FIBRE REINFORCED SPRAY CONCRETE FOR COMPLIANCE WITH SITE SAFETY REQUIREMENT

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ABSTRACT

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 contri-buted 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.

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 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 deforma-tion of the rock. (Especially useful for primary sprayed concrete linings).

The residual strength can be prescribed when the concrete characteristics are used in a structural design model. Indeed relevant material properties are especially useful when we used sprayed concrete in temporary support or final lining to meet the safety requirement. For different project a complete test program were launched in order to validate the use of steel fibre reinforced spray concrete and determined clear perform-ance according to project requirement. The paper will describe and explain the test procedure and present the results obtained by this test program.

Keywords: Steel fibre, performance, spray-concrete, testing method.

RESUMEN

En años recientes, en varios países se han llevado a cabo múltiples investigaciones y ensayos sobre el comportamiento del concreto reforzado con fibras de acero. Los resultados han contribuido a mejorar la caracterización del Concreto Reforzado con Fibras de Acero (SFRC), y por lo tanto han permitido llegar a un mejor entendimiento del comportamiento de este material y especificar requerimientos mínimos de desempeño para cada proyecto. La norma europea EN 14487-1 menciona las diferentes formas para especificar la ductilidad de concreto lanzado reforzado con fibras en términos de la resistencia residual y de la capacidad de absorción de energía. También menciona que ambas formas no son precisamente comparables El valor de la energía absorbida medido en un panel se puede especificar cuando –en el caso de colocación de pernos en roca– se hace énfasis en la energía que debe ser absorbida durante la deformación de la roca. (Lo cual es especialmente útil en revestimientos primarios de concreto lanzado). La resistencia residual se puede especificar cuando las características del concreto están determinadas en el modelo de diseño estructural. Las propiedades relevantes de los materiales son especialmente útiles para cumplir con los requerimientos de seguridad cuando se usa concreto lanzado en apoyos temporales o en revestimientos definitivos. Se lanzó un programa completo de pruebas para diferentes proyectos con el fin de validar el uso de concreto lanzado reforzado con fibras de concreto y para definir claramente su desempeño de acuerdo a los requerimientos de cada proyecto. El artículo describe y explica el procedimiento de pruebas y presenta los resultados obtenidos mediante este programa.

Palabras clave: fibras de acero, desempeño, concreto lanzado, método de prueba.

RESUMO

Várias pesquisas e testes sobre o comportamento do concreto reforçado com fibras de aço têm sido realizados nos últimos anos em vários países. Eles têm contribuído signi-ficativamente para uma melhor caracterização do Concreto Reforçado com Fibra de Aço (SFRC) permitindo assim, obter uma melhor compreensão do comportamento des-te material e para especificar os requisitos mínimos de desempenho para cada projeto.

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A norma europeia EN 14487-1 menciona as diferentes formas de especificar a ducti-lidade do concreto pulverizado reforçado com fibra em termos de resistência residual e da capacidade de absorção de energia. Ele também menciona que ambas as formas não são exatamente comparáveis. O valor da absorção da energia medida em um pai-nel pode ser prescrito quando –em caso de chumbador– a ênfase é colocada sobre a energia que deve ser absorvida durante a deformação da rocha. (Especialmente útil para revestimentos primários de concreto pulverizado). A força residual pode ser pres-crita quando as características do concreto são usadas em um modelo de projeto es-trutural.

Na verdade, as propriedades relevantes dos materiais são especialmente úteis quando usamos concreto pulverizado em suporte temporário ou em revestimento final para cumprir com os requisitos de segurança. Para projetos diferentes, um programa completo de testes foi lançado a fim de validar o uso do concreto pulverizado reforçado com fibra de aço e que determinou o desempenho claro de acordo com a exigência de projeto.O documento irá descrever e explicar o procedimento do teste e apresentar os resultados obtidos por este programa de teste.

Palavras-chave: fibra de aço, desempenho, concreto-pulverizado, método de teste.

INTRODUCTION

European standard EN 14487 includes different ways of specifying the ductility of Fibre Reinforced Sprayed Concrete (FRSC) in terms of residual strength and energy absorp-tion capacity. It also indicates that both ways are not exactly comparable. The residual strength approach can be adopted when the concrete characteristics are used in a structural design model. The energy absorption value measured for a panel can be ad-opted when, in the case of ground support, emphasis is placed on the energy which has to be absorbed during the deformation of the ground (which is especially useful for primary sprayed concrete linings).

In order to assess the structural behaviour of FRSC in a tunnel lining, a test was de-veloped in France by the National Railway Company (SNCF) in cooperation with the former Alpes Essais Laboratory (AFTES text the recommendation on fibre reinforced sprayed concrete technology and practise –published in 1994). This panel based test was also in-cluded in the EFNARC recommendations in "European Specification for Sprayed Concrete" and has, since 2005, been included in the European standard EN 14487 for sprayed concrete. The test method described in EN 14488 is intended to de-termine the energy absorbed under the load/deflection curve. Panels intended for this flexural-punching test must be made in forms measuring at least 600×600×100 mm. Care must be taken to obtain an even surface and a thickness of 100 mm. Spraying must be carried out using the same properties and conditions as recommended for the works; constituents, machine, lance holder and spraying methods, in particular, must be identical.

During the test the panel is supported on its four edges and a central point load is applied through a contact surface of 100×100 mm2. The load deflection curve is re-corded and the test is continued until a deflection of 25 mm at the central point of the slab is reached. The load-displacement curve typically indicates that during the test several cracks develop which then act as plastic hinges that allow redistribution of loads through the steel fibres bridging the cracks. Once the peak load has been reached, after the load redistribution effect has been realised, the fibres start to be pulled out of the matrix. Fibre shape and steel strength determine whether the fibres will break, or preferably, be pulled out.

From the load-deflection curve, a second curve is generated resulting in a plot of the absorbed energy (in Joules) versus the central deformation or deflection. This ap-proach is an attempt to simulate 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 deformation of the structure, the EN panel test approach does away with the need for a design model and immediately evaluates the energy absorption and load bearing capacity of a lining.

It has to be stated very clearly that a statically indeterminate slab test is a structural test to check the behaviour of a speci-men representing a construction. It is not a test to determine material properties to be used as design values. The EN panel test allows a check of the suitability of a material to be used under given circumstances and to control its behaviour at the Ultimate Limit State. It is also a very efficient way to com-pare different fibre types and dosages related to the intended purpose.

If the capacity for energy absorption of SFRS is specified, it must be determined using a panel specimen as per standard EN 14488-5. Based on this panel test, three SFRS classes (E500, E700, and E1000) are defined (European Standard EN 14487-1 Sprayed concrete, definitions, specifications and conformity) as follows:

- 500 Joules for sound ground/rock conditions.
- 700 Joules for medium ground/rock conditions.
- 1000 Joules for difficult ground/rock conditions.

These values are proposed for a concrete class C30/37, usually specified for temporary ground support. Compressive strength grades that are either too low or too high may have undesired side effects. In case of concrete with a higher compressive strength, the performance criteria proposed by the EN standard should be increased in order to keep the same level of ductility required for safety.

The panel test is also appropriate for a comparison of different fibre types and dosages. It allows a comparison between mesh reinforcement and fibre reinforcement, provided that the failure mode is in accordance with EN 14487-1. Indeed the perform-ance criteria based on this test were established to compare steel mesh and steel fibres (materials with the same modulus of elasticity, E). That is why these criteria do not appear to be appropriate with macro-synthetic fibre reinforced shotcrete due to their mode of failure. Some recommendation as in Filand imposed an additional criteria: Fmax/Fl >1,2 with:

Fmax = Maximum load.

Fl= Load at the first crack.

The relative importance of load carrying capacity at small crack widths, and hence at small deflections and rotations, has recently assumed much greater importance to the designers of civil engineering tunnels. Due to the very low E-modulus of macro-synthetic fibres and the mode of failure observed with this type of fibre, the panel test is not suitable to compare steel fibres and macro-synthetic fibres. When using macro-synthetic fibre reinforced shotcrete another criterion should be used. According to EN14487-1, this criterion should be based on the residual strength. Various interna-tional standards (ASTM, Japanese Standards and EN standards) have proposed clear procedures to determine the residual strength of Fibre Reinforced Shotcrete/Concrete.

1 NEW TEST METHOD TO DETERMINE FLEXURAL STRENGTH

1.1 Test description

Based on European Standard EN 14651 tes Method for steel fibre concrete –Measuring the flexural tensile (limit of proportionality, LOP, Residual strenstrength), the new test was developed to investigate the flexural toughness of shotcrete. The panel has the same dimensions as the EN14488-5 square panel test and measures 600 mm square by 100 mm thick. The panel is loaded in simple centre-point bending and the distance between the lower supports is 500 mm. It has a central notch and this notch is 2 mm wide (saw cut) and 10 mm deep, see Fig. 1. The panel test was conducted in a 1000 kN hydraulic servo-controlled testing machine, and the panels were subjected to a lat-erally-distributed line load under deformation control with a deformation rate of 0.2 mm/min. Four LVDTs were used to analyze the displacement at the mid-span and sup-ports at both ends, and the difference between the deformations at mid-span and at the supports was calculated to be the net mid-span displacement. Three crack gauges, located at the middle and each side of the panel, were placed in the middle of the notch for evaluation of the Crack Mouth Opening Displacement (CMOD). Fig. 2 shows the arrangement of strain gauges on the side of the specimen and Fig. 3 shows the LVDT's used to determine the deflections required for a plot of applied load versus mid point deflection.

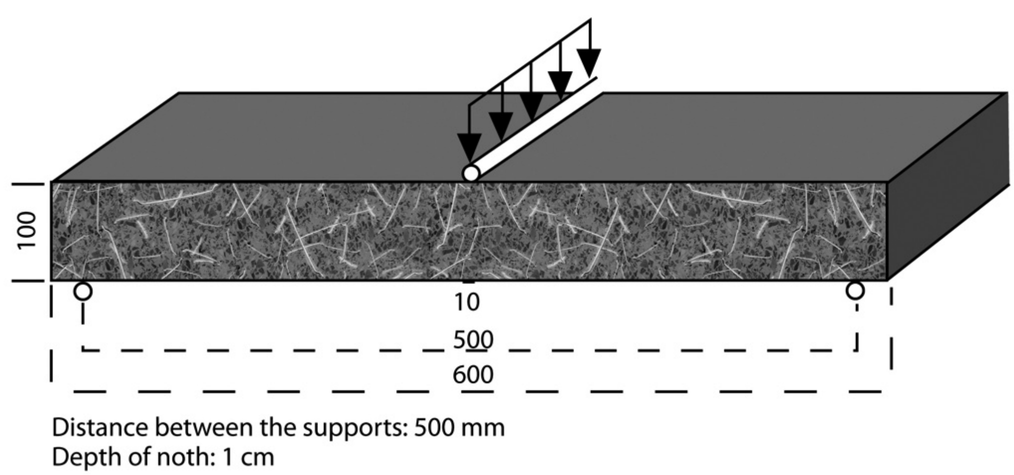


Fig. 1. Dimensions of specimens and load method.

1.2 Advantages of proposed test procedure

The proposed test procedure enables a contractor who proposes a SFRS mix design to check that it meets or exceeds the "mechanical" performance properties specified for a particular project. In order to improve the validity of the test results, the following re-quirements in terms of the test panel preparation are proposed: the geometry and di-mensions of the specimens, as well as the production method adopted, should reflect, as nearly as possible, that which will be used in actual structures. The intent of this approach is to achieve the same fibre distribution, in the test panel, as will be found in the finished structure. This test should also be suitable for establishing the perform-ance of other Steel Fibre Reinforced Concrete applications where plate elements are employed e.g.spray concrete.

Fig. 2. Arrangement of stain gauges.

Fig. 3. Set up of the panel test.

The mechanical properties obtained from this test include the residual flexural strength at the following deflections:

- $f_{R,1}$ = residual strength at a CMOD = 0.5 mm.
- $f_{R,2}$ = residual strength at a CMOD = 1.5 mm.
- $f_{R,3}$ = residual strength at a CMOD = 2.5 mm.
- $f_{R,4}$ = residual strength at a CMOD = 3.5 mm.

The dimensions of the test specimen must, however, also be acceptable for handling within a laboratory (no excessive weights or dimensions). The test is designed to be suitable, as far as the equipment requirements permit, for use in a large number of normally equipped laboratories (no unnecessary sophistication). The geometry should be the same as that in the EN 14488-5 plate test for energy absorption so that a common geometry is used for both statically determinate and statically indeterminate tests. Using a common specimen geometry will make it easier to manage a test pro-gram because the same procedure can be used to produce the specimens as for the EN 14488 panel test. There will also be a lower scatter in results than for a normal beam test.

The notch provides more relevant values just after the first crack according to fib/RILEM recommendation. The measured values can be used to plot the mean resid-ual flexural tensile stress and characteristic residual flexural tensile stress versus crack opening curves. Reverse calculation can then be applied to the results of this test to produce uni-axial tensile stress versus crack opening curves, information which can then be used in the dimensioning method detailed in the "Interim Recommendation concerning UHPFRC" edited by AFGC-SETRA.

2 FLEXURAL TESTS ON PANELS WITH STEEL AND MACRO SYNTHETIC FIBRES

2.1 Comparative test program

The following sets of specimens were included in the investigation (Table 1). It in-cludes different dosages and fibre types.

Tabla 1. Identification of specimen sets.

Fibre	Concrete Grade	Fibre Content (kg/m³)
NC	C30	0
SF20	C30	20
SF30	C30	30
SF40	C30	40
PP6	C30	6

The grade of the plain concrete was designed to be C30 (28 day cube compressive strength of 30 MPa). The dosages of steel fibres were 20kg/m3, 30 kg/m3, 40kg/m^3 and the macro-synthetic fibre content was 6 kg/m3. Four series of panels, each of them including nine specimens, were tested. The air content and slump flow spread of the fresh concrete were measured. All cube specimens were de-moulded after 1 day and cured in standard curing room. And compressive strength was tested after 28 days. The investigation program included:

1) Mix design of plain concrete for C30, and the influence of different fibre types and fibre dosages on the workability and on the air content of fresh concrete, and on the compressive strength after 28 days.

2) Flexural testing of notched panels with different fibre types and dosages. The load-deflection curves, load-CMOD curves and deflection-CMOD curves of the notched panels were plotted and investigated.

3) An investigation of the energy absorption capacity of FRS notched panels with steel fibres and macro-synthetic fibres was carried out. The energy absorption-deflection curves and energy absorption-CMOD curves were evaluated.

4) The flexural strength and residual flexural strength at various deflections for steel fibre and macro-synthetic fibre reinforced panels were analyzed, and the stress-crack width (σ-ω) relationship for FRC panels was established.

2.2 Materials

In this test program, the mix design for the FRC was as follows: PC 32.5 I Portland cement 373 kg/m^3, fly ash 93 kg/m^3; aggregate 45% (1-5 mm) and 55% (5-10 mm), superplasticizer 1%, water binder ratio 0.45. Two types of fibre were examined:

• A macro-synthetic fibre called Synmix (length 50 mm, equivalent diameter 0.85 mm), at a dosage rate of 6 kg/m^3.

• A macro steel fibre called Dramix RC65/35BN (length 35 mm, diameter 0.55 mm), including approximately 14500 fibres/kg, at dosage rates of 20, 30 and 40 kg/m^3.

The main performance parameters of the fibres are shown in Table 2.

Tabla 2. Properties of fibres.

Type	E modu-lus (MPa)	Tensile strength (MPa)	Melting point	Den-sity (kg/m3)
Steel	210 000	1345	1500° C	7850
Synthetic	5 000	600	160° C	910

Young's modulus, E, is the material stiffness characteristic which describes the defor-mation tendency of a material. In a composite material such as fibre reinforced con-crete, a significant and effective reinforcement effect can only be obtained when the reinforcing component, such as the fibres, have a higher modulus than the concrete matrix (E modulus for concrete is about 35000 MPa). Indeed, because of their low elastic modulus synthetic fibres must undergo large displacements, corresponding to large crack openings, to generate appropriate stress across the cracks. Therefore, in aged and cracked structures made of concrete reinforced with macro-synthetic fibres, cracks are much larger than in those with steel fibres at the same volume fraction and the deformation of these structures may also be significant (Rossi, 2009).

According to Hooke's law, $\sigma = E\varepsilon$, the higher the stiffness of a reinforcing material (higher Young's modulus), the better the crack controlling effect, and hence the lower the deformation and crack openings. For the same tensile loads in the fibres, the elon-gation of the fibres will be more than 20 to 40 times higher for macro-synthetic fibres compared with steel fibres.

3 RESULTS AND ANALYSIS

3.1 Properties of fresh concrete

The properties of the concrete mixes produced in this investigation are listed in Table 3. From this table it can be seen that the plain concrete showed good workability. However, with an increase in the fibre content, the slump-flow decreased. Neverthe-less, the slump-flow of all the mixes was greater than 40 cm and the fresh concrete showed good flow ability and segregation resistance. The steel fibres were distributed uniformly in the concrete and no balling was observed. The macro-synthetic fibre at a dosage rate of 6 kg/m^3 showed a similar effect on the slump flow as the steel fibre at a dosage rate of 40 kg/m^3.

Tabla 3. Properties of the mixes included in investigation.

Parameter	Mix				
	NC	SF2	SF3	SF4	PP
		0	0	0	6
Slump flow (cm)	**68**	**50**	**50**	**42**	**43**
UCS 28 days (MPa)	**36**	**34**	**34**	**33**	**33**

Unconfined Compressive Strength (UCS) tests were carried out according to Chinese guideline CECS 13 (China Association for Engineering Construction Standardization, Technical Specification for Fibre Reinforced Concrete Structures, 1989). The mean val-ues of compressive strength for all the samples tested at 28 days are illustrated in Table 3. It can be seen that the addition of fibres has no significant influence on the compressive strength.

Main results of this test programme

The results of this test programme are as follows. The fibres do not show a clear influ-ence on the compressive strength of concrete. The workability of fresh concrete was found to decrease slightly with an increase in fibre content. The fibres were found to be evenly distributed in the matrix, and there was no balling effect or segregation evi-dent.

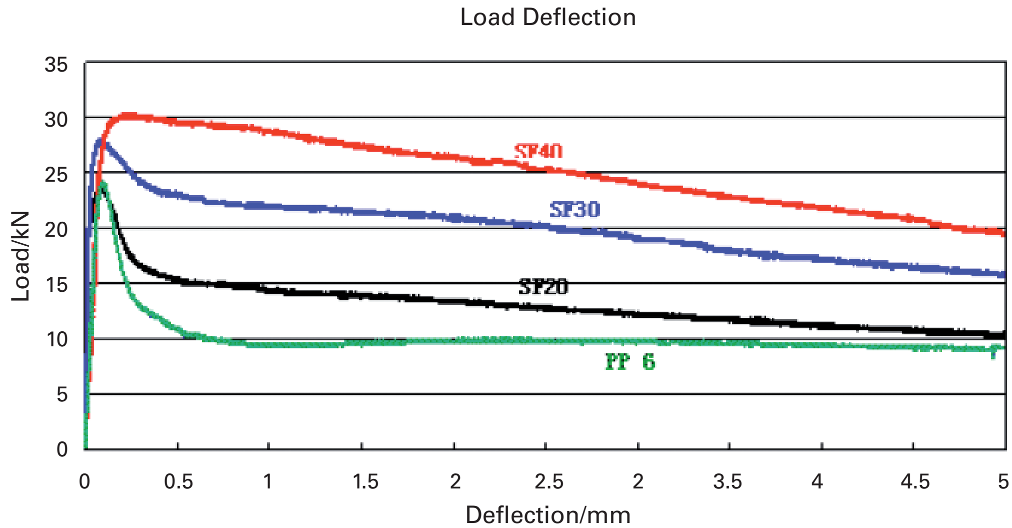


Fig. 4. Comparison of load-deflection curves of FRC panels with different fibres. Each plot represents the mean result for each set of nine panels.

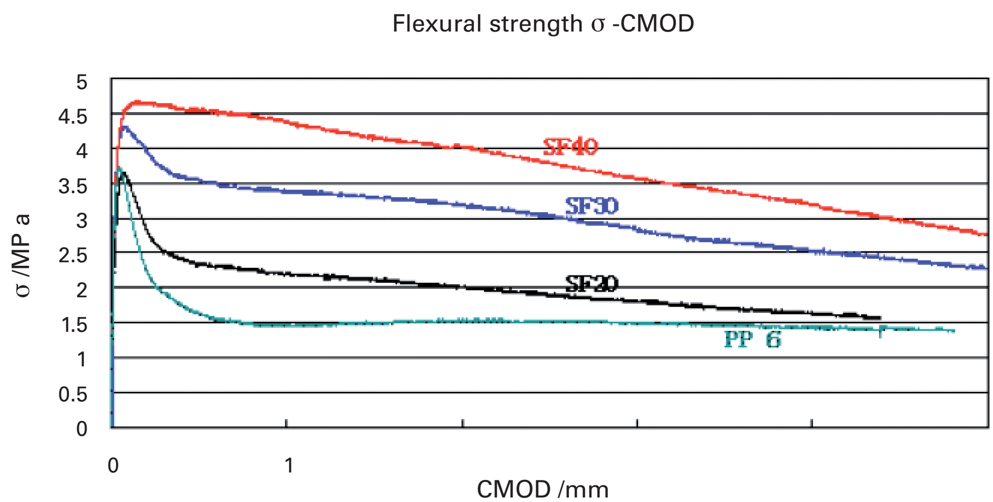


Fig. 5. Comparison of flexural strength in the FRC compared to CMOD.

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 higher load car-rying 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 crack-ing 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 ad-dition 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 en-ergy-absorption provided by the steel fibres is stronger than that of the macro-synthetic fibres in this trial.

One point should also be considered in regard to the mechanical properties of fibres. It concerns the aspect of creep. The creep of a material describes how it deforms with time under a constant applied load. Steel fibres at the levels of load common in con-crete structures do not creep or hardly ever. This is not typically the case for synthetic fibres. The effect of creep on real structures can result in acceptable deflections, rota-tions and crack widths becoming unacceptable with time (ref 6/7/8).

The geometry of the panel is 600 mm square by 100 mm thick, the distance be-tween the lower supports was 500 mm, the notch was 2 mm thick (saw cut) and 10 mm deep and all the instrumentation system to measure the CMOD will be useful to better understand this phenomena specifically for sprayed concrete using polymer fi-bres.

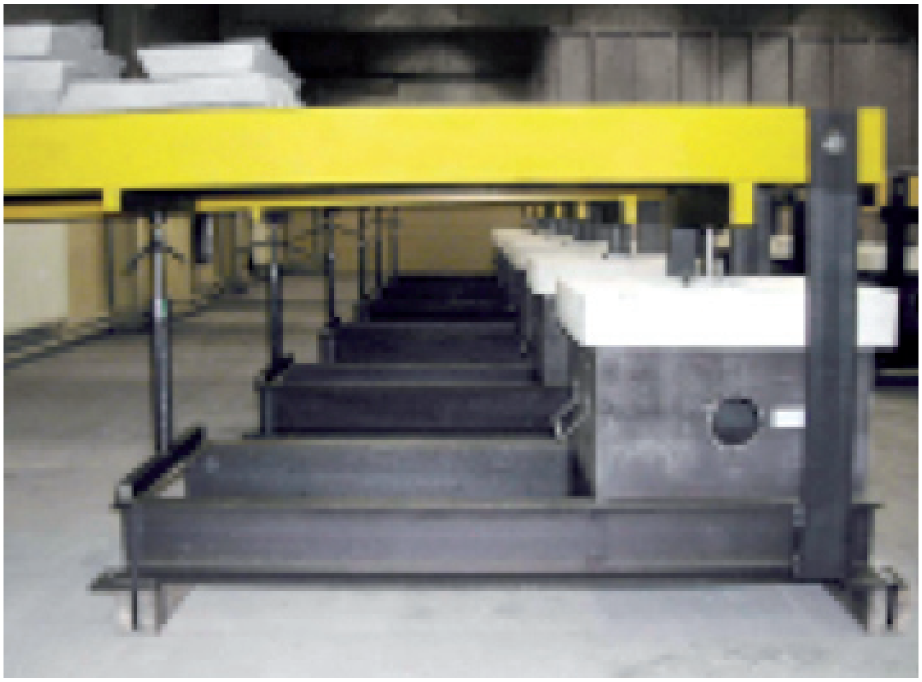
4 CREEP

It is important to consider the creep behaviour of the material as the final lining will be cast many months later. Creep test has shown that steel fibre RC65/35BN will not creep over the time.

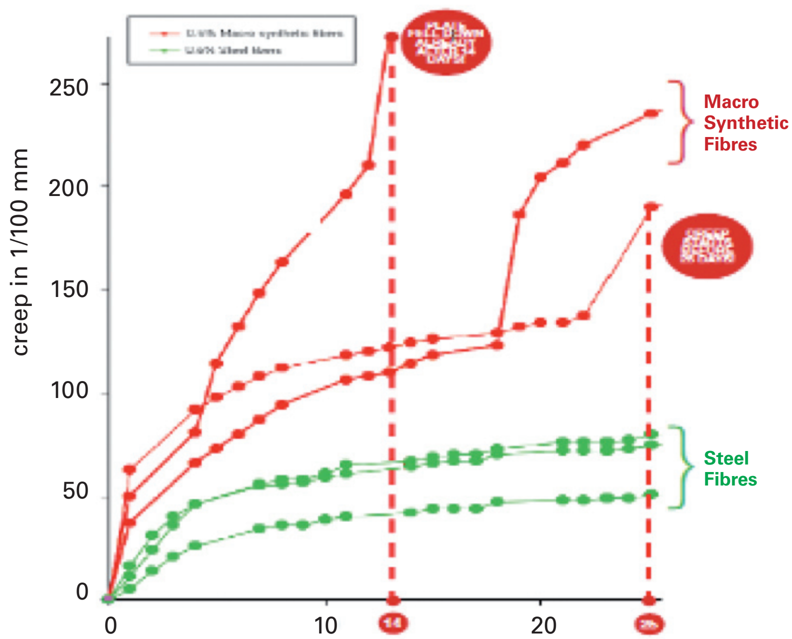
Compared to underground , tunnel linings usually consist of material that are much more uniform and whose be-haviour is better understood , such as cast in situ concrete. However in the case of sprayed concrete used immediate support, it has already been observed that it has already been observed that is early age properties (both in terms of strength and stiffness) change considerably during the construction period. This phenomenon should be taken in account in tunnelling design because the stress re-lease around the tunnel depends on the distance from tunnel face and thus the exca-vation rate . For this reason, the global behaviour of a supported tunnel is influenced both the increase in stress due to the tunnel advancement and the increase of the me-chanical properties of the shortcrete as it hardens (L.Borio Torino university , Bernadini Parma University). More over creep may exert a significance influence on the stress and strains in the lining (the BTC, 2004).

That’s why some test have been conduct to understand this phenomena .the result confirmed that steel fibre remain the best material to take in account this phenomenon and to provide the safety required in tunnelling.

The plates have been tested in a displacement controlled manner as described in EN 14488-5. At a deflection of 3 mm the loa d has been removed.The plates are now ready tobe subjected to the creep test and have been reloaded with 60 % of the ap-plied load at adeflection of 3 mm.



Picture 7: Creep test set up.
The deflection is measured and shown on the Y-axis in 1/100 mm as on the graph.

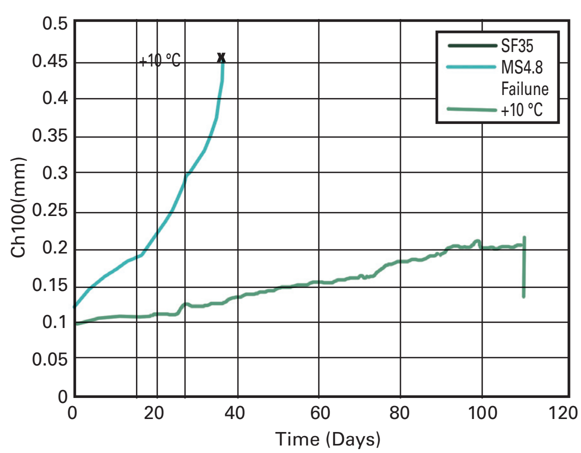


Picture 8: Creep test result curve creep 1/100mm-days.

We can observed from picture 8 ,that some plate with polymer fibre fell down after 14 days .Indeed we should create structures which are capable to take up the required loads and deformation today , but due to the creep effect of the material , crack open-ing and deformation could become too big and result in an unacceptable structure to-morrow.

New test result have been recently conduct in University of Bologna, "Long term be-haviour of steel and macro-synthetic-fibre reinforced concrete beams". This report con-firm that creep deformations may be extremely important especially as far as macro-synthetic fibre reinforced concrete are concerned .

Futher more this report the importance of temperature . "Indeed during the second test, the temperature was inci-dentally increase by 10°C for a period of 11 days.During this period the beam reinforced with polymer (MS4.8) fibre showed a significant in-crease in the slope of the CMOD curve while the beam with Steel Fibre (SF35) was less sensitive to the temperature change".



Picture 9 : CMOD (crack mooth opening displacement) increase over time for the beams SF35 and MS4.8.

This curve underligne the influence of temperature (during the long term tests, the beam were kept in a climate room at 20° C and RH 60%) , as an increase of only 10° C will greatly increase the creep phenomena of polymer fibre . We should notice that this level of temperature could be reach in some underground environnement.

Dramix steel fibre (anchorage with hook end, E module>200 00Mpa) play a positive role from early age to hardening concrete. The performance of fibre reinforced shot-crete is measured according to the three-point bending test of European standard EN 14487-1 Sprayed Concrete.

5 CONCLUSION

The European standard EN 14487-1 mentions the different ways of specifying the duc-tility of fibre reinforced sprayed concrete in terms of residual strength and energy ab-sorption capacity. It also mentions that both ways are not exactly comparable. The en-ergy 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 deforma-tion of the rock. (Especially useful for primary sprayed concrete linings). 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 (hypesrtactic test allowing inde-terminate multicrack process). 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 structural test method; this method serves to quantify and illustrate the ductile behavior of a steelfi-bre reinforced sprayed concrete tunnel lining. The residual strength can be prescribed when the concrete characteristics are used in a structural design model.

In order to improve the approach to get the residual strength, a new test method described in this paper will fulfil the 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 labo-ratory (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.
- No need to cut beam from a panel.
- The specimen could also be sprayed on the job site.
- The scatter will be lower than with the current standardised beam test.

Further more the mechanical properties obtained from this test include the residual flexure strength at the following deflections currently used by the designer:

For SLS design=> $_{fR,1}$=residual strength at a CMOD = 0.5 mm.

For ULSLS design=> $_{fR,4}$ = residual strength at a CMOD = 3.5 mm.

For all this test procedure seems to be relevant for this type of investigation in order to provide to an engineer useful information regarding the performance of FRS materials. This test could be used in the future to determine the residual strength and to compare different types of fibre reinforced concrete.

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