Specifying quality control measures for steel fibre reinforced concrete (SFRC)

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Introduction

Ensuring the quality and performance of steel fibres and ultimately the steel fibre reinforced concrete (SFRC) they reinforce is critical. The challenge faced by engineers involved in designing SFRC elements is to unambiguously specify the performance required, so as to achieve in the finished structure the performance that was assumed in design.

This article discusses the importance of specifying steel fibres that can guarantee a minimum level of quality and performance and through referencing international standards and guides, provides suggestions on quality control measures that could be implemented when setting up a production facility to manufacture SFRC.

Provided there is a good distribution of reliable quality steel fibres at close enough spacing, developing cracks in the concrete matrix are quickly cut off. If this is achieved crack growth will be resisted and localised stresses redistributed, thereby providing a ductile failure mode to an otherwise brittle concrete matrix. Compare this to conventional reinforced concrete, where, because steel wire or bar is straining over larger distances, visible cracking is a natural consequence of the reinforcement carrying significant loads.

Also, conventionally reinforced concrete design is carried out using the properties of the concrete and the properties and location of the steel. Compare this to steel fibre reinforced concrete where the properties of the steel fibres and concrete are not considered on their own, but rather as constituents in a composite material. The properties of this composite material have to be determined through laboratory based testing — an appreciation of test variation, quality control and statistics is paramount to ensuring the properties used in design accurately represent the insitu concrete for the project.

Performance criteria

The fibre dosage required to achieve an effective 3-D network will depend on the fibre length, tensile strength, anchorage, distribution and number of fibres per kilogram (fibre count). Designs are then carried out based on the toughness requirements of the SFRC.

There are some basic principles that should be used and the steel fibre dosage should satisfy all of the following criteria:

- Minimum dosage to achieve sufficient fibre overlap
- Dosage required to achieve minimum performance level according to EN 14889-1[1]
- Dosage based on project performance values

Minimum fibre dosage to achieve fibre overlap, based on spacing theory

With mesh it is generally accepted that in order to control crack widths the bars should not be too far apart. Crack widths are a function of the strain and hence stress in the bar, the concrete cover and the bar spacing.

The same can be said of fibre reinforcement. If fibres are too far apart there will tend to be insufficient overlap to ensure that a developing crack will not be able to find a path between the fibres. The general spacing theory recommendation given in Brite EuRam[2] and adopted in EN14487-1[3] suggests that the maximum average spacing between fibres should not exceed 45% of the fibre length with the spacing being determined from a formula provided by McKee[4]. For structural applications such as tunnel linings the average spacing is often decreased below the 45% value nominated above.

Average fibre spacing = [(volume of one fibre)/(volume fraction of fibres)]$^{1/3}$

Where:

Volume of one fibre = π x d2/4 x L for round/wire fibres

Fibre volume fraction = fibre dosage in kg/m^3 divided by the density of steel

= w (kg/m3) / 7850kg/m^3

Substituting the maximum fibre spacing (0.45L) into the above formulae and solving for w gives the minimum fibre dosage as:

$$w = (7850 \times \pi \times d2/4 \times L)/4/(0.45L)^3$$

Which can be expressed in terms of the aspect ratio of a steel fibre (L/d) as:

$$w = (7850 \times \pi)/4/0.453/(L/d)^2$$

Table 1: Minimum dosage based on steel fibres with different aspect ratios when s = 0.45 L

Aspect Ratio (L/d)	40	45	50	55	60	65	80
Minimum dosage (kg/m^3) when s = 0.45 L	43	34	28	23	19	16	10

Minimum fibre dosage according to EN 14889-1, system 1 for structural use

This is the only performance based quality control manufacturing standard for steel fibres. In addition to monitoring and controlling the fibre characteristics that influence the performance (length, diameter, tensile strength etc) in SFRC, manufacturers must also declare a fibre dosage to meet a nominated minimum level of performance (1.5MPa at 0.5mm CMOD, and 1.0MPa at 3.5mm CMOD). This information is detailed on a CE label and for the first time designers, concrete companies etc. are presented with an opportunity to compare the expected performance of different fibres at pre-tender stage.

There are two types of classification, system 1 for structural use and system 3 for non structural use. In all cases where post crack strength values are used in design steel fibres should conform to system 1 and manufacturers should supply a Certificate of Conformity and a copy of the CE label for the respective fibre. A 'Declaration' of Conformity is not an independent 3rd party assessment of the fibre quality and should not be accepted in lieu of a Certificate.

This compares to ASTM A820-6[5], another steel fibre manufacturing standard commonly specified in project documentation. This standard, however, has no requirement to provide a minimum dosage to meet a prescribed level of SFRC performance. Manufacturers don't have to declare the target values for fibre tensile strength, length and diameter and the sampling regimes are not as stringent as EN14889-1. More importantly, testing and conformity to this standard are not always 3rd party verified. This means that the market place has no way of determining and comparing what level of quality or performance different fibre types may have when manufactured in accordance with this standard.

Dosage based on performance; residual strength values or energy absorption

The performance (ductility, toughness) of SFRC can be specified either in terms of residual/equivalent flexural strengths or as energy absorption.

Residual/equivalent flexural strengths are measured on beams[6] and must be used when SFRC is to be used in a structural design model, such as when designing precast segmental linings. This is the only test type suitable for confirming or establishing material properties that can be used in structural design and as such is the performance test discussed in this paper.

The energy absorption value measured on a square panel[7] is used, in the case of rock bolting, when the emphasis is put on the amount of energy which has to be absorbed during the deformation of rock. This approach tries to simulate the behaviour of the in-situ SFRC and gives a good indication of the actual load carrying capacity and energy absorption that can be achieved in the composite material when the reinforcement works to redistribute the stresses in the parent concrete and thereby effectively increases the load carrying capacity and energy absorption of a sprayed concrete lining.

Energy absorption can also be calculated using a round panel test[8]. This test determines the energy absorption capability of the individual components of the composite, firstly for the uncracked concrete panel and then, subsequent to cracks forming, for the fibres bridging the cracks in the panel. As such it can be suitably employed as a quality control measure for steel fibre reinforced shotcrete/concrete.

High strength or high performance concrete

The tensile strength of the fibre must be consistent with that of the concrete matrix. If there is any uncertainty or lack of control on the upper limit of concrete strength, then a high carbon (>2000MPa tensile strength[9]) steel fibre should be considered.

An example of this is where through achieving the project concrete durability requirements the net effect is an increase of the concrete strength; such as pre-cast segments in some desalination plants. Further information should be sought from the steel fibre manufacturer.

Other Engineered Products

Other engineered products such as steel, concrete and LVL (Laminated Veneer Lumber) are all manufactured under a quality controlled process where the design properties are verified in the manufacturing facility and the published and codified values are used by engineers when carrying out structural design.

There are a series of quality control 'gates' set up to measure and control the manufacturing process. When a new product is being developed extensive performance testing is carried out initially which provides a large sample of data, this enables reliable statistical analysis of results and is used to determine material properties. These properties are typically characteristic (lower fifth percentile) and 'minimum' average values.

These results and the QC data will provide evidence that the manufacturing process is in control. Once this has been established, performance testing of the finished product will reduce and the results are added to a running tally of previous data.

The performance testing is used as an indication of manufacturing control only; the QC gates are used on a day to day basis to monitor and control production and to ensure material is manufactured within specification.

Characteristic values

When determining material properties it is assumed that the distribution of results will be approximately 'normal', so that a frequency distribution curve of a large number of sample results would be of the form shown in **Figure 1**.

A characteristic strength is taken as that value below which it is unlikely that more than 5pc of the results will fall[10]. Common student tables can be used to determine this value based on sample size and test variation.

Figure 1: Normal distribution of strength values

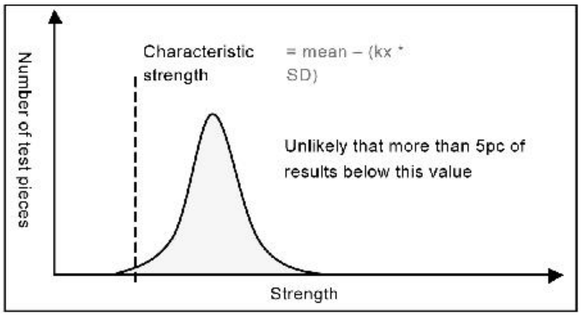
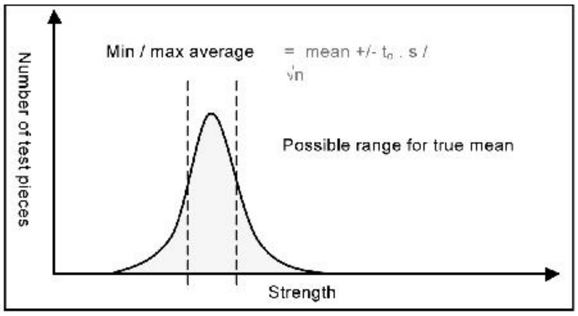


Figure 3: Mormal distribution of strength values

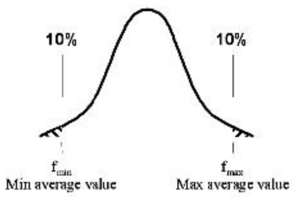


Minimum average values

The average value calculated in a sample is only an estimation of what the average will be in the whole population, in this case, all the SFRC the batching plant produces.

The size of this variation will depend on the number of units tested in the sample and the inherent standard deviation or coefficient of variation intrinsic to the nominated test method. For example, shown in **Figure 2** it is possible to see the number of units required in a test sample to achieve the same statistical accuracy (+ or — 10%) when the coefficient of variation of the test methods are different.

Figure 2: Distribution of average values for COV = 15pc & 30pc[12]



Coeff. of variation	s/av (%) =	15	
n	t90	fmin	fmax
3	1,886	0,84	1,16
4	1,638	0,88	1,12
5	1,533	0,9	1,1
6	1,476	0,91	1,09
7	1.44	0,92	1,08
8	1,415	0,92	1,08
9	1,397	0,93	1,07
10	1,383	0,93	1,07
11	1,372	0,94	1,06
12	1,363	0,94	1,06
13	1,356	0,94	1,06
14	1.35	0,95	1,05
15	1,345	0,95	1,05
20	1,328	0,96	1,04
30	1,311	0,96	1,04

RDP: min. 5
check if variation max. 15%

	s/av (%) =	30	
n	t90	fmin	fmax
3	1,886	0,67	1,33
4	1,638	0,75	1,25
5	1,533	0,79	1,21
6	1,476	0,82	1,18
7	1.44	0,84	1,16
8	1,415	0,85	1,15
9	1,397	0,86	1,14
10	1,383	0,87	1,13
11	1,372	0,88	1,12
12	1,363	0,88	1,12
13	1,356	0,89	1,11
14	1,35	0,89	1,11
15	1,345	0,9	1,1
20	1,328	0,91	1,09
30	1,311	0,93	1,07

Beams: min. 15
check if variation max. 30%

The minimum average (or true average) is a value that it is statistically unlikely that the average value will fall below, **Figure 3**. And as mentioned, is a function of the number of test pieces in the data set, the spread of results (COV) and a fractal taken from student tables such as the ones found in ISO 12491[11].

Both these values are influenced by the variability or scatter of test results and the number of test pieces in the sample. High variation & low number of test pieces = lower characteristic or average values.

What causes scatter?

The variability of the beam test has been discussed elsewhere, some references can be found at the end of this paper[12,13]. There are a number of different factors that can influence the variability of results, namely:

- Number of test pieces in a sample
- Fibre quality; consistent dimensions, tensile strength
- Ratio of fibre length to max aggregate size
- Batching and mixing
- Casting of test piece
- Size of test piece, cracked area
- Laboratory equipment and experience

Variability that can be controlled specifically through quality control is discussed further.

Number of tests

In Australia for large infrastructure projects it is common practice for ready mix companies, at tendering stage, to carry out limited testing (2 or 3 RDP panels, or 3 beams, sometimes less if a beam or panel are damaged) to confirm a fibre type and dosage to satisfy the design properties.

Statistically you can't derive properties on individual results and are penalised for small sample sizes. A consequence of this is that comparing the performance of two different SFRC mixes (same concrete strength, different fibres) can lead to grossly underestimating (or over estimating) the expected performance and it is entirely possible that two very different materials could show the same post crack strengths. This can lead to additional cost for the client if the fibre dosage has to be increased during production as test data builds.

Casting a beam

The method[14] used to cast beams for toughness testing can adversely influence results. Avoid using a small scoop to fill the beam mould, this can affect the fibre distribution and orientation and creates possible discontinuities in the mix. Sample straight into the mould preferably from a chute or conveyor or if this is not practically possible, into a large bucket which can fill the mould in one uninterrupted and consistent pouring action. Try to avoid rodding the mould to achieve compaction, rather, use external vibration.

Quality control

The philosophy should be to establish a manufacturing process for the SFRC that is in control, through setting up QC gates to measure aspects of production that will influence performance; such as checking the correct concrete constituents are being used, steel fibres are checked against CE labeling, concrete strength tests, fibre dosage and distribution etc. And to carry out enough initial beam tests to reliably establish and confirm the specification design values.

The following relate specifically to steel fibres and SFRC, similar specifications, quality control and testing should be established for the other concrete constituents and on the plain concrete; following national (or international) standards such as AS1012, AS1141 etc.

EN14487-1 Sprayed concrete, definitions, specifications and conformity

This is a good start for quality control measures for fibre reinforced concrete, it's specifically for shotcrete, but some of the sampling regimes could be applied for general SFRC production; Table 12 shows a particularly useful summary and is also included within some manufacturers literature[15].

Inspection of concrete constituents, steel fibres EN14889-1 Steel fibres for concrete

Steel fibres should comply with system 1 for structural use. CE label **and** Certificate of Conformity should be supplied to the project engineer and concrete plant.

The CE label which is attached to every pallet of product supplied to market can be used at the batching plant as part of their QC checks to ensure the correct fibre is being used. The CE label can also be used by the project engineer to ensure the minimum dosage has been satisfied and to compare the expected performance of different fibre types on offer at tender stage.

Dosing fibres

The fibres should be added in a controlled and traceable way. As such automatic dosing equipment is becoming widespread in Europe and in Australasia for tunnelling projects.

The equipment can be linked to the central batching system which allows accurate dosing and provides a record for QC documentation. A visual inspection is common practice to determine whether random distribution and the separation of collated fibres has been achieved.

Figure 4 shows two Incite dosing machines that can hold approximately 1500kg of steel fibre. When dosed using such a machine the fibres are typically supplied in 1000-1100kg bulk bags.

The one on the left has steel fibres and the one the right has micro synthetic fibres, both of which discharge the exact dose of fibres onto a conveyor belt leading to the hopper.

Figure 4: Incite dosing equipment

Steel fibre content

Various methods to determine fibre quantity in fresh or hardened concrete are well documented in several European standards[16] or guides[17], the most common of which relate to sprayed concrete but the same approach could be used for general SFRC production.

EN14487-1 defines[18] the type of structure into 3 categories, for example strengthening of the ground for a road or rail tunnel is classed as 'category 3'. This will influence the recommended minimum batch size for sampling. E.g. Every 100m3 of concrete for category 3 structures

Conformity is proven on the basis of measuring the fibre content of samples taken from the concrete mix used for production. This can be done by a wash-out test or magnetic separation of the steel fibres. **Table 2** suggests criteria for conformity.

It's important not to specify the project fibre dosage as a minimum dosage for this testing, because the only way to achieve this in absolute terms is to dose at a higher level for every batch of concrete produced.

Each test result, $\overline{m}_{SF,res}$, is derived from three partial test results, $m_{SF,i}$

Each partial test result is to be randomly taken from one batch of concrete and shall not be less than 10 litres (this is a change to the advice in EN 14721, which suggests 3 litres). The sample container shall be filled in one pour, directly from the mixer or from the conveying equipment.

The fibre dosage should be determined at least

- At the beginning of each production day
- After each interruption of the production
- After modifications or repairs of the production facility
- Once every *100m3(or as defined by the project engineer)*

Table 2: Conformity Control of the Steel fibre dosage[19]

production	quantity of n results in a row	criterion 1	criterion 2	criterion 3
		mean value of n test results $\overline{m}_{SF,n} = \frac{\sum_{1}^{n} m_{SF}}{n}$ kg/m³	each test result $\overline{m}_{SF,res} = \frac{\sum_{1}^{3} m_{SF,i}}{3}$ kg/m³	each partial test result $m_{SF,i}$ kg/m³
initial (< 35 results)	3	$\geq 0{,}90 \cdot m_{f,targ}$	$\geq 0{,}85 \cdot m_{f,targ}$	$\geq 0{,}80 \cdot m_{f,targ}$
continuous (≥ 35 results)	≥ 15	$\geq 0{,}95 \cdot m_{f,targ}$	$\geq 0{,}85 \cdot m_{f,targ}$	$\geq 0{,}80 \cdot m_{f,targ}$
$m_{f,targ}$: target fibre dosage				

Establishing/monitoring material properties

pre-production Initial Type Testing (ITT) & Quality Production Control (QPC)

Once the quality controlled manufacturing process has been established and is in order it's then possible to carry out Initial Type Testing (ITT) to establish or confirm the specified residual flexural strength values, these are then used as the basis to compare on-going quality production control (QPC) in conjunction with the quality control measures already discussed.

The minimum number of initial tests and at what frequency for on going testing are commonly debated topics. All things remaining equal, the larger the initial sample, the more reliable the results will be. One suggestion is:

(The statistics here come from ISO 12491 *Statistical methods for quality control of building material*, this and EN 1990 are the standards typically used as the basis for establishing and monitoring material properties of engineered building products.)

Initial type testing (ITT)

Minimum of 10 beams
Target sample variation (COV = standard deviation/average) should be ≤ 25%

Calculate characteristic value (lower 5%ile)

Calculate minimum average

Minimum average value

$\mu = x - t_o \cdot s / \sqrt{n}$

When:

μ = minimum average

x = sample mean

s = sample standard deviation

n = no of test pieces

t_o = from ISO 12491 table 3, when $t_p = 0.90$

Quality production control (QPC)

Individual results ≥ ITT 5%tile

Rolling min average of n = ITT test sample size ≥ ITT min average

Rolling COV of n = ITT test sample size ≤ 25%

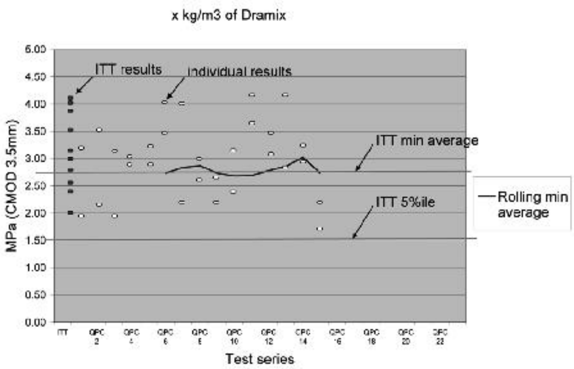
There are several different options that could be used for the frequency of this testing, for example:

- 2 beams every other day, with a rolling 10 results used to track the minimum average or
- 10 beams every 2 weeks, or other interval as decided by the project engineer

The advantage of testing beams every other day is that there is a constant check of individual results to compare against the ITT 5%tile limit.

Example of quality control graph tracking test results

Figure 3: QPC based on 2 beams per sample, tracked minimum average value based on rolling 10 QPC test results



From this example is can be seen that the minimum average value drops down slightly below the ITT min average, this should be a trigger to closely examine all other QC data, if it had continued to reduce significantly then further investigation would have been necessary. If the quality control gates are doing their job then it's possible that this slight reduction in performance had already been picked up and corrected before the beams were tested; for example, through a drop in fibre content.

ITT should be repeated if there is a significant change in constituent materials, composition, personal or equipment such as but not restricted to:

- higher water/cement ratio;
- aggregate type or supplier;
- maximum aggregate size;
- admixtures or additions;
- cement type, class or source;
- fibre type or supplier

Conclusion

- Setting up a quality controlled manufacturing process for SFRC is critical to ensuring the properties used in design are delivered to site
- A uniform fibre content and distribution is essential to ensuring reliable and consistent SFRC properties and the toughness performance, amongst other things, is correlated to the number of fibres bridging a crack[20]
- Carrying out limited testing at tender stage to determine fibre type and dosage can underestimate the actual performance of the SFRC
- EN14889-1 is currently the only performance based manufacturing standard for steel fibres. The CE label can be used by the engineer to compare the expected performance of different fibre types and by the pre-cast plant as a QC check to ensure the correct fibre is being used in production

Future outlook

New Zealand has provisions for SFRC in their NZS3101:2006[21] Concrete Structures Standard, this means engineers can consider this material under the framework of the NZ Building Code. At this stage Australia has no such provisions.

The steel and timber industry have comprehensive manufacturing standards for their respective products. These standards detail the quality controlled manufacturing process and provide guidance on how to determine AND monitor material strength properties.

In turn these properties are intimately linked to and published in the relevant national design Standards used by engineers. A similar approach for SFRC would ensure a clear and transparent link from published material strengths to design rules for engineers and, importantly, make certain there was a consistent quality controlled process for manufacturing this exciting engineered material.

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