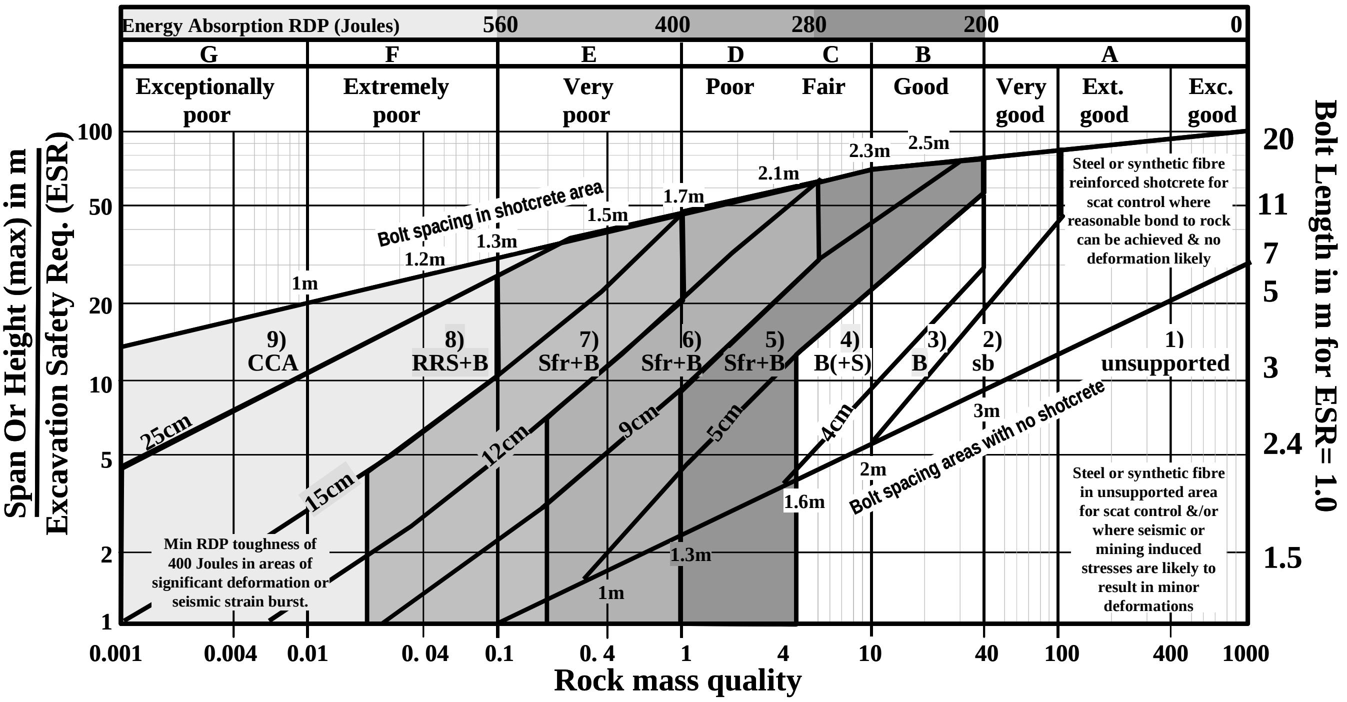


Figure 1 – Modified Barton Chart

the introduction of the Round Determinate Panel (RDP) test.

In the RDP test a 800mm diameter panel is supported on three points and the central point load vs deflection is measured. Energy absorbed is calculated and the result at a deflection of 40mm reported as the standard assessment. The developer, Bernard (2001) recognises 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. A r^2 correlation of 0.88 was found for:

$$\text{EFNARC}_{25\text{mm}} \text{ (Joules)} = 2.5 \times \text{RDP}_{40\text{mm}} \text{ (Joules)}$$

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 10mm deflection. An r^2 correlation of 0.82 was found for :

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

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 certified results provide a reliable assessment of fibre performance in concrete.

In all tests the deflection criteria is somewhat arbitrary. The panel tests were specifically developed for shotcrete assessment. Typically in NATM tunnelling methods it is accepted that large deflections need to occur to enable the ground to stabilize and take the load. This accounts for why such large deflections are quoted compared to 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 to underground openings is in determining the strength and deformation properties of the ground and matching it with the chosen support structure. Though a great deal of resources are utilised in trying to quantify the strength and deformation properties of the ground, and sophisticated modelling programs have been developed for analysing ground behaviour, there is presently no link between the behaviour of the ground and the reaction of thin FRS linings. As a decision regarding the FRS lining must be made 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 et al (1998) attempt to link FRS performance and ground condition.

The Norwegian Concrete Association “Sprayed Concrete for Rock Support” (1993) acknowledges that no documented design models exist incorporating the parameters of flexural tensile strength and toughness. It’s general design approach is based on the widely recognised 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 measure is summarised in a single chart, 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 fibre reinforced).

Table 1. Correlating Morgan’s TPL’s to Q-system rock classes & FRS performance

Ground Condition		Standard deflection criteria		High deflection criteria		
					Indicative dosage kg/m^3 of high performance fibre	
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 fibre design**

The Template Method by Morgan et al. (1990) does not provide any guide to the use of SFRS or toughness characteristics required for tunnel or mine drive linings. However, Morgan (1998) does provide some insight into the use of SFRS 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 for cracking of the SFRS lining, squeezing 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.
- 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 fibre is providing mainly thermal and shrinkage crack control and perhaps some enhanced impact resistance.

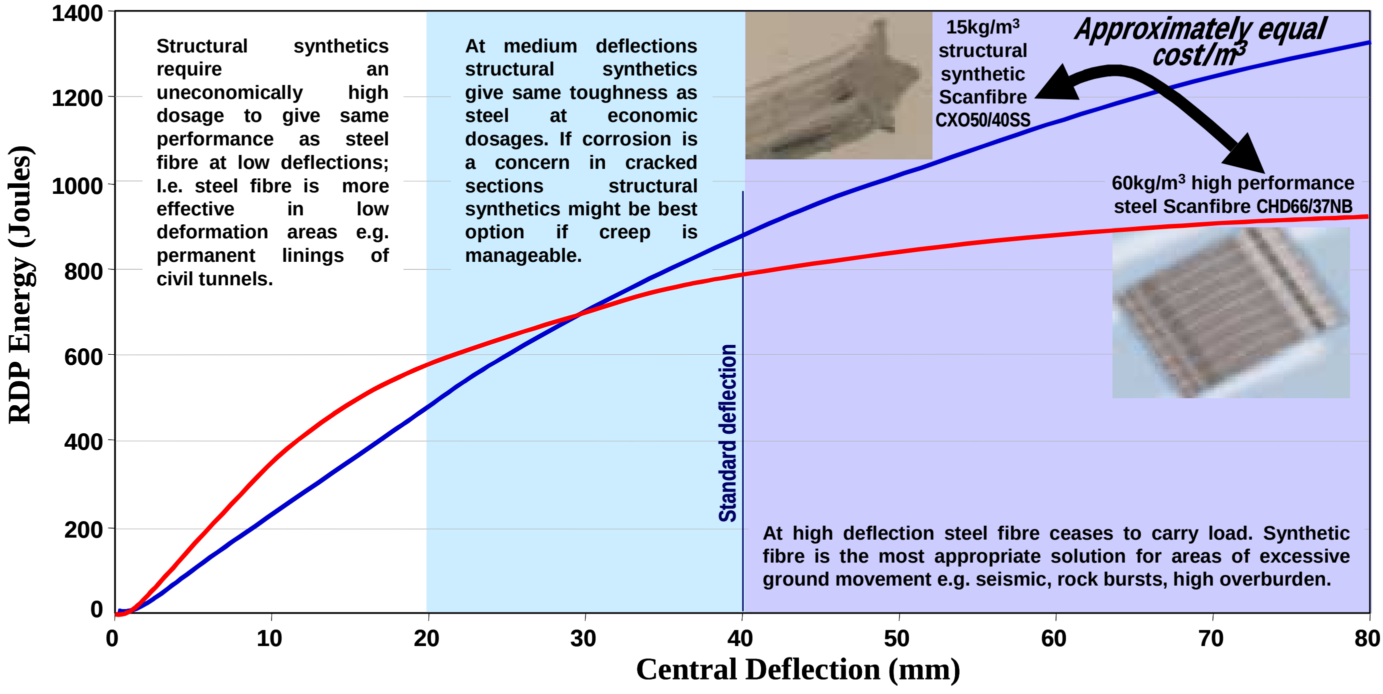
4 LINKING “Q” VALUES AND FRS PANEL TEST RESULTS

The deficiency with 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 fibres (Clements 1996, Bernard 1999) the SFRS generically expressed in the Barton chart could range in toughness from 400 to 1400+ Joule 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 TPL’s 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 & 2 of Table 1.

Morgan’s TPL’s are based on ASTM C1018 beam

RDP and EFNARC panel test results are generally compared at a set deflection (40mm and 25mm respectively). While, performance of two fibres may be equal at these deflections they may differ significantly at lower or higher deflections. For example structural synthetics work well at higher deflections and steel fibres work better at lower deflections.



Structural synthetics require an uneconomically high dosage to give same performance as steel fibre at low deflections; I.e. steel fibre is more effective in low deformation areas e.g. permanent linings of civil tunnels.

At medium deflections structural synthetics give same toughness as steel at economic dosages. If corrosion is a concern in cracked sections structural synthetics might be best option if creep is manageable.

At high deflection steel fibre ceases to carry load. Synthetic fibre is the most appropriate solution for areas of excessive ground movement e.g. seismic, rock bursts, high overburden.

Figure 2 Performance as a Function of Deflection

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 (col 3, Table 1), based on Morgan's values of TPL and published performance data. For these EFNARC toughness ranges, the most suitable fibre type and dosage can be estimated taking into account an appropriate fibre rebound of, say, maximum 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 (col 4, Table 1). The values from col 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 fourteen 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 analysed. In operations where a large volume of FRS was used, the type, (or general description) and dosage of the fibre was generally specified based on previous testing programs and/or experiences. The toughness of the FRS used was determined by relating the characteristic of the concrete mix, fibre type and dosage to test results in the public domain.

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

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

Of the fourteen 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) and MRMR (Laubscher, 1990). Eleven of the fourteen mines were able to provide some measure of Q or a range of Q's 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, i.e. no support necessary.

These results verified the toughness levels in the "modified Barton chat" (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 Joule should be used based on EFNARC panel tests (1996). In extreme cases this should be 1400 Joule.
- 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".
- Un-reinforced 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 the ground is subject to minor deformation, post-bolted FRS should be used.

6 STRUCTURAL SYNTHETIC FIBRES

Large diameter (0.5-1.0 mm) Structural Synthetic Fibres (SSF) are typically manufactured from polypropylene and, while quite similar in size to steel fibres, tend to vary significantly in other regards (Table 2).

As a crack in concrete opens, the strain is distributed over the length of the fibre between anchorages.

Steel fibre has a high elastic modulus and hence the extension and crack opening is small even though the load is carried along the fibres entire length (approx 50mm).

The typical dosage rate of structural synthetic fibres to achieve similar deflection control to steel fibre is approximately 1:4 by wt 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 fibre to give the same deflection control. Hence, SSF are deformed to give high mechanical bond and anchor-

Table 2. Fibre Properties

Property	Steel	SSF
Specific Gravity	7.85	0.9-0.91
Strength (MPa)	300-1800	130-690
Elastic Modulus (10^3 MPa)	200	3.4-4.8

age over approximately 2mm. In effect the better the anchorage the higher the performance. Steel fibre anchored in the same way would lead to brittle failure at low deflections due to fibre breakage.

7 PERFORMANCE TEST ON FRS

RDP energy absorbed vs deflection test results are shown in Figure 2 for fibre dosages of approximate equal cost per cubic metre of concrete. Whilst the performance is similar at around the standard deflection it is not similar across the entire deflection range. Table 3 compares the results for two “High Performance at High Deflection” (HP_{HD}) steel fibres with a SSF dosed at 10kg/m^3. Considering the SSF fibre is around 4 times the cost/kg of these steel fibres it is clearly uncompetitive in low deflection situations and very competitive in high deflection situations.

In Figure 2 energy absorption of the steel fibre shotcrete has stopped increasing at around 40mm deflection. It is important to recognize that this means that the load supported has dropped to zero. The SSF 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 fibres 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 lining resistance meet. The “Low Performance Low Cost” (LP_{LC}) fibre does not increase load capacity (also shown in table 4) but does increase the potential for stability in low deflection situations, albeit at much higher deflections than the high toughness steel fibre. Similarly the theoretical support reaction for structural synthetic fibre shows a higher potential for stability than high performance steel fibre. However, in low ground movement situations the deflection for stability would be higher.

Table 3 : RDP test Results

RDP		Fibre Dosage (kg/m^3)			Approx.
Defl. (mm)	Energy (Joules)	Steel		SSF	Crack Width
		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 3mx3mx150mm slabs

	Load (kN)	
	Max	1st crack
Plain Concrete	200	180
6mm bars @ 200c/c top	320	200
6mm bars @ 200c/c top & bottom	380	280
20kg HP_{HD} steel fibre	350	220
30kg HP_{HD} steel fibre	>345	290
20kg LP_{LC} steel fibre	200	180

Table 3 shows that increasing toughness, by changing from a low performance to a high performance fibre at the same dosage or by increasing the dosage of high performance fibre, 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.

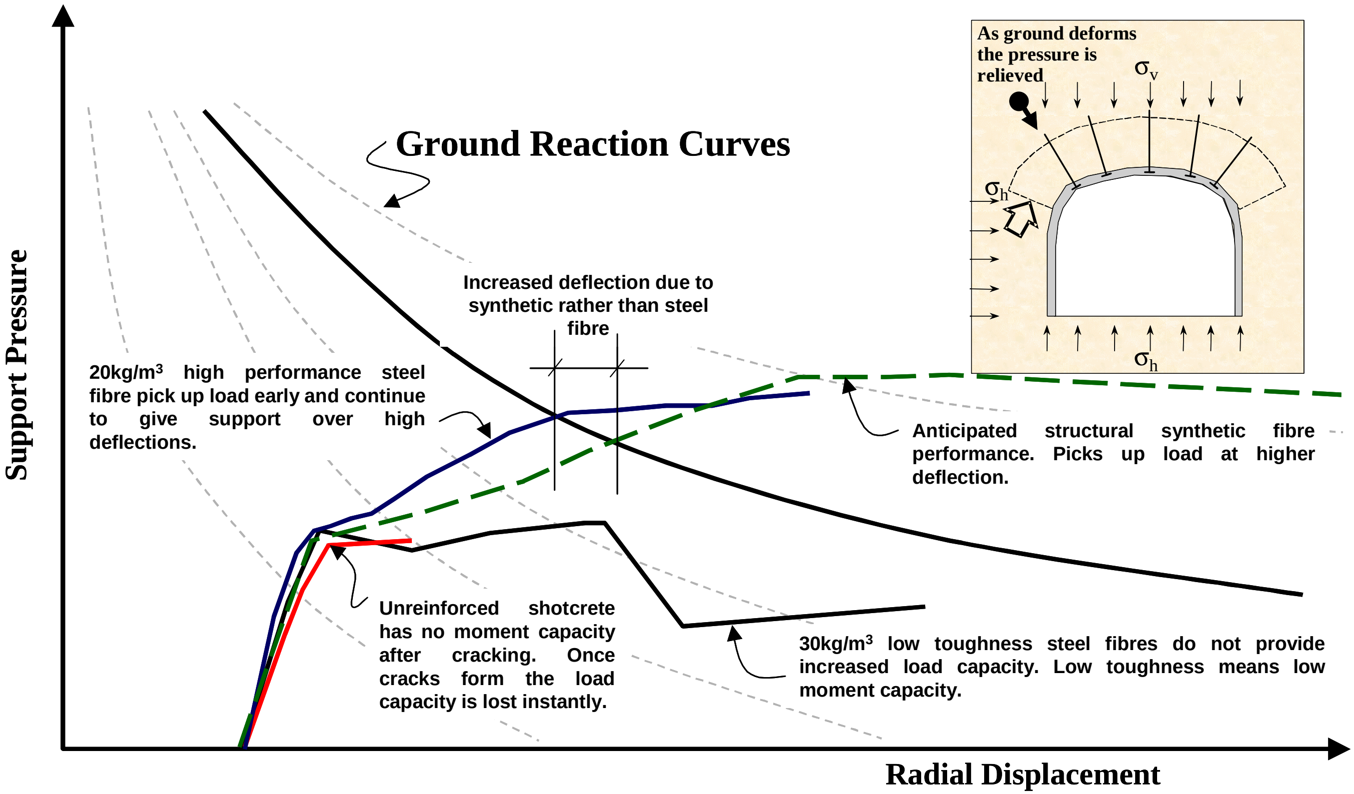


Figure 3 : Interaction of the ground lining and support to show point of stability

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

- At this deflection crack widths are becoming large (approx 4mm). A lower deflection might be recommended if sufficient supporting data becomes available
- There is excellent correlation with Fe3 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 fibres and aesthetics of civil structures. At such low deflections SSF will be uneconomic compared to steel. It might also be that low unit cost steel fibres perform better than steel fibres designed for high deflection.

For low deflections situations the moment of resistance required 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_{10mm} results and JSCE F_{e3} strengths (Table 5) can be used for specification.

High Deflection - Where high deflections are permitted structural synthetic fibre can provide the load capacity without corrosion and at a lower cost/m^3 than steel fibre. As these fibre continue to carry increasing load at RDP_{80mm} it would seem reasonable to use an 80mm deflection criteria. However, many laboratories are unable to tests to such high deflections and 40mm maybe the most appropriate criteria for some projects.

RDP energy absorption values given in column 4 Figure 1 and Table 1 are for 40mm deflection. It might be appropriate to increase the RDP_{40mm} values by 50% for 80 mm deflections criteria (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 & 7 give indicative dosages of high performance fibres to achieve the given performance.

10 CONCLUSIONS

Toughness is the defining characteristic of fibre reinforced shotcrete. There are many toughness test methods available internationally, but the Round Determinate Panel test overcomes reliability problems found with other standardised 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 i.e. 10mm and 80mm, for situations where crack widths must be limited and areas where high deflections are allowed respectively.

Table 5 – Performance For Low Deflection Situations

F_{e3} (MPa)	RDP_{10mm} (Joules)	Indicative dosage kg/m^3 of high performance fibre	
		CXO50/40SS	CHO65/35NB
2	150	9.5	15
3	200	13	25
4	250	18	37.5
5	300	-	50
6	350	-	60

Where deflection must be limited calculated flexural strength requirements (F_{e3}) can be converted to 10mm RDP values for specifications. Steel fibres will generally prove more economic than SSF at low deflections.

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

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