2015

Fibre Reinforced Spray Concrete: Minimum Performance Requirement to Meet Safety Needs

Benoit de Rivaz
Bekaert Maccaferri Underground Solutions

Fibre Reinforced Spray Concrete:
Minimum Performance Requirement to Meet Safety Needs

Benoit de Rivaz[1]

[1] Bekaert Maccaferri Underground Solutions BVBA, SkylinE40, Korte Keppestraat 21/02, 9320 Erembodegem – Aalst, Belgium; PH: +32 53 43 10 10; Email: benoit.derivaz@bm-underground.com

ABSTRACT

To analyse the performance of fibre concrete, we must take into account the combination of fibre and concrete as a composite material, which means integrating the transfer of the concrete matrix charges to the fibres network. This transfer is schematically shown in three distinct steps, identified on the following graph:

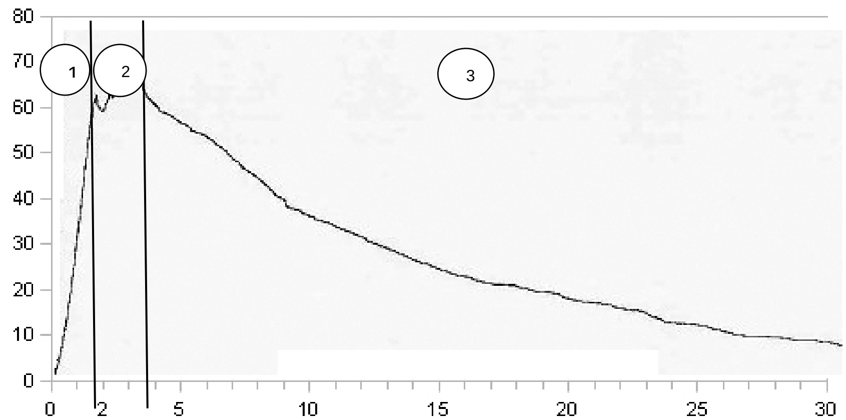

Figure 0 - Typical energy absorption curves

The European standard EN 14487-1 mentions the different ways of specifying the ductility of fibre reinforced sprayed concrete in terms of residual strength and energy absorption capacity. It also mentions that both ways are not exactly comparable.

However the different ways to check the energy absorption and residual strength are often less well known, and lead to confusion. The main purpose of this paper will be to offer an insight into the different main testing procedures (EN, ASTM) used for spray concrete projects.

This should help to answer the following questions: “which testing procedure, with which performance criteria, at which deformation?” and “for which spray concrete application and why?”

This paper will also present proposals based on the return of experience which aim to improve specifications of fibre reinforced sprayed concrete for underground support.

PAPER

Intro: TESTING FIBRE REINFORCED SPRAY CONCRETE

Multiple research studies and tests on the behavior of steel fibre reinforced concrete have been carried out in recent years in various countries. They have greatly contributed to a better characterization of Steel Fibre Reinforced Concrete (SFRC), and have thus allowed to gain a better understanding of the behavior of this material and to specify minimum performance requirements for each project.

This paper will present the material property determination using standardized testing methods and some improvement in the test procedure for sprayed concrete in order to:

- obtain a mechanical property to be used as input for the dimensioning method
- be in line with International recommendation as model code 2010, edited by FIB

European standard EN 14487-1 [1] mentions the different ways of specifying the ductility of fibre reinforced sprayed concrete in terms of residual strength and energy absorption capacity. It also mentions that both ways are not exactly comparable.

The energy absorption value measured on a panel can be prescribed when - in case of rock bolting - emphasis is put on energy which has to be absorbed during the deformation of the rock. This is especially useful for primary sprayed concrete linings (EN 14488-5: Testing sprayed concrete, part 5: Determination of energy absorption capacity of fibre reinforced slab specimens) [2].

The residual strength can be prescribed when the concrete characteristics are used in a structural design model.

The performance of steel fibre reinforced (SFRC) concrete can be tested in different ways. In this paper, two methods are described to evaluate the post-crack behaviour of SFRC.

1. EN14488-5 SQUARE PANEL TEST

Test Method Description

The plate test EN 14488-5 is designed to determine the absorbed energy from the load/deformation curve as a measure of toughness. The test is designed to model more realistically the biaxial bending that can occur in some applications, particularly in rock support. The central point load can also be considered to replicate a rock bolt anchorage. This test has proven to be of considerable benefit.

The square panel test, also called the EFNARC panel test, is simulating at a laboratory scale the structural behavior of the system anchor bolt - sprayed concrete under flexural and shear load.

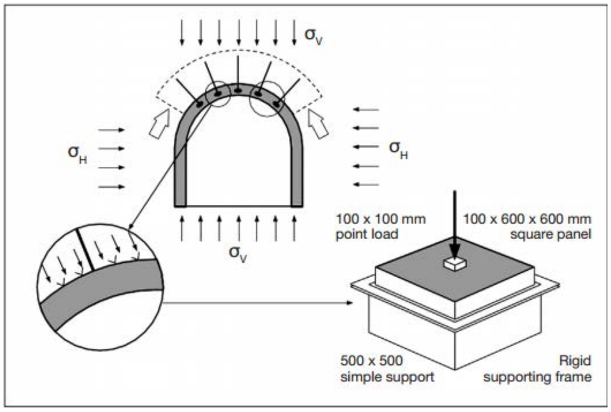

Figure 1: Sprayed concrete under flexural and shear load

This test allows to check the load bearing capacity for an imposed deformation and to control the capacity of absorbing energy under large deflections. Different reinforcement systems can be tested and compared and performance criteria can be established for different tunnel types and ground conditions. The panel test is much more appropriate than the beam test to determine the performance of SFRC (steel fibre reinforced sprayed concrete):

- ⇨ A panel corresponds much better with a real tunnel lining than a beam; the panel support on the 4 edges simulates the continuity of the sprayed concrete lining.
- ⇨ As in reality, steel fibres act in at least two directions and not just in one direction, which is the case in a beam test; the fibre reinforcing effect in a panel is very similar to the real behaviour of a SFRS lining.
- ⇨ SFRS can be compared very easily with a mesh reinforced sprayed concrete to be tested in the same way.
- ⇨ No numerical material properties, such as post-crack strength values, can be determined from the square panel test due to an irregular crack pattern; however this has never been the intention of this test method; this method serves to quantify and illustrate the ductile behaviour of a steel fibre reinforced sprayed concrete tunnel lining.

A fibre reinforced slab specimen is in this test subjected to a load, under deflection control, through a rigid steel block positioned at the centre of the slab. The load-deflection curve is recorded and the test is continued until a deflection of at least 30 mm is achieved at the centre point of the slab. From this curve, a second curve is calculated, giving the absorbed energy as a function of the slab deflection.

The slab specimens need to be prepared according to the regulations of EN14488-1.
A mould with inner dimensions 600 x 600 mm, and an inner height of 100 mm shall be positioned within 20° of the vertical (unless another orientation has been specified) and sprayed with the same equipment, operator, technique, layer thickness per pass and spraying distance as the actual work. Immediately after spraying the thickness of the concrete specimens shall be trimmed to a thickness of 100_0^{+5} mm.
In practise we should know, that we mainly directly spray in a panel 600*600*100 worldwide, which is the best and easier procedure.

The test (see Figure 2) shall be displacement controlled, with a constant rate of $1_{-0.1}^{+0.1}$ mm/min at the centre of the slab. The load and deflection shall be continuously recorded with the data logger of the XY-plotter until a deflection of at least 30 mm is obtained.

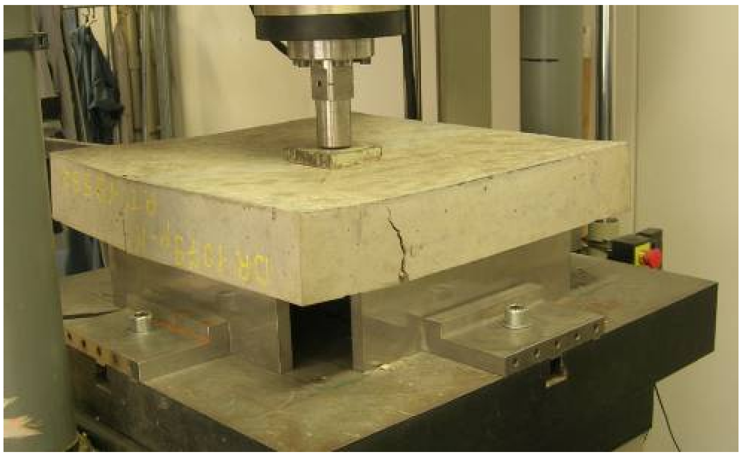

Figure 2: EN14488-5 Testing on steel support

The result that needs to be expressed is the energy absorption until a deflection of 25 mm is obtained, which can be calculated as the area under the load-deflection curve between 0 and 25 mm deflection. This procedure was established for steel fibre to compare the behaviour with steel mesh assuming a similar mode of failure.

The main performance criteria that can be applied for a reference concrete **C30/37** x are described in the EN 14 487. According to the geological and geotechnical context, it must be determined for each project. However, Asquapro guideline [3] provides the following indications:

Table 1: Specification for a classic concrete class C25/30 to C30/37 at 28 days

Application	**Minimum energy absorbing class**	**Energy absorption in J, for a 25 mm arrow**
Sprayed concrete acting as a <u>protective skin</u>, and for tough rocks / soils	E500	500
Sprayed concrete acting as a <u>resistant skin</u>, and for medium rocks / soils	E700	700

Beyond a C30/37, the energy values must be higher and the fracture ductility of concrete verified). Thus, for a C40/50 concrete, ASQUAPRO proposes the following requirements (table 2).

Table 2: Specification for a concrete class C40/50

Application	**Minimum energy absorbing class**	**Energy absorption in J, for a 25 mm arrow**
Sprayed concrete acting as a protective skin, and for tough rocks / soils	E800	800
Sprayed concrete acting as a resistant skin, and for medium rocks / soils	E1000	1000

The Barton's Chart introduces performance criteria for SFRC based on EN plate test only:

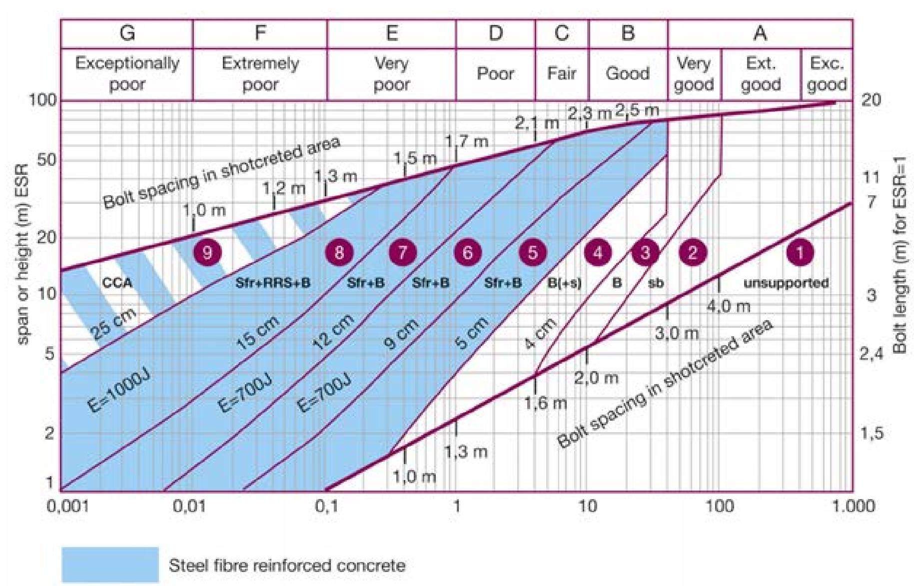

Figure 3: Barton Chart

Note: Concerning the Determinate round panel test = RDP TEST (ASTM 1550)

A central point load is imposed on a round specimen measuring 75 mm thick x 800 mm diameter, supported on three radial points located on a 750 mm diameter. The use of three pivoted supports ensures that load distribution **is always determinate**.

- There is no multi-crack, as the EN plate test (continuous support) does not allow any load redistribution
- There is no simulation at a laboratory scale of the structural behaviour of the system anchor bolt -sprayed concrete under flexural and shear load, as is the case with the EN plate test or Norway round plate test
- There is no correlation between the EN plate test in terms of energy absorption and the RDP test as we have between the Norway round plate test and EN plate test, both realized on continuous support. (We cannot compare a test with continuous support (Underterminal panel test with a test acting as a beam (Round Determinal Panel) test. We cannot compare different deflections at 25 mm Square Panel and 40 mm, even 80 mm RDP test.
- The deflection up to 5 mm central deflection is applicable to situations in which the material is required to hold cracks tightly closed at low levels of deformation. Examples include final linings in underground civil structures such as railway tunnels that may be required to remain water tight. The energy absorbed up to 40 mm is more applicable to situations in that the material is expected to suffer severe deformation in situ (for example, shotcrete linings in mine tunnels and temporary linings in swelling ground). Energy absorption up to intermediate values of central deflection can be specified in situations requiring performance at intermediate levels of deformation. A displacement of 40 mm is used to assess performance at high levels of deformation where large crack can be tolerated.
- 4omm deflection on RDP test mean 10mm crack opening (Model code 2010 refer at 0,5 mm for SLS and 2,5 mm for ULS)

Restrictive specifications for reinforced sprayed concrete for underground support [4]

The minimum recommendation for sprayed concrete is an absorbed energy value greater than 500J. The following graph shows that such a value can be obtained when the concrete matrix is of good quality, but it does not ensure good post-crack stress absorption (sharp drop and limited post-peak absorption).

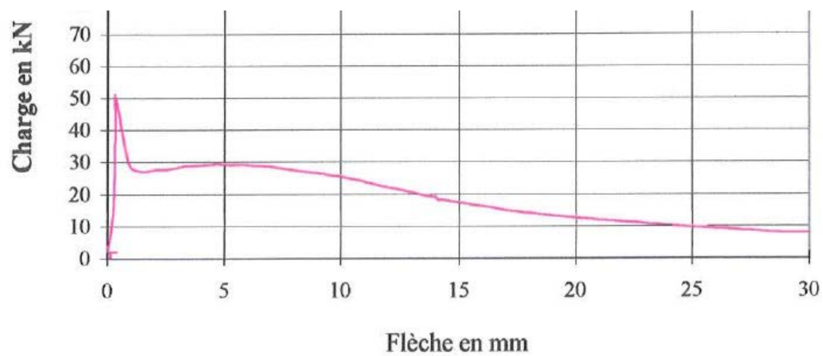

Figure 4: Unsatisfactory load-deflection curve in spite of 500J energy

However, a higher energy absorption value does not necessarily guarantee the appropriate behaviour for the substrate (cf. Figure 1 which represents a concrete that exceeds 800J). Consequently, ASQUAPRO [5] proposes to analyse each of the curves obtained according to the test in EN 14488-5 as follows (at least three curves per test):

1. The maximum load of the elastic zone ($F_{\textbf{el-max}}$) must correspond to a deflection value less than 2 mm.
2. The minimum load after cracking and up to a deflection equal to 5 mm must be greater than 70% of $F_{\textbf{el-max}}$.

Based on the study of a significant number of curves (conducted by test laboratory Sigma Béton), this 70% value seems appropriate to select quality concretes. It allows, for example, the concrete in Figure 4 to be rejected, in spite of its 500J energy.

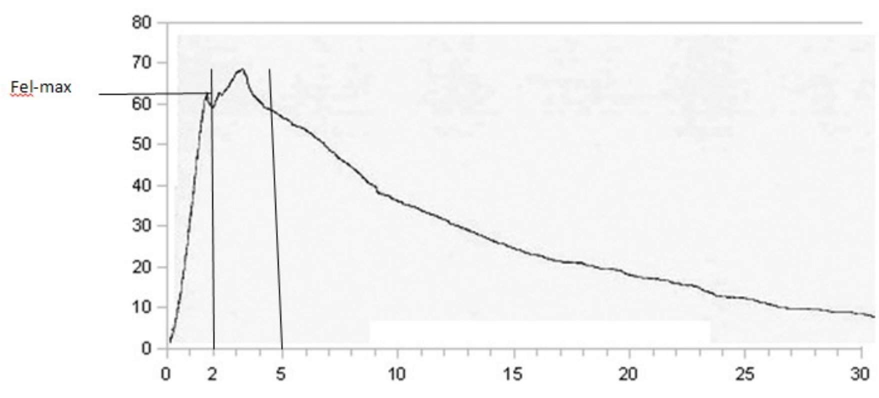

Figure 5: Typical energy absorption curves (xx: axes to be added)

Furthermore, ASQUAPRO also proposes to specify the following points (some of these are included in the requirements of the standard but are not always observed in practice):

- ⇨ Prepare 4 slabs for the energy absorption capacity test (3 + 1 back-up) to obtain average values over at least 3 test runs.
- ⇨ Strictly observe the thickness of the slabs: 10 cm, +5 mm, -0. If their thickness exceeds 10.5 cm, the slabs are rejected.
- ⇨ The slabs must still be whole after the test.
- ⇨ In addition to the customary requirements, the test reports must include photos of the interior sides of each slab after testing, possibly after water spraying to clearly reveal the multicracking phenomenon.

Criterion for conformity: three tested slabs should not exhibit any value less than the specified energy.

2. EFNARC THREE POINT BENDING TEST ON SQUARE PANELS WITH NOTCH

Test method description

A practical method to determine the tensile behaviour of SFRC for shotcrete applications is a 3-point bending test on square panels. This test combines the output of the EN14651 [7] with the advantages of the EN14488-5 test (the same moulds can be used and due to the larger cracked section, the scatter is lower).

Disadvantages are the weight of the specimens (EN14651 beams are more user friendly) and the attention that needs to be paid to finishing the sprayed surface in order to execute a perfect 3-point bending test. After all, the rollers need to be in contact with the concrete specimen over the whole length.

Figure 6: Three point bending test on square panel with notch

This test method is promoted by EFNARC [6] for the following main reasons:

- ⇨ The geometry and dimensions of the specimens, as well as the spray method adopted will ensure distribution of the fibres in the matrix, which is close as possible to that encountered in the real structure.
- ⇨ The dimensions of the test specimen will be acceptable for handling within a laboratory (no excessive weights or dimensions).
- ⇨ The test will be compatible, as far as the experimental means permit, with use in a large number of standard equipped laboratories (no unnecessary sophistication).
- ⇨ The geometry will be the same as in the plate test for Energy Absorption
- ⇨ The plate could be sprayed on the job site.
- ⇨ No need to sawn a prism from a panel which influences the result
  The notch will provide a slower cracking process, thereby reducing the risk of a sudden fall

By analogy with EN 14651, this test defines the residual flexural strength (fr1, fr3) according to the updated international standard (MODEL CODE 2010) [8]. The mechanical property obtained will serve as input for the dimensioning method.

The slab specimens need to be prepared according to the regulations of EN14488-1.
A mould with inner dimensions 600 x 600 mm, and an inner thickness of 100 mm shall be positioned within 20° of the vertical (unless another orientation has been specified) and sprayed with the same equipment, operator, technique, layer thickness per pass and spraying distance as the actual work.

Immediately after spraying, the thickness of the concrete specimens shall be trimmed to a 100_0^{+5} mm. It is very important to make sure that the spraying side of the specimen is perfectly flat, otherwise problems can be caused during testing.

This requirement is certainly the point to evaluate with more experience from job site and see the best practise to implement in the future.

We should use very good formwork and smoothen the upper surface immediately after spraying. This is a key requirement in order to:

- ⇨ get a perfect three point bending test, as the rollers should be in contact over the whole line with the specimens.

- ⇨ avoid problems in the beginning of the test to stabilize and end up with a perfect linear curve in the elastic part of the test (due to the roller/specimen contact, which is not constant).

- ⇨ avoid problems to control the test after the first crack.

Supports are stiff in one direction and moving in another one. The notches are made with a table saw. The flat surface, which is in contact with the mould is resting on the plate of the table saw. When the table saw is cutting in this way, the notch depth is not constant over the whole area, but this is not important. The section which is left, is constant in this way, and it is this value which is used during the calculations. To be even closer at the real value, we measure at the two sides, and take the average.

The testing machine should be capable of operating in a controlled manner, producing a constant rate of displacement (CMOD or deflection), and have a sufficient stiffness to avoid unstable zones in the load-CMOD curve or the load-deflection curve. A total stiffness of the system of 200 kN/mm (including frame, load cell, loading device and supports) is advised.

All rollers should be made of steel and have a circular cross section with a diameter of 30-1+1 mm. Two of the rollers, including the upper one, shall be capable of rotating freely around their axis and of being inclined in a plane perpendicular to the longitudinal axis of the test specimen. The distance between the centres of the supporting rollers shall be equal to 500-2+2 mm.

The load measuring device needs to have an accuracy op 0.1 kN and the linear displacement transducer an accuracy of 0.01 mm. The data recording system should be able to record load and displacement at a rate not less than 5 Hz.

In the case of a testing machine controlling the rate of increase of CMOD, the machine shall operate from the start of the test with a CMOD-increase of 0.05 mm/min and data logging at minimum 5 Hz. When CMOD = 0.19 mm, the machine shall operate at a CMOD-increase of 0.18 mm/min and a minimum data logging of 1 Hz. The test shall not be terminated before a CMOD value of 3.5 mm is obtained.

In case of controlling the increase of deflection, the machine shall start the test with a deflection increase of 0.06 mm/min with a data logging of minimum 5 Hz. When the deflection reaches 0.26 mm, the deflection increase shall be changed to 0.25 mm/min until a final deflection of 4.5 mm, and a data logging of minimum 1 Hz.
If the crack starts outside the notch, the test result should be rejected.

The test results which need to be expressed are the limit op proportionality (LOP) and the residual flexural strength (see Figure 13).
The limit of proportionality $f_{ct,L}^{f}$ is calculated as:

$$f_{ct,L}^{f} = \frac{3}{2} \cdot F_L \cdot \frac{l}{bh^2} \qquad (1)$$

where F_L is the maximum load between CMOD 0 and 0.05 mm or deflection 0 and 0.08 mm.
The residual flexural strength $f_{R,x}$ needs to be evaluated at four different displacements.

$$f_{R,i} = \frac{3}{2} \cdot F_{R,i} \cdot \frac{l}{bh^2} \qquad (2)$$

where $F_{R,i}$ is the residual load at:
- i = 1: CMOD = 0.46 mm or deflection 0.63 mm
- i = 2: CMOD = 1.38 mm or deflection 1.89 mm
- i = 3: CMOD = 2.30 mm or deflection 3.16 mm
- i = 4: CMOD = 3.22 mm or deflection 4.42 mm

l = the span between the supports (nominal distance 500 mm)
b = the width of the concrete sample (nominal value 150 mm)
h = the residual height of the concrete sample (nominal value 125 mm)

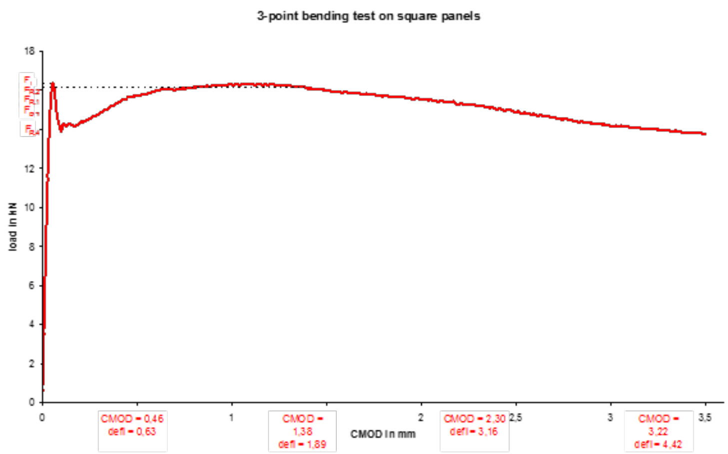

Figure 7: Load displacement curve of a 3-point bending test on square panels

The dimensions of the plates in a 3-point bending test on square panels are different than the dimensions of the beams in the EN14651 test. Because of this, the relation between the CMOD and the deflection is different as well.

Three definitions need to be taken into account (see also Figure 8):

- CMOD: crack mouth opening displacement: linear displacement measured at the bottom of the notch of the beam

- Deflection: linear displacement, measured by a transducer, between the bottom of the notch and the horizontal line which connects the points located in the middle of the beam, above the supports.

- CO: Crack opening: linear displacement measured at the top of the notch of the beam

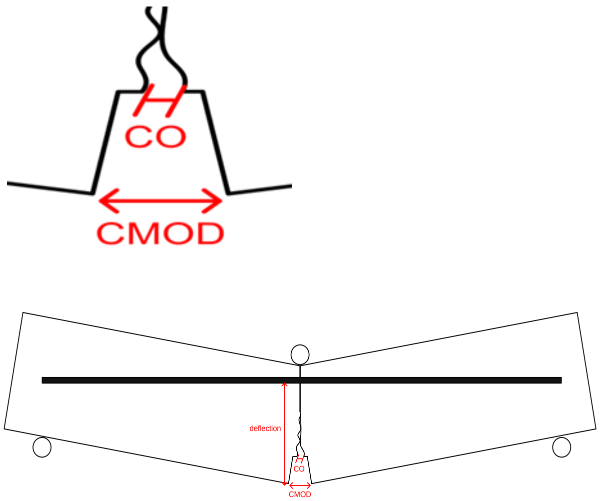

Figure 8: Definition of crack opening, CMOD and deflection

The purpose is to evaluate the 3-point bending test on square panels at the same crack opening as the EN14651 beam test. The next formulas approach the geometrical correlation between CMOD, deflection and crack opening:

$$crack\ opening = \frac{4 \cdot deflection \cdot (0{,}9 \cdot h)}{span} \qquad (3)$$

$$CMOD = \frac{4 \cdot deflection \cdot (0{,}9 \cdot h + notch\ depth)}{span} \qquad (4)$$

Where:

- span is the distance between the supports (nominal value 500 mm)
- h = the residual thickness of the concrete specimen (nominal 125 mm for the EN14651 beams and 90 mm for the square panels)
- notch depth is the depth of the saw cut (nominal 25 mm for the EN14651 beams and 10 mm for the square panels)

Table 3: correlation table between CMOD, crack opening and deflection

what	EN14651			3-point bending test on plates		
	CMOD	Deflection	crack opening	crack opening	Deflection	CMOD
	mm	mm	mm	mm	mm	mm
evaluation residual flexural strength	0,50	0,45	0,41	0,41	0,63	0,46
evaluation residual flexural strength	1,50	1,36	1,23	1,23	1,89	1,38
evaluation residual flexural strength	2,50	2,27	2,05	2,05	3,16	2,30
evaluation residual flexural strength	3,50	3,18	2,86	2,86	4,42	3,22

Test result and minimum performance requirement

The results of this test program conducted at Dalian University of Technology [9] are mentioned below:

The grade of the plain concrete was designed to be C30/37 on cast concrete.
The dosages of steel fibres type Dramix 3D 65/35BG were 20kg/m³ (SF20) to 30 kg/m³ (SF30) 40kg/m³ (SF 40), and the macro-synthetic fibre content was 6 kg/m³ (PP6).

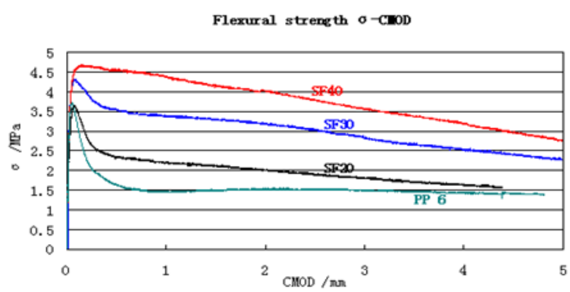

Figure 9: Comparison of flexural strength in the FRC compared to CMOD

The flexural strength was improved with the addition of fibres. Compared with the SF 20 mix, the flexural strengths of the SF 30 and SF40 mixes increased by 18.1% and 28.2%, respectively. A SFRC panel with greater fibre content indicates a higher load carrying capacity after the incidence of first cracking. The addition of fibres also helps the panels to maintain a better residual load carrying ability.

The flexural strength of the Macro synthetic fibre PP6 mix was similar to that of steel fibre SF20, but after first cracking the load bearing capacity of the PP6 mix dropped by about 60%. This means that the PP fibres have a lower influence on the residual strength than steel fibres. The addition of fibres can increase the energy-absorption capability of concrete panels and this benefit increases with an increase in the fibre content. The improvement in energy-absorption provided by the steel fibres is stronger than that of the macro-synthetic fibres in this trial.

The first draft of the New Model code, 2010, criterion is defined by fR1k/flk where:

- fR1k = characteristic residual strength at CMOD = 1.0mm and
- flk is characteristic flexural strength at first crack.

The draft of the code states that fibre reinforcement can substitute (also partially) conventional reinforcement at ultimate limit state if **fR1k/flk > 0.4**.

Test result example from job site

For the Violay Tunnel the requirement was 700 joules minimum at 25 mm considering a concrete class C30/37. The samples have been sprayed on the job site and tested in the Sigma Béton Laboratory.

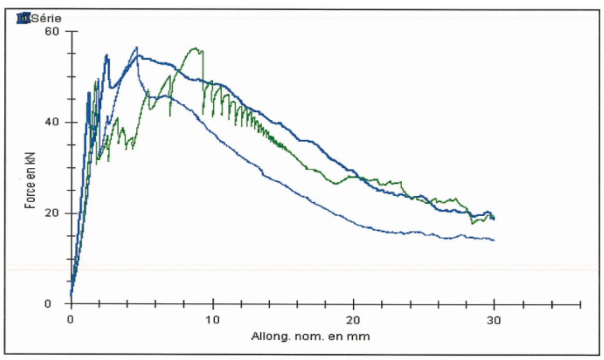

Figure 10: Dramix RC65/35BN 25kg/m³ Curve load –deflection –Sigma report

This curve also show that the Fmax (Load max) is always higher than Fl(first crack) which is a key parameter to follow. The load-displacement curve indicates that during the test several cracks are developed. The steel fibres bridging the cracks are generating a perfect load distribution. Once the peak has been reached and the maximum load redistribution effect has been realized, the fibres are being pulled out. Fibre shape and steel strength determine whether the fibres will break or preferably will be pulled out.

Main value three curve at 25mm => 875 Joules > **700 joules**

A specific additional test program was done during the prequalification procedure on job site in order to evaluate the **residual strength**.
For the residual strength the test method proposed is the three point bending test on a square panel with notch (EFNARC test procedure).

This test provides additional information about the material properties and allow to check if we meet minimum toughness required by main international standard at different deformation

The purpose of the different deformation levels is to give flexibility to the designers in the choice of the required deformation of the sprayed concrete under service conditions.
This test was also realized to check the performance criteria of polymer fibres versus steel fibres and the conformity with some minimum requirement.

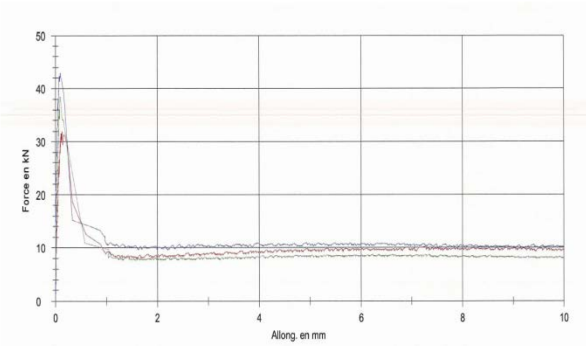

Figure 11: Curve Load –deflection with 6kg/m³ macro-polymer fibre

The Model Code, edited by FIB in 2010, states that fibre reinforcement can substitute (also partially) conventional reinforcement at ultimate limit state if fR1k/flk > 0.4.

Dramix steel fibres (anchorage with hook end, E module > 200 00 Mpa, tensile strength > 1300 MPa) play a positive role from the early age to hardening concrete.

Product specification

A new ISO 13270 standard has been published in 2013.

The new ISO standard is important for FRC for following reasons:

1. Reference document for steel fibres for concrete.
2. In countries where EN 14889-1 is not applicable, or in countries where no other national standard on fibres is issued, this ISO standard can be used.
3. National standard commissions can use the ISO 13270 standard as a blue print for the next national standard.

Some important points mentioned by this standard:

- Tolerances on diameter and length:
    - 2 classes are described: more relaxed class B, the same as EN 14889-1 standard, and more stringent class A

- Example of a fibre in class B:
    - Nominal length of 60 mm can be between 54 and 66 mm
    - Nominal diameter of 0,75mm can be between 0.666 and 0.825 mm.

- An L/D 80 fibre can be in reality a 65. (54/0,825) but according the ISO class B they can still call it an 80 class.

Therefor it is essential to stress the importance in specifying that the tolerances of the fibres must be according to class A.

This ISO standard also confirms the following : *Steel fibres are a suitable reinforcement material for concrete because they possess a thermal expansion coefficient equal to that of concrete, their Young's Modulus is at least 5 times higher than that of concrete and the creep of regular carbon steel fibres can only occur above 370 °C.*

CONCLUSION

All standards and methods of characterization are available to specify and check the minimum performance of the sprayed concrete reinforced with steel fibre in account Energy absorption, residual strength and creep requirement for each project.

Energy Absorption(EN14488-5) + Residual strength (EFNARC three point bending test on square panels with notch) obtained from a spray panel (600 mm,6000 mm,100 mm) will be easy, faster and cheaper to implement on the job site and provide a better quality control and material properties knowledge .

The choice of type of fibres and their dosing are determined by the project's performance requirements during the prequalification test and the proper understanding of the material properties.

REFERENCES

- "Testing Sprayed Concrete – Sampling fresh and hardened concrete". EN14488-1, April 17, 2005.
- "Testing sprayed concrete – part 5: Determination of energy absorption capacity of fibre reinforced slab specimens". EN14488-5, February 27, 2006.
- "Test method for metallic fibre concrete – measuring the flexural tensile strength (limit of proportionality (LOP), residual)". EN1461:2005, April 3rd, 2005.
- Larive C. "Restrictive specifications for reinforced sprayed concrete for underground support". World Tech Floor, 2013, Geneva, Asquapro.
- Asquapro. "Use of fibres in the reinforcement of sprayed concretes for tunnels temporary support".
- Efnarc. "Three point bending test on square panel with notch".

- FIB. Model Code, 2010.Prof. Ding. “Investigation of fibre influence on the mechanic behavior and post-crack behavior/toughness of notched steel fibre and PP-fibre reinforced concrete”. Panel Institute of Structural Engineering, Dalian University of Technology, May 27, 2009.