



TUNNELLING APPLICATIONS: SHOTCRETE REINFORCEMENT

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UNDERGROUND SOLUTIONS



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INTRODUCTION

My aim is to familiarize the reader with the behaviour of steel fibre reinforced concrete (SFRC), to draw his attention to the specific characteristics of this product when applied as temporary reinforcement, underline the importance of the performance criteria described by the EN standard and propose a relevant technical solution to reach together a better quality and safety on each job site.

This text is meant primarily for those who are active in the construction market (clients, contractors, consulting engineers, construction firms), more specifically in the field of underground structures constructed by traditional method (NATM).

Initially, shotcrete was applied either plainly or reinforced with conventional reinforcing steel-welded meshes or even occasionally with chain link meshes. It was, however, not until the early seventies that the first

experimental work was undertaken with Steel Fibre Reinforced Shotcrete (SFRC).

SFRC is defined as a mortar or concrete, containing discontinuous discrete steel fibres, which are pneumatically projected at high velocity on to a surface.

Since then, SFRC has been used extensively in most of the world's industrialized nations, for a wide variety of applications. Uses of SFRC have varied from rock slope stabilization and underground support to structural rehabilitation.

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 characterization 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.

During the period 2005-2007, the European Standardization Organization CEN issued a large number of standards on sprayed concrete.

The publication of European standards specifically dealing with steel fibres, as well as the sprayed concrete application, allow to define performance criteria and to specify minimum relevant requirements for each project. Steel fibre, and especially Dramix® reinforced concrete, has been the reference for tunnel reinforcement for more than 25 years and will continue to be in the future.

Special thanks to Ann Lambrechts & Gan Cheng Chian for their constructive inputs.

1. Application Field

This document discusses design, test methods and application of sprayed concrete with Dramix® steel fibre concrete, more particularly when used in tunnels as temporary support.

This guideline can only be used for steel fibre reinforced shotcrete, and not for synthetic fibre concrete - with low modulus of Young ($E < 35 \text{ Gpa}$) - due to reasons described in "2.3.2.1 Energy absorption". The evaluation of the rock quality and associated design requirements are described in "3. System performance requirements".

2. Materials

2.1 Concrete

Concrete quality in accordance with EN 206, produced and delivered according to local concrete standards:

- Concrete quality: C30/37
- Maximum aggregate size: 12 mm.

The grading of aggregates will be in accordance with the applicable standards. Sprayed concrete mix design is determined by the same principles which apply to concrete mix design. The prime factors controlling strength and quality are the water/cement ratio, the grading of the aggregates and the degree of consolidation achieved.

There are however a number of design considerations in which sprayed concrete differs from conventional structural reinforced concrete. The major differences lie in the aggregate grading and the cementitious content of the sprayed concrete design.

The concrete composition must be engineered in order to obtain homogeneous distribution of the steel fibres and good finishing ability. For detailed information, please consult our recommendations on handling, dosing and mixing, as well as our product data sheets. ([available upon request](#))

The concrete class is always a compromise between many requirements:

- Durability
- Mini-compressive/tensile strength required by the project for demoulding, stacking, installation and service life of the ring
- No brittle failure to avoid spalling and bursting

Many projects require concrete that is situated around C50/60.

2.2 Steel fibres

Dramix® steel fibres are designed especially for the reinforcement of concrete. They are made of prime quality harddrawn steel wire to ensure high tensile strength at extreme close tolerances. Provided with hooked ends, they deliver optimum anchorage.

Minimum fibre recommendations for sprayed concrete in tunnel applications:

1. Fibres to comply with European standard EN 14889-1 and ISO 13270: minimum dosage (kg/m³) required per fibre type
2. Fibres with CE marking system 1, steel fibre for structural use (conform EN 14889-1- 2006) For more details, CE info sheet on request.

According to EN 14889, a minimum performance level must be reached. As such for every fibre type a minimum dosage is required to have CE marking system 1.

3. Fibres out of drawn wire, with a tensile strength of steel wire > 1.000 MPa min (The tensile strength of the wire must be consistent with that of the matrix, for High Performance Concrete (HPC) steel wire with a high tensile strength is required)
4. Dimensional tolerances in accordance with the table below:

Property	Symbol	Deviation of the individual value relative to the declared value	Deviation of the average value relative to the declared value
Length and developed height > 30 mm ≤ 30 mm	l, ld (if applicable)	± 10 %	± 5 % ± 1,5 mm
(Equivalent) diameter > 0,30 mm ≤ 0,30 mm	d	± 10 %	± 5 % ± 0,015 mm
Length/diameter ratio	λ	± 15 %	± 7,5 %

The length shall be measured with a marking gauge (accuracy of 0,1 mm). In an irregular cross section, the developed length of the fibre shall also be determined to calculate the equivalent diameter. Straightening of the fibre is necessary, it shall be done by hand or, if this is not possible, by hammering on a level of wood, plastic material or copper using a hammer or a similar tool. While straightening, the cross section must stay unchanged. The diameter of the fibre shall be measured with a micrometer, in two directions, approximately at right angles, to an accuracy of 0,01 mm. The fibre diameter shall be the mean of the two measured diameters.

5. Best anchoring system: hooked ends for optimum anchorage
6. Fibre length: in the range of 30-35 mm
7. Maximum fibre length: 2/3 of the hose diameter of the spraying machine
8. Minimum fibre length: 2 times the maximum coarse aggregate size
9. Glued fibres for improving homogeneous distribution

2.3 Steel fibre concrete

The performance of Dramix® reinforced concrete is mainly determined by the following characteristics:

- The performance of the fibre in the matrix (geometry, length/diameter ratio, method of anchorage, tensile strength, etc.)
- The performance of the concrete matrix
- The amount of fibres in the mix

In order to define the steel fibre concrete specification, a three steps analysis must be made.

1. Minimum dosage for a needed fibre overlap.
2. Minimum total fibre length.
3. Dosage based on performance:
 - Energy absorption
 - Residual strength

2.3.1 Minimum L/D ratio

According to the European standard EN 14487-1, the average distance (s) between steel fibres should be lower than 0,45 lf in order to ensure a minimum overlap between fibres.

The value for a minimum overlap between fibres may be estimated as: $s = \sqrt[3]{\frac{\pi \times d_f^2 \times l_f}{4\rho_f}}$

Where :

- l_f is the length of the fibre
- d_f is the equivalent diameter of the fibre
- ρ_f is the fibre percentage

s should be lower than 0,45 lf to ensure a minimum overlap

The formula and “s” limits are taken from the thesis of D.C. Mc Kee, University of Illinois, Urbana 1969:

“The properties of an expansive mortar reinforced with random wire fibres.”

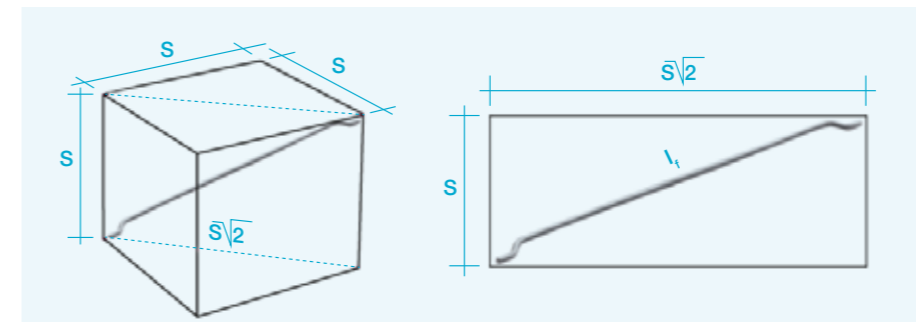


Fig. 1: Minimum dosage based on minimum total length

Aspect ratio (lf/df)	40	45	50	55	60	65
Min. dosage (kg/m ³) when s < 0,45 lf	43 kg/m ³	34	28	23	19	16 kg/m ³

Minimum dosages of steel fibres based on different aspect ratios and steel fibre spacing.

2.3.2 Minimum total fibre length in situ:

In addition to the requirement of the minimum overlap according to the Mc Kee theory, we also recommend a minimum total length of wire fibre.

Indeed, in order to ensure the minimum network effect to provide a specific multicrack process generating the redistribution of the loads through the crack-bridging steel, **we recommend a minimum steel fibre length per cubic meter concrete of 10.000 ml/m³.**

This recommendation is based on two decades of experience, during which a great number of analyses have been carried out, observed on the plate test described in the “2.3.3.1. Energy absorption”.

Aspect ratio: l/d (length/diameter)	Minimum kg/m ³ according to min. overlap	l	D	fibres/kg	Total fibre length
40	43 kg/m ³	30	0,75	9.000	11.610
65	20 kg/m ³	35	0,55	14.500	10.150

Example to reach three criteria: CE-minimum performance level, Mc Kee “2.3.1.” & minimum total fibre length “2.3.2.”

The crack pattern observed on the plate test (see “2.3.2”) should be as displayed:



Fig. 2: The crack pattern observed on the plate test

Back up to understand the behaviour of SFRC in real structures

Indeed, resistance to uniaxial tension is the most important mechanical characteristic to be taken into account when dimensioning structures in SFRC. However, this behaviour in tension is directly related to the cracking process of the material in the structure, subject to this tensile force. Therefore, it is worth summarizing this process very briefly. It consists of 3 stages:

- Step 1: **microcracking of the material** which corresponds to pseudo-elastic behaviour.
- Step 2: **local cracking which consists of the appearance of a macro-crack.**
The maximum tensile stress that the material can withstand is reached when one macro-crack develops (i.e. the tensile strength of the material).
- Step 3: **propagation of the macro-crack, one micro-crack opens.**

The fibres may play a role during these various cracking stages. Before the macro-cracks appear, the fibres will “join up” the microscopic cracks. By doing this, they delay the appearance of macro-cracks and increase the direct tensile strength of the material in the structure. Two factors are important in this first stage:

- The density of the microscopic cracks before they localize: the greater the number of micro-cracks, the higher the probability that the fibres will “encounter” these microscopic cracks, and thus the greater the action of these fibres on these microscopic cracks.
- The proportion of fibres (reasoning identical to the previous one).

The fibres are also able to join up macro-cracks during post-cracking behaviour. On one hand this limits crack opening in the structure at a given service load. On the other hand, it delays the failure of structure due to the appearance of collapse mechanisms (ultimate behaviour).

SFRC cracking in relation to the mechanical system

With the limit conditions and the applied stresses, a given structure will constitute a mechanical system. This system may be either isostatic or hyperstatic with a varying degree of hyperstaticity.

This multiple cracking process is noticeable in statically indeterminate structures with moderate steel fibre dosages (0,5% vol.). In a simple isostatic tensile or bending test, the multiple cracking process happens at more important dosages (typically > 2% vol. for axial tensile tests and > 0,5% vol. for flexural tensile test).

The higher the degree of hyperstaticity (as temporary support in tunnels), the greater the redistribution of the stresses and the higher the volume of material required for the structure. This results in a greater density of microcracks. The plate test is a hyperstatic test, close to the real structure observed in a sprayed concrete tunnel. The crack pattern of SFRC (with a great number of multi-cracks) guarantees a good behaviour and provides the safety required.

2.3.3 Performance criteria:

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.

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

The energy absorption value measured on a panel can be prescribed when - in case of rockbolting - emphasis is put on energy which has to be absorbed during the deformation of the rock. (Especially useful for primary sprayed concrete linings).

2.3.3.1 Energy absorption:

In order to check the structural behaviour of SFRC in a tunnel construction, a related test has been developed in France by the National Railway Company SNCF and the former 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 slab is also published in the EFNARC recommendations and is included in the European standard EN 14487 for sprayed concrete.

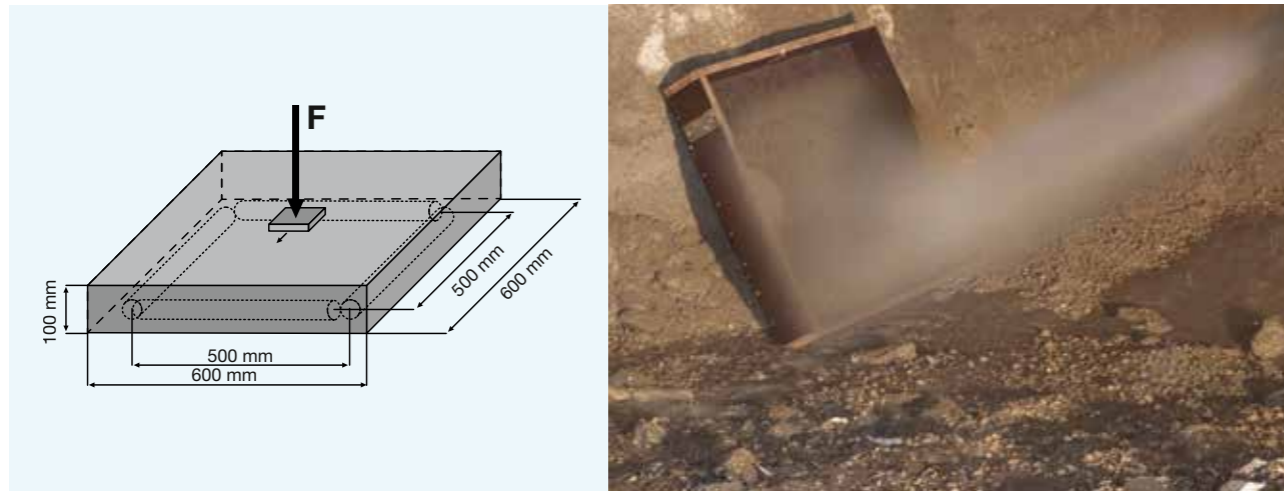
The test plate usually used (600 x 600 x 100 mm panels) (see EN 14488-5) is designed to determine the energy absorbed from the load/deflection curve.

Slabs intended for the punching-flexion test shall be made in moulds of 600 x 600 x 100 mm. In this case, care will be taken to obtain an even surface and a thickness of 100 mm.

Spraying shall be carried out rigorously under the same conditions as recommended for the real tunnel execution: constituents, machine, lance holder and spraying methods in particular.

A test slab is supported on the four edges and a central point load is applied through a contact surface of 100 x 100 mm². The load deflection curve is recorded and the test is going on until a deflection of 25 mm at the central point of the slab is reached.

Fig.3 Test slab dimensions



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.

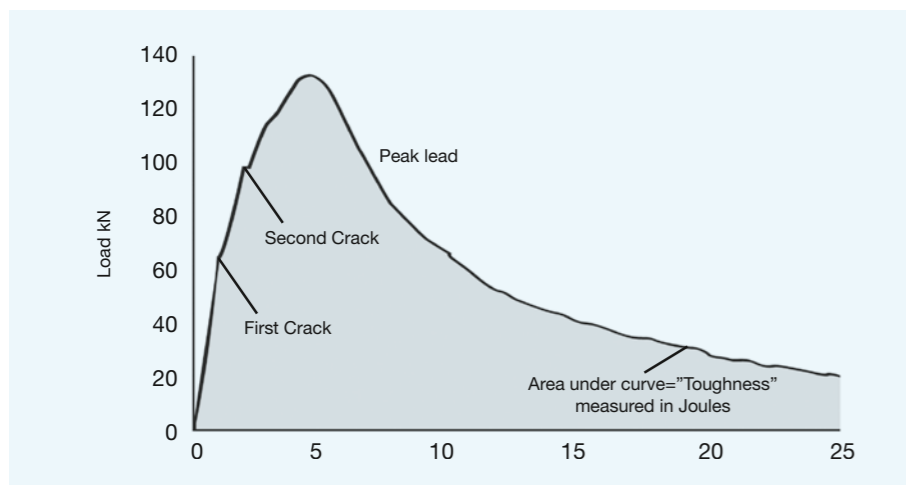


Fig.4 Typical load - deflection curve for steel fibre reinforced sprayed concrete panel

From the load-deflection curve, a second curve is drawn resulting in the absorbed energy (Joules) as a function of the slab deformation or deflection. This approach tries to simulate the real lining behaviour. It gives a good idea of the load bearing capacity and the energy absorption of a shotcrete lining.

Instead of determining a material characteristic, which requires a proper design model in order to calculate the allowable solicitation of the structure, the French approach allows to skip that step and immediately check the energy absorption and the load bearing capacity of the lining.

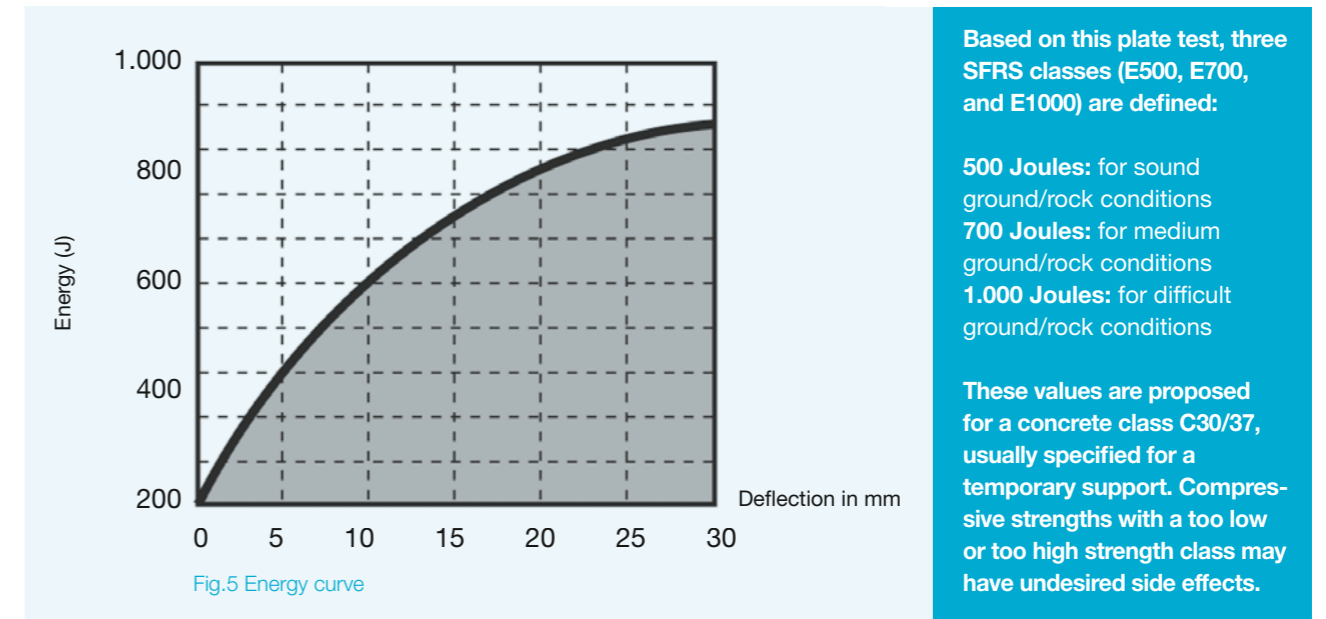


Fig.5 Energy curve

It has to be stated very clearly that the statically indeterminate slab test is **a structural test to check the behaviour of a construction**. It is **not a test to determine material properties** to be used as design values.

The EN slab test allows to check the suitability of a material to be used under given circumstances and to control its behaviour in an ultimate state. It is also a very efficient way to compare different fibre types and dosages related to the intended purpose.

Numerical values to be recommended were obtained from corresponding slab tests using wire mesh types, which have proven in the past to be efficient under given loading conditions. If the capacity for energy absorption of the material is specified, it has to be determined using a slab specimen as per standard EN 14 488-5.

According to the Asquapro recommendation the following restrictions in the specifications are proposed:

1) It depends on the geological and geotechnical context. This must be determined for each project. However, we can give general indications.

Specification table 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 protective skin , and for tough rocks / soils	E500	500
Sprayed concrete acting as a resistant skin , and for medium rocks / soils	E700	700

Beyond a C30/37, the energy values must be higher and the fracture ductility of concrete verified (see following criteria). Thus, for a C40/50 concrete, we can propose the following requirements:

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

2) To better assess the quality of the spray concrete and guaranty the minimum ductility, the following criteria are required for each load-deflection curve obtained as per NF EN 14488-5:

- F_{el-max} must be obtained for a deformation less than 2 mm
- $F_{post fiss}$ min. between 0 and 5 mm $\geq 0.7F$

Conformity for energy absorption capacity is obtained when at least two of three test panels have an energy absorption capacity not lower than the specified energy absorption capacity according to the specified class given.

For the same concrete matrix, the amount of absorbed energy is significantly influenced by the fibre type (e.g. aspect ratio length to diameter, anchorage type) and the fibre dosage. **The higher the aspect ratio and fibre content, the better the performance of the SFRS.**

2.3.3.2 Residual strength:

Different international standards propose a clear procedure to determine the residual strength as:

a) ASTM standards

ASTM C1609/C1609M-05 can be used to determine the post-crack flexural strength of SFRS. In this test method, the post-cracking strengths are termed residual strengths, and are reported at deflections of a span/600 and a span/150. The residual strengths required to be reported for a typical 4 inch. (100 mm) deep specimen are termed $f_{100,0.5}$ and $f_{100,2.0}$, where the subscript indicates the specimen depth in millimeters, and the deflection. In this test method, the first-peak and ultimate strengths (modulus of rupture) are also reported. ASTM C1399 may be used to determine the average residual strength of an SFRS beam specimen. The beam is cracked in a controlled manner, then the load versus deflection curve is generated. Residual loads are determined and averaged at specified deflections, and the engineering strength after cracking is reported.

b) EN specification

Classification of residual strength is based on strength level specification at a certain deformation range in accordance with EN 14488-3. It is denoted by the combination of symbols for the specified deformation range. This means that the residual strength shall exceed 3 Mpa, between 0,5 mm and 1 mm deflection.

The specifications regarding residual strength are related to the deformation conditions of the rock mass. A higher degree of rock deformation will demand higher deflection capabilities of the concrete lining.

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. For design purposes, the deflection limit of the deformation level can be considered in terms of the equivalent angular rotation for a beam cracked at mid span. (e.g. for a beam of 450 mm x 125 mm x 75 mm test in accordance with EN 14488-3):

Three typical rock deformation ranges have been identified:

- D1 corresponding with a deformation = $l/250$
- D2 corresponding with a deformation = $l/125$
- D3 corresponding with a deformation = $l/56$

Correspondingly, four residual strength levels, S1 to S4, have been defined, which in combination with applicable deformation range can be specified in terms of residual strength class.

An illustrative example is given in Figure 6 for a typical fibre reinforced sprayed concrete beam. This beam fulfills the requirement for residual strength class D1S3 (as well as D2S2 and D2S1).

	Deformation range		Strength level (minimum strength, MPa)			
	Deflection (mm)	S1	S2	S3	S4	
D1	0,5 to 1	1	2	3	4	
D2	0,5 to 2					
D3	0,5 to 4					

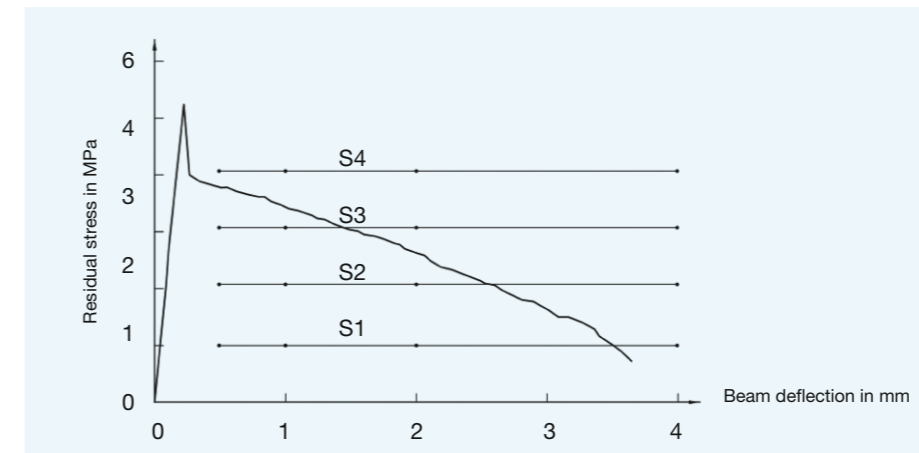


Fig. 6: EN specification

Conformity of residual strength is obtained when:

1. The mean value of test results obtained from 3 test specimens fulfills the requirement for the specified residual strength boundary up to the deflection limit appropriate for the specified deformation level.
2. No individual test result shall in any point (corresponding to the specified deformation level) show a residual stress that is lower than 10% of the stress corresponding to the boundary of the specified strength class.

c) EFNARC three point bending test on square panel with notch

In order to improve the approach, a new test method must fulfill following requirements:

- The geometry and dimensions of the specimens, as well as the casting method adopted, should ensure distribution of the fibres in the matrix, which is as close as possible to that encountered in the actual structure.
- The obtained mechanical property will serve as input for the dimensioning method.
- The dimensions of the test specimen should be acceptable for handling within a laboratory (no excessive weights or dimensions).
- The test should be compatible, as far as the experimental means permit, with use in a large number of normally equipped laboratories (no unnecessary sophistication).
- The geometry should be the same as in the plate test.
- There could also be sprayed on the job site.
- There should be lower scatter than with the current standardised beam test.

Characterization test:

Test specimen geometry and dimension: a 600 mm square by 100 mm thick specimen.

This 3-point bending test is carried out on the test specimen, previously notched in its middle. The distance between the lower supports is 500 mm. The rough surface is the upperside in the test.

The notch is 2 mm thick (saw cut) and 1 cm deep. A movement sensor bridges the notch in its centre. The test is carried out at an imposed crack opening rate. It generates the Force-Crack opening curve.

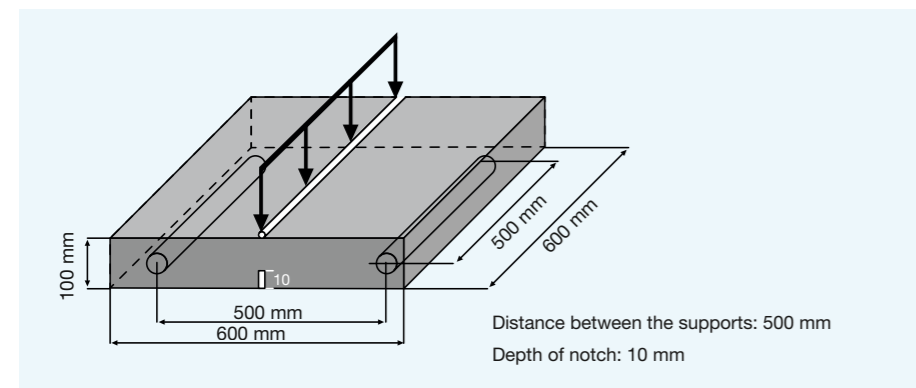


Fig. 7: Alternative test proposal

Based on this test, the following data will be available for the engineer:

Analogically to EN 14651, one can define the following flexural strength:

f_L = "limit of proportionality"

$$f_L = 3/2 \times F_L \times l/b (h_{sp})^2$$

where F_L = max load F before line 0,05 mm

Residual flexural strengths

$f_{res,1}$ = residual strength on CMOD = 0,5 mm

$f_{res,2}$ = residual strength on CMOD = 1,5 mm

$f_{res,3}$ = residual strength on CMOD = 2,5 mm

$f_{res,4}$ = residual strength on CMOD = 3,5 mm

$f_{res,i} = 3/2 \times F_{res,i} \times l/b (h_{sp})^2$ where $F_{res,i}$ = load F corresponding with the CMOD or deflection on these points.

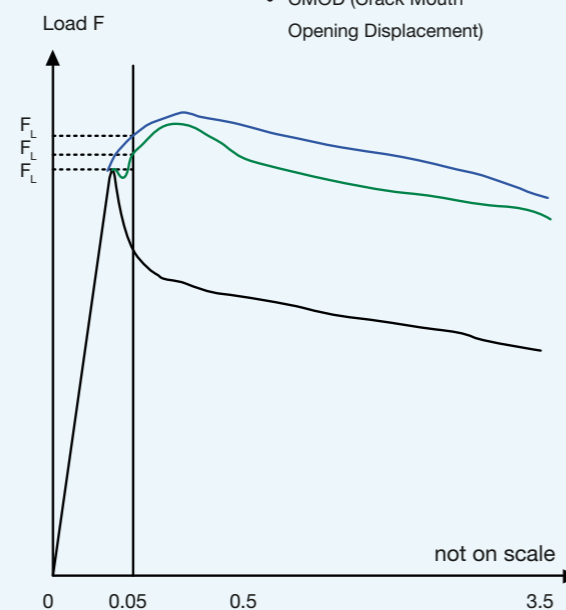


Fig. 8: Mechanical test

In order to classify the post-cracking strength of FRC a linear elastic behaviour can be assumed by considering the residual strength:

- $f_{res,1}$ for Service Limit State (SLS)
- $f_{res,3}$ for Ultimate Limit State (ULS)

"fibre materials with a young's modulus which is significantly affected by time and/or thermo-hydrometrical are not covered by this model code"

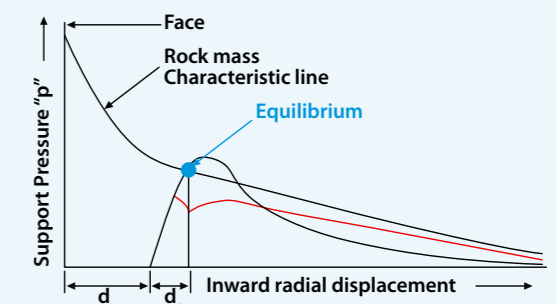
To determine the performance of a SFRS, the plate test according to EN 14488-5 is much more appropriate than the beam test:

1. A plate corresponds much better with a real tunnel lining than a beam; the slab supported on the 4 edges simulates the continuity of the shotcrete lining.
2. 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 slab is very much similar to the real behaviour of a SFRS lining.
3. SFRS can be compared very easily with a mesh reinforced shotcrete to be tested in the same way.
4. "The plate test 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 proved to be of considerable benefit."

The plate test is appropriate in the pre-construction test program. It can be applied to check the parameters affecting the steel fibre reinforced concrete quality requirements as specified in the project documents. Routine quality control should include strength tests and wash-out tests to check the steel fibre content in place. The plate test is also appropriate for a comparison of different fibre types and dosages. It allows for a comparison between mesh reinforcement and fibre reinforcement concrete, provided that the failure mode is in accordance with EN 14 487-1 Sprayed concrete, definition, specification and conformity. That is why this test is only used to compare steel mesh and steel fibres (material with same modulus of Young).

Fig.9: Load carrying capacity

The relative importance of load carrying capacity at small crack widths, and hence small deflections and rotations, is recently of much greater importance to the designers of civil engineering tunnels (see figure).



5. Due to the very low E-modulus of macro-synthetic fibres and the mode of failure observed with this type of fibres, **the plate test is not sufficient to compare steel fibres and macro-synthetic fibres**. Another criterion based on the residual strength, as D1S3, must be added according to EN14487-1.

Furthermore, **macro-synthetic fibres tend to creep 7 to 20 times more than steel fibres** after 1 year. That is why the designer should only recommend steel fibres for this application.

In short: it is also well known that the bonding of a synthetic fibre in concrete matrix performs poorly. The age of the concrete has a considerable impact on this bond mechanism (any improvement is very noticeable from the bottom upwards). This means that the older the concrete the better the synthetic fibres are bonded and the better its mechanical strength. But when you need a temporary support, **at young concrete age, you can't expect any relevant performance of synthetic fibre concrete.**

3. System performance requirements

3.1 Rock quality and stabilizing measures

Evaluation of general rock stability should be based on geological mapping of the excavated rock cavern. The stability may be calculated from the registered rock parameters and forces acting in the system.

Several empirical classification systems have been developed based on data from earlier excavations. The two most widely used rock mass classifications are Bieniawski's RMR (1976, 1989) and Barton et al.'s Q (1974).

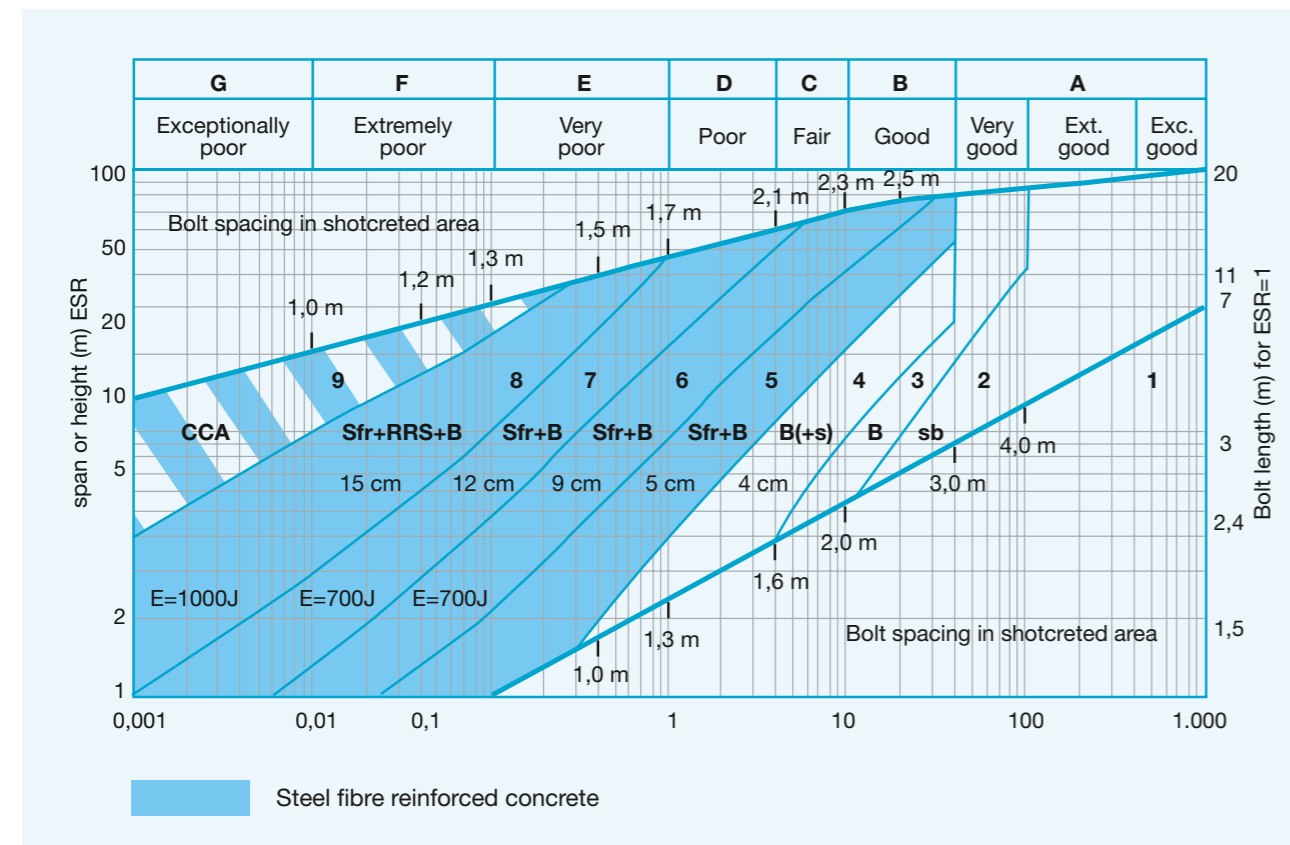
Both system methods incorporate geological, geometric and engineering parameters to arrive at a quantitative value for the rock mass quality.

3.2 Q-system

The Q-system developed by Barton et al.'s (1974, 1993) is internationally by far the most applied classification system and is based on the following parameters:

- RQD Rock quality designation
- Jn Joint set number
- Jr Joint roughness number
- Ja Joint alteration number
- Jw Joint water reduction factor
- SRF Stress reduction factor

Fig. 10: Q-system



Reinforcement Categories

1. Unsupported
2. Spot bolting, **sb**
3. Systematic bolting, **B**
4. Systematic bolting, (and unreinforced shotcrete, 4-10 cm), **B(+s)**
5. Fibre reinforced shotcrete and bolting, 5-9 cm, **Sfr+B**
6. Fibre reinforced shotcrete and bolting, 9-12 cm, **Sfr+B**
7. Fibre reinforced shotcrete and bolting, 12-15 cm, **Sfr+B**
8. Fibre reinforced shotcrete > 15 cm, reinforced ribs of shotcrete and bolting, **Sfr+RRs+B**
9. Cast concrete lining, **CCA** (references on request via: contact@bm-underground.com)

E=700J & E= 1.000J: The energy absorption in fibre reinforced concrete at 25 mm bending during the plate test according to EN 14488-5.

The energy absorption in the Barton Chart should be determined exclusively with the EN plate with reference concrete type C30/37.

The six parameters are assigned numerical values according to their influence on the stability and entered in the following formula:

$$\text{Rock mass quality } Q = (RQD/Jn) \cdot (Jr/Ja) \cdot (Jw/SRF)$$

The relation between the Q values and the recommended stabilizing measures is given in detail in "fig.10 Q-system"

Relation between cavern type and the ESR value:

Temporary mines, etc.	3,5
Vertical shafts, rectangular and circular respectively	2,0 – 2,5
Water tunnels, permanent linings, addits...	1,6
Storage caverns, road tunnels with little traffic, access tunnels...	1,3
Power stations, road and railroad tunnels with heavy traffic, emergency shelters	1,0
Nuclear power plants, railroad stations, sports arenas...	0,8

4. Dramix® proposal

Sprayed concrete can either be applied as a dry mix or as a wet mix:

For a C30/37 concrete class:

Energy absorption class	Fibre type	Dosage in the Wet mix method	Dosage in the Semi dry mix method
E 700	Dramix® 3D 65/35BG	25 kg/m ³	30 kg/m ³
E 1000	Dramix® 3D 65/35BG	35 kg/m ³	40 kg/m ³

Tests on the job site should confirm this dosage with the concrete mix used for the project.

This dosage proposal is based on experience and on a great number of test results, taking into account the percentage of lost fibres due to the rebound:

- Dry method 20% (15% to 30%)
- Wet method 10% (5% to 15%)

Mind: the value of energy absorption can be increased by using a higher concrete strength at 28 days during the characterization test. This should not be a target. Indeed, for safety reasons, we aim at reaching a high level of ductility and semi-rigid temporary support. Maximum compressive strength for the characterization test should not exceed C30/37. Strength after a few hours, even after a couple of minutes, may be more important and more critical than the 28-days strength. If not, one needs to change the design philosophy.

To understand the role of a temporary support:

While driving a tunnel, the existing, primary balance of forces in the rock mass will be changed into a new, secondary and also stable state of balance. This can only be achieved through a succession of intermediate stages accompanied by various stress distribution processes.

Rock deformation control is a main issue:

- On one hand, deformation should be kept to a minimum so that the primary state of stability and the compressive strength of the rock are not weakened more than is inevitable.
- On the other hand, deformation is actually desirable to the extent that the rock formation itself acts as an overall ringlike support, minimizing costs for excavation and supports. Sprayed concrete, particularly the primary lining, has a fast support role. Strength after a few hours, even after a couple of minutes, may be more important and more critical than the 28-days strength.

At that point in time, in some cases, the supporting role of the sprayed concrete's high(er) early strength can be obtained using the right accelerator. There are a lot of new products introduced into the market.

The NATM method is based on the so-called semi-rigid lining with high ductility behaviour. This method aims at avoiding the risk of brittle materials that act as a first stage support. The NATM method creates a new status of equilibrium mostly followed by an inner lining which should accept the necessary deformation but which guards against the development of rock load.

5. Execution details

In the case of double shell tunnel construction, a waterproof membrane combined with a geotextile is placed between the steel fibre reinforced sprayed concrete support and the final cast in situ concrete layer. This in-between layer serves as a buffer leveling out any irregularities of the sprayed concrete. No special conditions must be taken into account to avoid penetration of fibres through the waterproof membrane.

The practical experience on many sites as well as test results in independent laboratories clearly confirm that there are no problems with the membrane/ protection sheets in combination with steel fibre reinforced sprayed concrete, such as Dramix® 3D 65/35BG.

A test report is available on request: contact@bm-underground.com

6. Durability

Dramix® steel fibres can be seen as a proven technology to create durable solutions.

Two different cases are to be considered when analyzing the corrosion of metallic fibres and their behaviour:

- The fibre does not cross a crack emerging on the surface. Apart from some staining that could affect the appearance of the structures, fibre corrosion does not lead to any serious problems for the durability or the bearing capacity of these structures in SFRC.
- The fibre crosses a crack emerging on the surface. The bearing capacity of the SFRC is not significantly affected by crack openings of 250 µm and less.

It has to be underlined that the problem of stains, as referred to above, can be almost entirely eliminated by:

- Optimizing the SFRC formulation. These mixes are then sufficiently rich in cement paste to avoid any fibres cropping out on the surface.
- Using metallic fibres which enhance the corrosion resistance.

7. Quality control

Production control comprises all measures necessary to maintain and regulate the quality of the sprayed concrete in conformity with the specified requirements.

Production control includes:

- Inspection of constituent materials
- Inspection of the basic mix
- Inspection of sprayed concrete properties

The characterization tests concerning the materials, the freshly mixed concrete and the hardened concrete all constitute the full identity sheet for a given SFRC. They are performed once only at the beginning of each job site which uses SFRC. These tests are executed in laboratory.

Table - Control fibres sprayed concrete properties - Extract from EN 14487-1

TYPE OF TEST	INSPECTION/ TEST ACCORDING TO	Minimum sampling frequency									
		Strengthening of ground			Repair and upgrading			Free standing structures			
		Category 1	Category 2	Category 3	Category 1	Category 2	Category 3	Category 1	Category 2	Category 3	
CONTROL OF FRESH CONCRETE											
1	Water/cement ratio of fresh concrete when using wet mix ratio	By calculation or by test method			Daily			Daily		Daily	
2	Accelerator	From record of quantity added			Daily			Daily		Daily	
3	Fibre content in the fresh concrete	According to prEN 14488-7	min 1	1/200 m ³ or 1/100 m ²	1/100 m ³ or 1/500 m ²	min 1	1/500 m ² min 2	1/250 m ³ min 3	1/200 m ³ or 1/1.000 m ² or min 1	1/100 m ³ or 1/500 m ² or min 2	1/50 m ³ or 1/250 m ² or min 3
CONTROL OF HARDENED CONCRETE											
4	Strength test of young sprayed concrete	prEN 14488-2	1/5000 m ² or 1/2 months	1/2500 m ² or 1/month	1/250 m ² or 2/month						
5	Compressive strength	EN 12504-1	1/1.000 m ³ or 1/5.000 m ²	1/500 m ³ or 1/2.500 m ²	1/250 m ³ or 1/1.250 m ²	1/500 m ³ or 1/2.500 m ² or min 1	1/100 m ³ or 1/500 or min 2	1/50 m ³ or 1/250 or min 3	1/500 m ³ or 1/2.500 m ² or min 1	1/100 m ³ or 1/500 or min 1	1/50 m ³ or 1/250 or min 3
6	Density of hardened concrete	EN 12390-7	When testing compressive strength			When testing compressive strength			When testing compressive strength		
7	Resistance to water penetration	EN 12390-8				1/1.000 m ² or min 1	1/500 m ² or min 2	1/250 m ² or min 3	1/1.000 m ² or min 1	1/500 m ² or min 2	1/250 m ² or min 3
8	Freeze/thaw resistance	See footnote (4)				1/1.000 m ² or min 1	1/500 m ² or min 2	1/250 m ² or min 3	1/1.000 m ² or min 1	1/500 m ² or min 2	1/250 m ² or min 3
9	Bond strength	EN 14488-4(1) EN 1542 (2)		1/2.500 m ²	1/1.250 m ²	1/1.000 m ² or min 1	1/500 m ² or min 2	1/250 m ² or min 3			
CONTROL OF FIBRE REINFORCED SPRAYED CONCRETE											
10	Fibre content of hardened concrete(3)	prEN 14488-7	When testing residual strength or energy absorption capacity			When testing residual strength			When testing residual strength		
11	Residual strength or energy absorption capacity	prEN 14488-3 or prEN 14488-5	1/2.000 m ³ or 1/10.000 m ²	1/400 m ³ or 1/2.000 m ²	1/100 m ³ or 1/500 m ²	min 1	1/2.000 m ² or min 2	1/500 m ² or min 3		1/2.000 m ² or min 2	1/500 m ² or min 3
12	Ultimate flexural strength	prEN 14488-3	When testing residual strength			When testing residual strength			When testing residual strength		
13	First peak flexural strength	prEN 14488-3	When testing residual strength			When testing residual strength			When testing residual strength		

Main requirements for hardened steel fibre reinforced concrete characterisation test:

Fibre content:

The fibre content shall be determined from a hardened sample in accordance with EN 14 488-7, when it is not practical to determine it from the fresh sprayed concrete. The sample shall be taken from in situ material unless otherwise specified.

Energy absorption capacity:

The energy absorption capacity shall be expressed as the average energy absorption capacity, determined in accordance to EN 14 488-5. The specified energy absorption for the required class shall meet the requirements of the project. Usually, the test is performed at 28 days.

Residual strength (if required by the project):

- The residual strength class of fibre reinforced concrete shall be determined for a specified deformation level. The stress-deflection curve shall be determined in accordance with a three-point bending test on a plate (600 x 600 x 100) sprayed in situ.
- The specified residual strength for the required class shall meet the requirements of the project and the minimum requirement indicated in the model code.
- The test is normally performed at 28 days, and this before the start and during the construction period.

Footnotes:

- For ground strengthening
- For repair
- This test is alternative to the one in line 4 when it is not practical to determine the fibre content from the fresh sprayed concrete.
- As no European Standard on this issue is available at the publication of this document, national standards apply.

8. Standard Specification text

Minimum specification points:

1. Fibres

- Fibres to comply with European Standard EN 14889-1
- Fibres with CE marking
 - Fibres out of drawn wire, with a tensile strength of steel wire > 1.000 MPa min.
- Dimensional tolerances according to EN 14889-1
- Fibre length: 30 or 35 mm

2. Performance

- Minimum total wire length/m³ should be 10 m (in situ) in order to guarantee the minimum network effect.
- Minimum overlap according to McKee Theory (l/d 65=16kg/m³ in situ, l/d 55 =23 kg/m³ in situ, l/d 40=43 kg/m³ in situ).
- The minimum class should be E 700 (700 joules minimum) for a C30/37 and E1000 recommended (1000 joules min.) for a concrete > C30/37 following EN 14 488-5
- f_{el-max} must be obtained for a deformation less than 2 mm
- $f_{post\ fiss}$ between 0 and 5 mm $\geq 0.7 f_{el-max}$
- According to the model code, fibre reinforcement can substitute conventional reinforcement if the following relation ship are fulfilled:
 - $f_{res,1/f} > 0,4$
 - $f_{res3fres1} > 0,5$
- f_{res1} (SLS) and f_{res3} (ULS) mini should be specified according to the design requirement.

3. Fibre concrete

- Glued fibre for optimal pumpability and to ensure a good distribution and homogeneity in the concrete. It is prohibited to use loose steel fibres that cause balls during mixing.
- Type of concrete: class C30/37

4. Quality

- Performance and control criteria should be specified following the EN 14487-1, taking account the requirement of the project.

9. Bibliography

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Recommendation for fibre reinforced sprayed concrete technology and practice

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EN 14 651

Test method for fibered concrete - Measuring the flexural tensile strength (limit of proportionality (LOP), residual) - Model code 2010 edited by fib

EN 14487-1

Sprayed concrete, definition, specification and conformity

EN 14488-1

Testing sprayed concrete: Sampling fresh and hardened concrete

EN 14488-2

Testing sprayed concrete, part 2: Comprehensive strength of young sprayed concrete

EN 14488-3

Testing sprayed concrete, part 3: Flexural strengths of fibre reinforced beam specimens

EN 14488-4

Testing sprayed concrete, part 4: Bond strength of cores by direct tension

EN 14488-5

Testing sprayed concrete, part 5: Determination of energy absorption capacity of fibre reinforced slab specimens

EN 14488-6

Testing sprayed concrete, part 6: Thickness of concrete substrate

EN 14488-7

Testing sprayed concrete, part 7: Fibre content of fibre reinforced concrete

EN 14489-1

Fibres for concrete, part 1: steel fibres - Definitions, specifications and conformity

EFNARC TEST PROCEDURE

Three point bending test on square panel with notch

ISO 13270

Benefit from our full service

1 For the concrete mix design, we take into account all relevant standards, as well as the specific load bearing requirements of your tunnel project. This will result in a specific steel fibre dosage tailored to your project, which guarantees **the most economical and qualitative result.**

Dramix® steel fibres are submitted to severe **quality control** according to international standards, including ISO 9001 and ISO 14001.

3 On top of the steel fibre quality control, dedicated tests for the entire steel fibre concrete mix are performed in **controlled testing laboratories.** We have our own concrete lab available to support you.

Thanks to our worldwide network, we are able to offer **on-site support** virtually anywhere. We also offer dedicated dosing equipment, which allows contractors to save time and work with the highest precision.

5 Our **global experts** bundle many years of tunnel construction experience. They closely monitor the latest developments in the field and regularly contribute their knowledge and opinion to the experts' community.

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