Creep behaviour of fibre reinforced sprayed concrete

Catherine Larive, CETU, France, catherine.larive@developpement-durable.gouv.fr
Damien Rogat, Sigma Béton, France, damien.rogat@vicat.fr
David Chamoley, CETU, France, david.chamoley@developpement-durable.gouv.fr
Nathan Welby, Nouvetra, France, nwelby@nouvetra.com
André Regnard, Asquapro, France, andre.regnard@yahoo.fr

Topic: Planning and designing tunnels and underground structures

Summary: Fibre Reinforced Sprayed Concrete (FRSC) is commonly used for underground support. Various types of fibres are suitable to reach the usually required specifications on energy absorption. However the use of FRSC still raises questions. One of them is about the long-term behaviour under sustained flexural load (creep). ASQUAPRO launched specific tests on this subject in October 2014, using six different fibres and a welded mesh. The experimental program and the test procedure to assess creep are presented. The principle of this creep test is the same as the energy absorption capacity test, but on a longer run. Preliminary testing has been carried out on two types of sprayed concrete, one reinforced with metallic fibres and the other with polymeric fibres. This preliminary testing showed significantly different behaviours but no failure after one year of testing. The pre-cracking procedure appears to have a significant influence on the results. New, more restrictive, specifications on the energy absorption test are also discussed.

Keywords:  creep, sprayed concrete, underground support, fibre

1. Introduction

Fibre Reinforced Sprayed Concrete (FRSC) has been commonly used for underground support reinforcement since the early 70s. This method allows for the replacement of traditional steel mesh which can in some circumstances be a difficult and dangerous installation process particularly when the geometry of the excavated structure is irregular.

Two principal macro fibre types are used to reinforce sprayed concrete for underground support: steel and polymeric fibres. Other types of fibres such as fiberglass and amorphous metallic fibres are available but are not used for this purpose.

Each of these fibre types are defined by their material composition, and also by their intrinsic mechanical performances, lengths, diameters, shapes, textures and so on.

All these characteristics contribute to establishing a particular fibre's performance level. However, the concrete matrix, mixing and casting conditions (equipment, operators, weather, etc.) and curing must also to be taken into account. That is why it is difficult to compare the performance of different fibres, as all these conditions are variable from one project to another.

In 2005 the idea of an experimental program testing several types of fibre in a single concrete matrix, using the same mixing plant, spraying equipment and spraying operator was raised by ITA's workgroup WG 12 “Shotcrete”. After discussion, the choice of the concrete matrix was taken but there was still a lack of consensus concerning the long term experiments: what kind of tests and what procedures should be used.
Asquapro decided to reactivate such an experimental program. To achieve this objective of comparison of different fibres, the first stage is to standardise the characteristics which have an impact on the results; the second stage is to define what kind of performance tests should be carried out.

After publication of Asquapro's latest specifications about “Fibre contribution to reinforce sprayed concrete for underground support”, it was decided to identify a creep behaviour testing procedure specially dedicated to fibre reinforced sprayed concrete for underground support.

We concentrated on creep behaviour because currently it is a limiting factor in the use of the Model Code design method [1] as well as generally being a risk factor that should be better evaluated and understood for all long term applications.

For short term experimentation, compressive strength tests are performed and completed along with residual flexural strength or energy absorption capacity measurements, depending on the design basis, through calculation methods or empirical considerations.

The long term creep test proposed by Asquapro is based on the energy absorption capacity test method (according to standard NF EN 14488-5) which is used for the sample’s pre-cracking phase and then completed with a punching-bending stress test under constant load. The test methods hyperstatic condition reproduces as close as possible the concrete’s configuration in a tunnel support reinforcement.

Long term experiments aim to study the durability of fibre reinforced concrete in different aggressive environments [2] or to study its long term mechanical behaviour (shrinkage or creep behaviour). This study focuses on creep, proposing a testing method useful for the empirical design of tunnel reinforcement but not be adapted for structural modelling.

On the basis of this creep test procedure, Asquapro started in October 2014 an experimental program thanks to the involvement of six major fibre suppliers. The financial support has also been provided by the CETU (Tunnels Study Centre), the SNCF (French National Railway Company) and RFF (French Railway Network). The different tests are carried out by the laboratory Sigma Béton, also a partner in this research campaign. The spraying of concrete was carried out by Nouvetra using a robot provided by the equipment supplier BMS.

The performance of the fibre reinforced concrete will also be compared to steel mesh reinforced concrete which is still in use for French railway tunnel repairs.

This paper presents the context of the research programme, the material used and the energy absorption capacity test results (according to EN14488-5). It also recalls the latest specifications stated by Asquapro, and then details the procedure for creep behaviour characterisation under punching-bending stress.

The results of the creep tests are not available at the time of publication but the results from the preliminary study which helped to refine the procedure are presented.

2. Asquapro experimental program context

2.1 Objectives

In one of Asquapro’s latest technical documents, the working group for the use of fibre to reinforce concrete in primary underground support [3] explained two principal conclusions:
the need to add new specifications to energy absorption tests (see §3);
the need to define a standard test, in order to evaluate the creep behaviour of FRSC and the potential risk of failure of cracked concretes under long term deflection load (see §4).

To fulfill those objectives, it was decided to commence an experimental campaign:
- to validate Asquapro’s criteria on energy absorption tests;
- to propose and validate a creep behaviour testing procedure;
- to study the creep behaviour of different types of fibres.

2.2 Material characteristics

The choice of the concrete mixture (concrete matrix) was realised to match a standard underground support mixture, using the wet sprayed technique. The recommendations stated in Asquapro’s sprayed concrete mix design manual were followed:
- Aggregates were chosen according to the Asquapro grading range (graph 1) which is slightly different from NF 95-102 in low levels.
- The concrete mixture had the recommended cement content of 400 kg/m³ (table 1).

In order to maintain the fresh concrete workability, minor adjustments with the superplasticizer dosage were necessary between the different mixtures (same concrete matrix but different fibre types).

The test panels were sprayed on the 21 and 23 of October 2014. A robot (Meyco Potenza), operated by a single worker, was used. The activator was electronically added to the mixture depending on the pump flow and the concrete sprayed in a continuous flow. Sika AF53 activator was used with a single 7% dosage for all the sprayed mixtures.

![Graph 1 – Granulates grading range](image)

**Table 1 – Concrete mix design**

<table>
<thead>
<tr>
<th>Component</th>
<th>Designation</th>
<th>Dosage (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0-4mm</td>
<td>1041.00</td>
</tr>
<tr>
<td>Gravel</td>
<td>4-11.2mm</td>
<td>729.00</td>
</tr>
<tr>
<td>Cement</td>
<td>CEM I 52.5N SR3 CE PM-CP2 NF</td>
<td>400.00</td>
</tr>
<tr>
<td>Adjuvant</td>
<td>Tempo11 (0.20% to 0.40%)</td>
<td>0.8 à 1,6</td>
</tr>
<tr>
<td>Water</td>
<td>w/c=0,475</td>
<td>190.00</td>
</tr>
</tbody>
</table>

2.3 Concrete implementation

The outside temperatures were quite different between the two days. The first day, the
ambient temperature ranged between 16°C to 25°C and 6°C to 14°C for the second.

2.4 Fresh concrete characterisation, fibre content

<table>
<thead>
<tr>
<th>Samples</th>
<th>Slump Test (mm)</th>
<th>Fresh concrete density (kg/m³)</th>
<th>Air content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF 01</td>
<td>190</td>
<td>2360</td>
<td>1,8</td>
</tr>
<tr>
<td>BF 02</td>
<td>230</td>
<td>2360</td>
<td>2,1</td>
</tr>
<tr>
<td>BF 03</td>
<td>180</td>
<td>2360</td>
<td>1,9</td>
</tr>
<tr>
<td>BF 04</td>
<td>220</td>
<td>2370</td>
<td>1,9</td>
</tr>
<tr>
<td>BF 05</td>
<td>210</td>
<td>2360</td>
<td>1,9</td>
</tr>
<tr>
<td>BF 06</td>
<td>180</td>
<td>2375</td>
<td>1,5</td>
</tr>
</tbody>
</table>

Fibre content measurements were taken on fresh concrete samples (capacity: 1 litre). The weight of the samples is slightly higher than the weight recommended in EN14488-7 Method B standard.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Fresh concrete dosage (kg/m³) Method B</th>
<th>Dry concrete dosage(kg/m³) Method A</th>
<th>Fibre dosage (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF 01</td>
<td>5,78</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>BF 02</td>
<td>12,06</td>
<td>23,2/20,5/31,3</td>
<td>30</td>
</tr>
<tr>
<td>BF 03</td>
<td>5,66</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>BF 04</td>
<td>12,12/8</td>
<td>26/19,2/24,2</td>
<td>30</td>
</tr>
<tr>
<td>BF 05</td>
<td>9,1/5,86</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>BF 06</td>
<td>21,78/31,35</td>
<td>39,1/31,6/31</td>
<td>25</td>
</tr>
</tbody>
</table>

Concrete slump measurements, fresh concrete densities and air contents are very similar for all the samples.

Table 3 – Fibre content in the specimens

The sampling tool has a circular shape (diameter 16cm*5,5cm high) which makes it easier to get through the fibre reinforced concrete. The analysis and the comparison with other measurements on hardened concrete (EN 14488-7 Method A standard) shows that this sampling method is not efficient (table 3). As the sample is collected from the upper layers of the concrete panels, it only gives approximate contents and it is probably too superficial (conditions that differ from the norm).

This type of test, if perfected, could be relevant on-site because it would potentially give an immediate indication about the compliance of the sprayed concrete operation without waiting for the energy absorption capacity test results.

One solution would be for EN 14488-7 standard to specify precisely a sampling tool suitable for checking accurately the fibre contents of the fresh concrete. Issues raised include the quantity of concrete removed for the sample. The standard states that 1 to 2 kg should be removed, but that may be too small to be representative of the fibre content. However, dealing with more bulky samples risks making the test too time consuming for on-site control. Moreover, this point seems not to be a problem when using the A method of the standard: Measurements were consistent for three similar steel fibre samples compared to the fibre content initially added during the mixing (table 3). However, some results on dry concrete show disproportionately high fibre content.

Figure 2–Concrete sampling cup tool
2.5 Hardened concrete characterisation

<table>
<thead>
<tr>
<th>Compressive strength at 1, 7 and 28 days</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 (MPa)</td>
<td>BF 01 BF 02</td>
</tr>
<tr>
<td></td>
<td>12,5 12,7</td>
</tr>
<tr>
<td>Day 7 (MPa)</td>
<td>BF 03 BF 04</td>
</tr>
<tr>
<td></td>
<td>35,4 36,3</td>
</tr>
<tr>
<td>Day 28 (MPa)</td>
<td>BF 05 BF 06</td>
</tr>
<tr>
<td></td>
<td>45,8 49,2</td>
</tr>
</tbody>
</table>

Table 4 – Compressive strength measurements

The compressive strengths of the fibre reinforced concrete samples were compared. As expected, they were very similar as the addition of fibre at these dose rates has a negligible effect on the compressive strength.

The differences observed between compressive strengths at day one were due to the varying outside temperature while the test panels were sprayed, resulting in differences in hardening rates. This difference was not seen at 7 days showing that the concrete spraying was homogeneous.

All concretes meet the criterion of this study, which is C30/37 class concrete.

3. Results and discussions about energy absorption tests

3.1 Discussion on Asquapro’s new criteria

The ductility of fibre reinforced concrete is the most important characteristic needed in underground tunnel support [4]. The concrete must be able to absorb the crack energy and the fibres must spread the mechanical stresses to avoid brittle failure.

The NF EN 14488-5 standard test is well suited to evaluate fibre reinforced concrete behaviour under punching-bending stress in hyperstatic support conditions. The level of energy absorption up to a 25 mm deflection is the value usually specified for sprayed concrete for underground support.

Asquapro’s recommendations on fibre reinforced concrete used for underground support [5] propose new criteria to analyse more precisely the loading curves obtained from the NF EN 14488-5 standard test.
These main new criteria are:

1) The maximal strength of the elastic zone (\(F_{\text{el-max}}\)) must match a deflection lower than 2 mm.
2) The minimal load after cracking (\(F_{\text{post fiss-min}}\)) until a 5mm deflection must be higher than 70% of \(F_{\text{el-max}}\).

To increase on-site efficiency, energy absorption measurements can be undertaken within 7 days and compared to measurements done for the standard performance tests (carried out at 7 and 28 days).

### 3.2 Comparison between 7 and 28 days results

<table>
<thead>
<tr>
<th>References</th>
<th>Energy at 7 day (J)</th>
<th>Energy at 28 day (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF 01</td>
<td>859</td>
<td>877</td>
</tr>
<tr>
<td>BF 02</td>
<td>668</td>
<td>801</td>
</tr>
<tr>
<td>BF 03</td>
<td>906</td>
<td>958</td>
</tr>
<tr>
<td>BF 04</td>
<td>799</td>
<td>1045</td>
</tr>
<tr>
<td>BF 05</td>
<td>703</td>
<td>836</td>
</tr>
<tr>
<td>BF 06</td>
<td>231</td>
<td>225</td>
</tr>
</tbody>
</table>

Energy absorption capacities were measured at 7 and 28 days after concrete spraying. It was confirmed that the 7 day results reached up to 85% of the 28 day values. This allows us to get an indicative 28 day result as early as 7 days, which can greatly increase on-site efficiency [6].

### Table 5- Average energy absorption rates according to EN 14488-5

One type of fibre reinforced concrete shows lower results than the others. This is due to the particular fibre typology: its elastic range is certainly higher but the drop in the load after cracking is faster and does not reach the performance requirements used in underground reinforcements. Nevertheless, it is useful in order to avoid cracks, either due to load or shrinkage, especially in aggressive environments and thus it is still pertinent to study its creep behaviour compared to other fibres.

### 3.3 Results analysis

In terms of test repeatability, it was often observed that one out of three samples showed significantly different results and thus we recommend preparing four test samples.

All the energy absorption rates meet the criterion stated for the underground support concrete specified in this study, that is:

\[ E_{\text{minimum}} > 500 \text{ Joules} \quad \text{and} \quad E_{\text{average}} > 600 \text{ Joules} \]

*Figure 3*-Energy absorption capacity test (NF EN 14488-5)
The study of the graphs shows that almost all the curves of the sprayed concrete studied meet criteria 1 and 2 as explained above. Nevertheless, there are some curves (for example Graph 3) that can meet the average minimum energy absorption criterion ($E_{average} > 600 \text{ J}$) but do not meet Asquapro’s criterion n°2 because the strength after cracking is below 70% of $F_{el\text{-max}}$. However, the shape of this curve and the final strength level is acceptable.

Graph 3 – Energy absorption capacity test curve

This criterion n°2 can be considered as a “screen” and ensures an acceptable concrete behaviour. If this criterion is not met, then the curve analysis must be sharpened to consider the range of deformation before the fibres can take the strength applied.

4. Creep procedure proposal

This procedure is designed in order to analyse the long term creep behaviour of fibre reinforced sprayed concrete used for tunnel support. The purpose is to add some long term results to the short term results obtained from the energy absorption tests. The creep test procedure involves the following steps:
- precracking the specimens;
- loading them for a specific time period at a specified load (first ‘high’, then ‘moderate’); and
- finally a residual energy absorption test.

4.1 Creep test procedure

The samples are the same as those used for the energy absorption standard test (EN 14488-5). Strict compliance of the square panel thickness is required (60x60x10 cm ±5).

First, the average maximal elastic peak $F_{conc}$ is measured on 3 concrete panels made with the same concrete mix design (without any fibres), loaded at 1mm/min speed. Then, the creep test frames are calibrated at two specified loading levels:

- 1st level: « high » loading: $F=39,62kN$ for the concrete matrix used
  120% of $F_{conc}$ is applied on the square panels.

The transition from the high loading level to the moderate loading level happens when a 2mm deflection is reached.

- 2nd level: « moderate » loading: $F=19,81kN$

The load is divided by 2, which brings the load applied to 60% of the maximal elastic strength of the non-reinforced concrete $F_{conc}$. 
Initially the panels are precracked at 7 day under a punching / bending stress with a loading speed of 1 mm/min until the first elastic limit peak is reached.

The panels are always kept on their test frame in order to prevent any change in the crack opening when they are moved onto the creep frames.

A LVDT displacement sensor is placed in the middle of each sample in order to monitor the deflection.

Measurements are monitored for 1 year. Results are analysed at 1, 3, 6 and 12 months. Some samples are subject to regular camera monitoring.

After the completion of the creep tests, the samples will be tested in residual energy absorption capacity. As with the creep tests carried out by Kaufman [2], the samples are first precracked up to 2mm deflection and then loaded from 48% to 62% (depending on the fibre dosage) of the corresponding strength at the 2mm deflection.

4.2 Preliminary study results

Two deflection levels (already used in some testing procedures) were tested for the precracking operation: 2mm and 3mm deflection. In both cases, the samples cracked to about 90% of their height, which we considered excessive. For the 3 mm deflection, the main crack width reached up to 1.5mm width on the lower face of the sample (see fig. 6). Note that it was observed (see graph 4) that the creep deformations measured on samples precracked at 3 mm deflection were up to 3 times bigger than samples precracked at 2mm deflection.
The level of precracking has a great influence on the creep deformations. Moreover, no behaviour differences can be seen between the different types of fibres during the precracking operation as it is performed under an imposed speed. That is why we chose to first precrack the samples only up to their elastic limit under a speed-controlled loading (1mm/min, as in the EN 14488-5 standard) and then continue to precrack them under a load-controlled stress higher than the concrete’s resistance (“high loading level”, §4.1).

This approach allowed us to determine one important parameter of the concrete behaviour which is its deformation speed under high load. This parameter is closely linked to the safety factor regarding the fibre use. This preliminary test was also used to verify the relevance of load (“F load”, §4.1). It also produced first comparative data between 3 different types of fibres: one polymeric macrofibre, one steel fibre and one amorphous metallic fibre (respectively type A, B and C; see graph 5).

*These fibres are not to be considered as representative of other fibres made with the same materials: many characteristics can be different between fibres made of the same materials.*

The samples were first pre-cracked to $F_{el\text{-}max}$ and then loaded up to 34,28kN. According to the creep test procedure, the load was reduced to 17,14kN (60 % of $F_{el\text{-}max}$) once the
deflection reached 2 mm for fibre A. The test was carried out for 175 days.

*Graph 5- Creep test curves according to fibre type*

### 5. Conclusions and prospects

The testing procedure proposed in this paper to study creep behaviour showed a first comparison between fibres where the applied load was only influenced by the concrete matrix performance. It is important that all the other parameters presented in the article are fixed in order to keep the comparison meaningful.

The continuing study will provide more information about the creep deformations of various fibre reinforced sprayed concrete and show if any disruptions are observed under statically indeterminate support conditions.

After 3 months, different behaviours are observed between fibres; no fibres have failed through rupture or pull-out even though some samples were loaded as soon as 24 hour after spraying. Meanwhile the information obtained from fresh concrete characterisation (fibre content) and from short term tests (energy absorption) are useful to improve on-site controls.

### Bibliography and references


### Acknowledgments

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