FIBRE SPRAYED CONCRETE RELEVANT TEST OF CHARACTERIZATION FOR DESIGN

PRÜFUNG VON FASERSPRITZBETON ZUR ERMITTLUNG VON BEMESSUNGSGRÖSSEN

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

This article 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

In den vergangenen Jahren wurden in vielen Ländern zahlreiche Untersuchungen und Prüfungen bezüglich des Verhaltens von Stahlfaserbeton durchgeführt. Diese Untersuchungen haben entscheidend dazu beigetragen den Stahlfaserbeton besser zu beschreiben. Dadurch konnte ein besseres Verständnis für das Verhalten dieses Material erlangt werden und die Erstellung von Leistungsanforderungen für spezifische Einsätze wurde möglich.

Der vorliegende Beitrag beschäftigt sich mit der Ermittlung von Materialeigenschaften mit Hilfe von Standardprüfungen und einigen Verbesserungen in der Prüfdurchführung für Faserspritzbeton, die:

- *dazu dienen mechanische Eigenschaften zu ermitteln, die als Grundlage für statische Berechnungen geeignet sind und*
- *im Einklang mit internationalen Empfehlungen, wie dem Model Code 2010, herausgegeben von der FIB, sind.*

1. Introduction

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). [3]

The residual strength can be prescribed when the concrete characteristics are used in a structural design model (EN 14488-3: Testing sprayed concrete, part 3: Flexural strengths of fibre reinforced beam specimens) [8].

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.

2. EN14488-5 square panel test

In order to check the structural behaviour of SFRS in a given construction a related test has been developed in France by the National Railway Company SNCF and Alpes Essais Laboratory.

This flexural – punching square slab test simulates very effectively the behaviour of a tunnel lining under rock pressure around an anchor bolt. This test procedure was part of the AFTES recommendation “Fibre reinforced sprayed concrete technology and practice“, edited in 1994 [9].

This test slab is also published in the EFNARC Recommendations and is included in the European standard EN 14 487 for sprayed concrete since 2006.

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.

Norwegian practice is according to EN 14488-1 to spray a panel 1000 x 1000 and cut it to 600 x 600 before testing. Central European practice is to spray 600 x 600! If you read EN 14488-5 in combination with EN 14488-1 you should spray bigger one and cut the samples out of it.

In practise we should know, that we mainly directly spray in a panel 600 x 600 x 100 worldwide, which is the best and easier procedure .This should be modified in EN as it does not make sense any more to make a difference if we spray with and without robot.

The specimens need to be cured according to EN12390-2 [2]. They should be left in the moulds for at least 16 hours, but no longer than 3 days, protected against shock, vibration and dehydration at a temperature of 20_{-5}^{+5}°C.

After removal from the mould, until immediately before testing, they should be cured in water at a temperature of 20_{-2}^{+2} °C, or in a chamber at 20_{-2}^{+2} °C and a relative humidity of minimum 95 %. Regular checks should be made to ensure that the surfaces of the specimens in the chamber are continuously wet.

Loss of moisture and deviations from the required temperature should be avoided at all stages of transport, by, for example, packing the hardened specimens in wet sand, wet sawdust or wet clothes, or transporting them in sealed plastic bags containing water.

According to EN14488-5, testing of these specimens shall normally be performed at 28 days on a machine that can test in a displacement controlled way, and has a minimum stiffness of at least 200 kN/mm (including frame, load cell, loading block and support frame). A calibrated electronic transducer with a resolution of at least 0.02 mm is required to measure the central slab deflection, as well as an electronic data logger or an XY-plotter to record the load-deflection curve.

The support is a rigid square frame of 20_{-1}^{+1} mm thickness and with inner dimensions 500_{-2}^{+2} x 500_{-2}^{+2} mm. Two possible examples are shown in Figure 1 and Figure 2. The smooth moulded side of the concrete slab is placed centrally on this support. The load is thus applied on the sprayed face of the slab with a rigid steel square block with a surface of 100_{-1}^{+1} x 100_{1}^{+1} mm, and a thickness of 20_{-1}^{+1} mm.

Figure 1: Support often used, but don't comply with EN

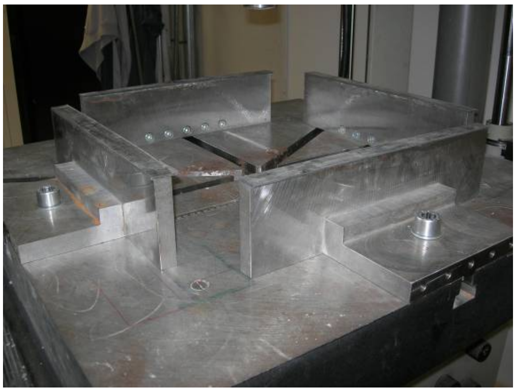

Figure 2: Support for EN14488-5 test

The test (see Figure 3) 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.

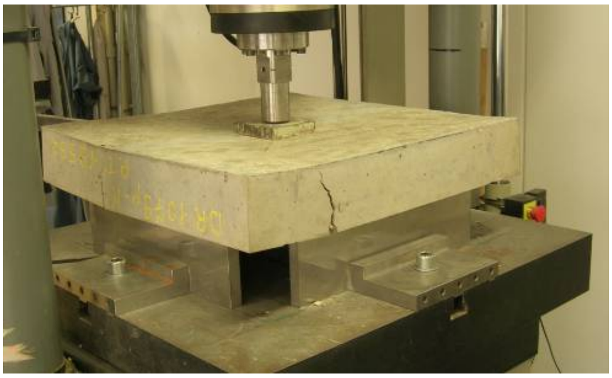

Figure 3 - EN14488-5 test

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 (see Figure 4).

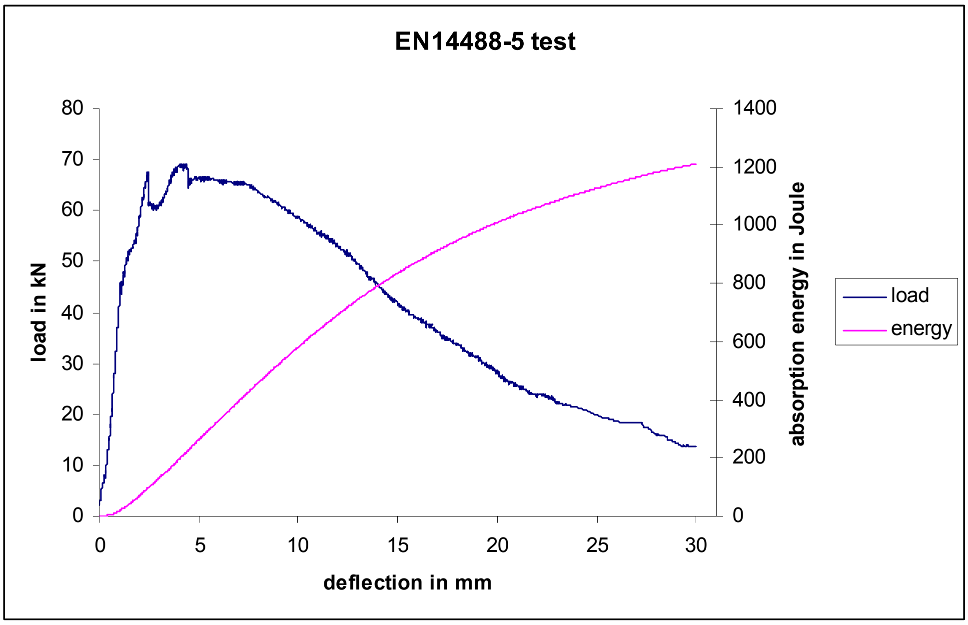

Figure 4: EN14488-5 load-deflection graph

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 are as follows (according to table 3, EN 14 487-1)

Table 1: Ductility classes according to EN 14487-1

DUCTILITY CLASS	ENERGY ABSORPTION IN JOULES FOR A DEFORMATION OF 25 mm
A	500
B	700
C	1000

If we increase the compressive strength, the performance requirement in Joules should be higher (fig. 5) in order to keep the same level of ductility and always $F_{max} > F_L$ (first crack).

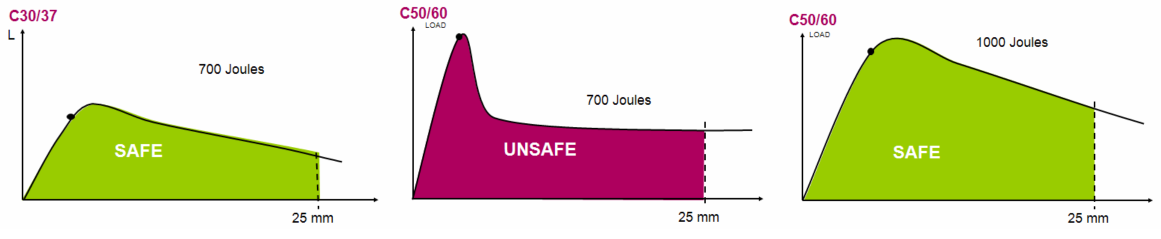

Figure 5: Examples for energy absorption results with FRC with low and high compressive strength

3. EFNARC three point bending test on square panels with notch [10]

3.1 Test method description

For the residual strength the test method proposed is a three point bending test on square panel with notch instead of the EN 14 488-3. This test combines the output of the EN14651 test (evaluate the tensile behaviour of SFRC) 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.

This test method is promoted by EFNARC 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 saw a prism from a panel which influences the result.
- The scatter will be lower than the current standardised beam test [10].
- 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 (f_{r1}, f_{r2}, f_{r3}, f_{r4}) according to the updated international standard (Rilem MODEL CODE). The mechanical property obtained will serve as input for the dimensioning method. [6]

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 smooth 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 specimens need to be cured according to EN12390-2. They should be left in the moulds for at least 16 hours, but no longer than 3 days, protected against shock, vibration and dehydration at a temperature of 20_{-5}^{+5} °C. After removal from the mould, the specimens shall be sawn through the specimen width at mid-span (see Figure 6).

The width of the notch shall be 5 mm or less, and the distance of h_{sp}, mentioned here, shall be 90_{-1}^{+1} mm.

The test specimens shall be cured for a minimum of 3 days after sawing until minimum 3 hours before testing, in water at a temperature of 20_{-2}^{+2} °C, or in a chamber at 20_{-2}^{+2} °C and a relative humidity of minimum 95 %. Regular checks should be made to ensure that the surfaces of the specimens in the chamber are continuously wet.

Loss of moisture and deviations from the required temperature should be avoided at all stages of transport, by, for example, packing the hardened specimens in wet sand, wet sawdust or wet clothes, or transporting them in sealed plastic bags containing water. Normally, testing shall be performed at 28 days.

Testing of the specimens is done in a 3-point bending test, but can be performed in two ways. In the first method, the crack (or notch) mouth opening displacement (CMOD) is measured, and a displacement transducer is mounted along the longitudinal axis at the mid-width of the test specimen. The distance between the bottom of the specimen and the line of measurement shall be less than 5 mm.

A second possibility is to measure the deflection instead of the CMOD. In that case a displacement transducer shall be mounted on a rigid frame that is fixed to the test specimen at mid-height over the supports. One end of the frame should be fixed to the specimen with a sliding fixture, and the other end with a rotating fixture. A thin plate fixed at one end can be placed at mid-width across the notch mouth at the point of measurement (see Figure 6).

The tests are preferably deflection controlled. To control the test with a CMOD, knives need to be glued next to the notch. It is possible that they come loose during the test due to a bad interlayer between the knives and the concrete. It is easier to mechanically fix the deflection transducer to the concrete specimens. Fewer test specimens and test results will be lost in this way.

Figure 6: 3-point bending test on square panels cast in situ test set-up

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 of proportionality (LOP) and the residual flexural strength (see Figure 7).
The limit of proportionality $f_{ct,L}^{f}$ is calculated as:

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

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.

$$f_{R,i} = \frac{3}{2} \cdot F_{R,i} \cdot \frac{l}{bh^2} \qquad (4)$$

where $F_{R,i}$ is the residual load according to EN 14 651 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)

NB : these value are corresponding to the beam EN 14 651

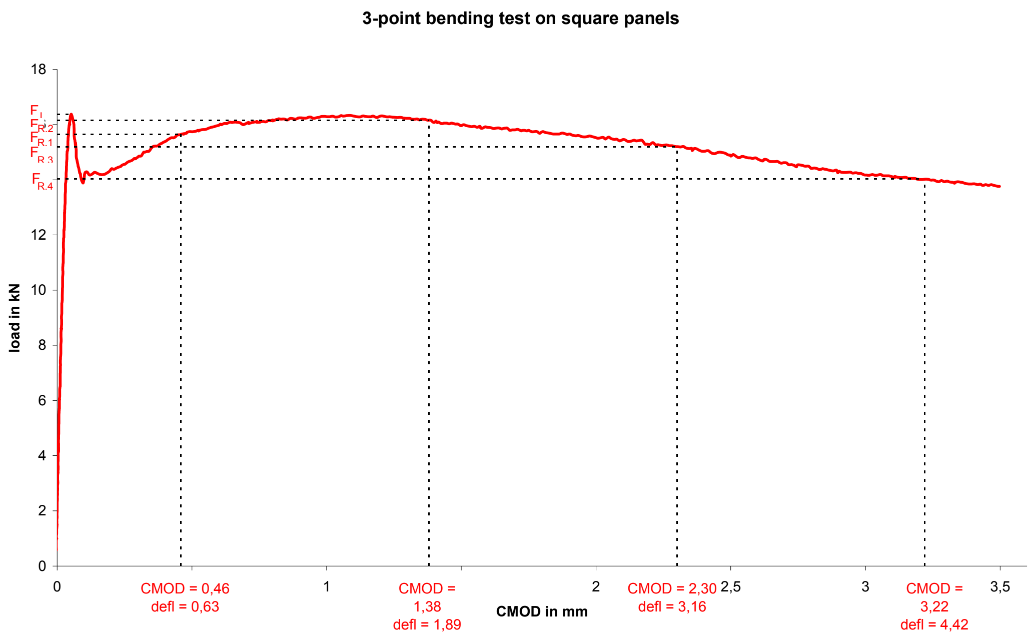

Figure 7 - Load-displacement curve of a 3-point bending test on square panels

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

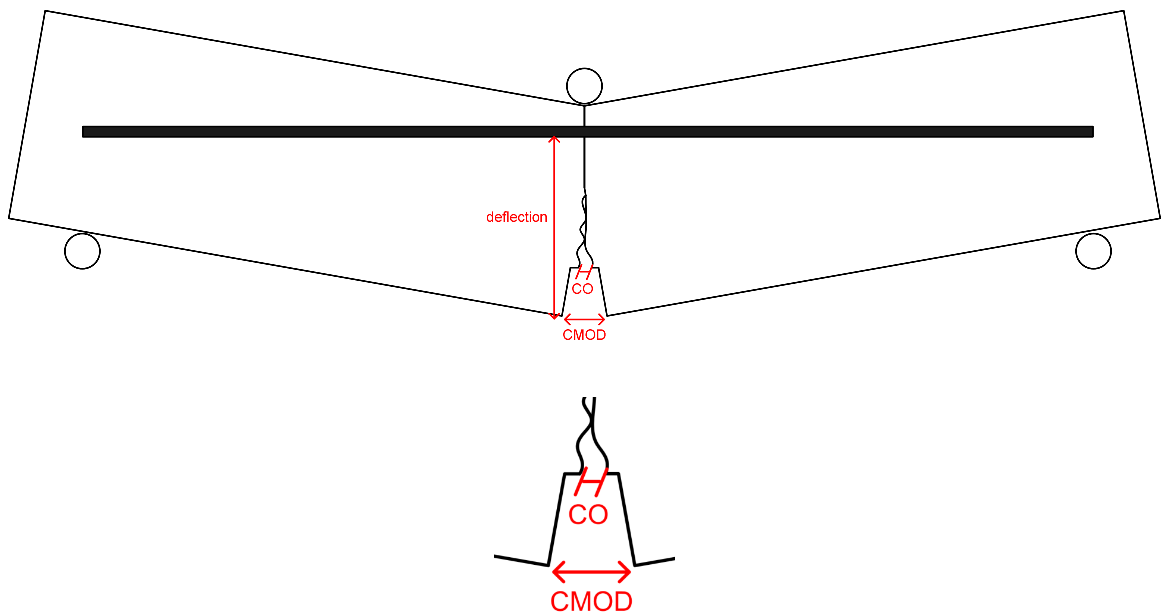

Figure 8: Definition of crack opening, CMOD and deflection

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:

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

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

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)

The above-mentioned formulas can be used to calculate the CMOD and deflection to evaluate the residual flexural strength in the 3-point bending test on square panels, as well as the testing speed and the test stop value.

The CMOD for changeover of the speed is 0.1 mm in the EN14651 test. The value of this point has been chosen as a function of the limit of proportionality. At 0.1 mm the CMOD will always exceed the deflection at the limit of proportionality.

Since the dimensions during the 3-point bending test on square panels are different, this point needs to be different as well. In this 3-point bending test on square panels, the load is

$$\frac{\frac{600.90^2}{500}}{\frac{150.125^2}{500}}$$ = 2.1 times higher than in a EN14651-test with the same f_L-value.

Therefore changeover of the speeds shall occur at a CMOD of 0.21 mm.

Table 2: Correlation table between CMOD and deflection

	Residual crack strength	CMOD (in mm)	Deflection (in mm)
EN14651 beam test	$f_{R,1}$	0.5	0.454
	$f_{R,2}$	1.5	1.364
	$f_{R,3}$	2.5	2.273
	$f_{R,4}$	3.5	3.182
3 point bending test on square panels with notch of 10 mm	$f_{R,1}$	0.5	0.631
	$f_{R,2}$	1.5	1.894
	$f_{R,3}$	2.5	3.156
	$f_{R,4}$	3.5	4.420

NOTE: The relation between crack opening, CMOD and deflection may be approximated by:

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

δ is the deflection, in millimetres;
CMOD is the *CMOD* value, in millimetres, measured at the bottom of the notch
h is the unnotched height of the specimen in millimetres

To evaluate the residual strength at the same crack openings as in EN14651, the loads need to be recorded at the CMODs or deflections which are mentioned in table 2.

3.2 Test result and minimum performance requirement

The results of this test program conducted at Dalian University of Technology [7] are as follows (Figures 9 to 11).

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

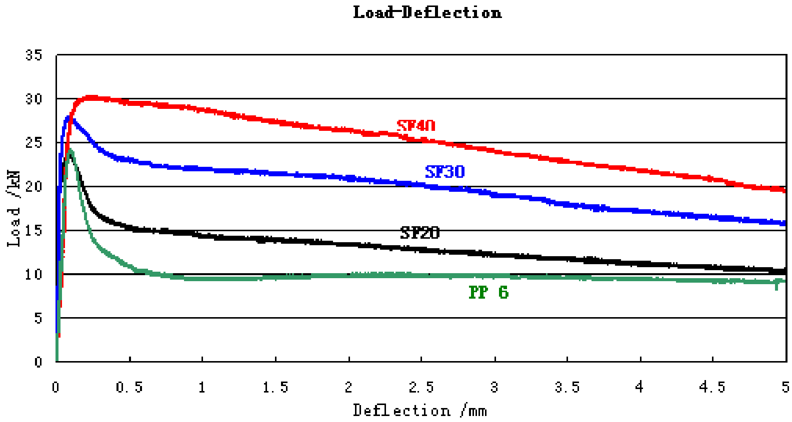

Figure 9: Comparison of Load-Deflection curves of FRC panels with different fibres. Each plot represents the mean result for each set of nine panels.[7]

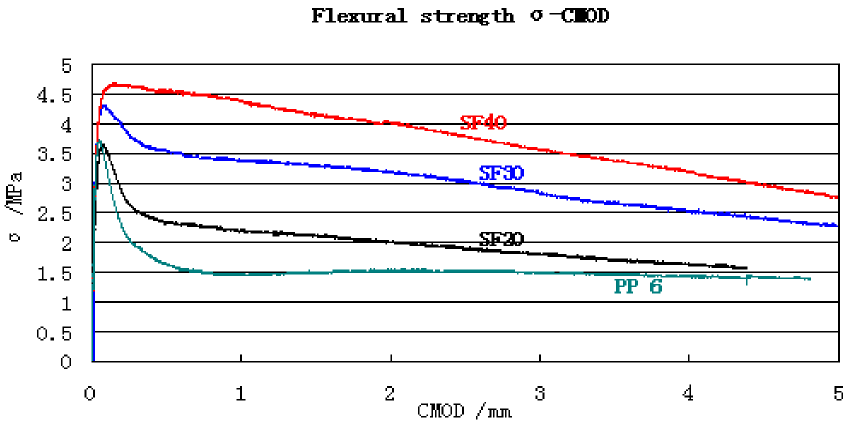

Figure 10: Comparison of flexural strength in the FRC compared to CMOD.[7]

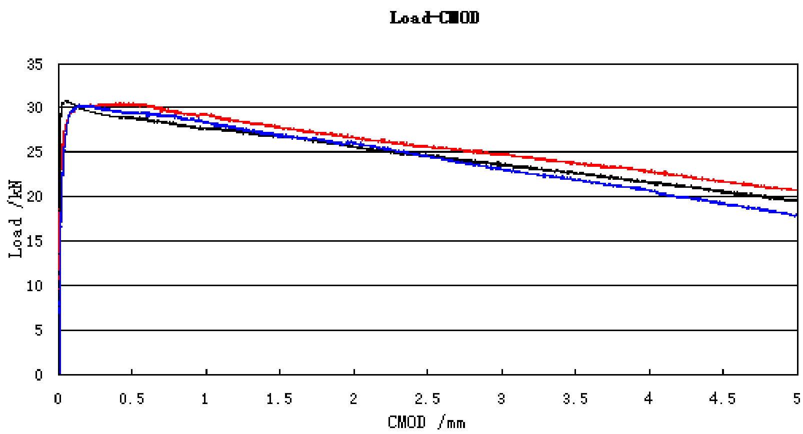

Figure 11: Three curves for PANEL with 40 kg/m^3 SF [7]

The flexural strength was improved with the addition of fibres. Compared with the SF20 mix, the flexural strengths of the SF30 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 PP6 mix was similar to that of 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 figure 11 is showing the law scatter with EFNARC three point bending test on square panel with notch with variation lower than 15 %. More investigation will be required to establish coefficient of variation but we have already noticed a positive effect on scatter of results if EN-beams are compared with panels, tested as EN-wide beams.

The first draft of the New Model code, 2010, criterion is defined by f_{R1k}/f_{lk} where f_{R1k} is the characteristic residual strength at CMOD equal to 1.0 mm and f_{lk} is the 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 $\mathbf{f_{r1k}/f_{lk} > 0.4}$. If we refer to the curve on the three point bending test, we can conclude that macro synthetic fibres often do not conform to the above standards of practice and cannot be used in concrete.

4. Conclusions

All standards and methods of characterisation 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 sprayed panel (600 x 600 x 100 mm) will be easier, 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.

5. References

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