

LONG-TERM MATERIAL PERFORMANCE CHECKED ON WORLD'S OLDEST UHPFRC ROAD BRIDGES AT BOURG-LÈS-VALENCE

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Abstract

Overpasses OA4 and OA6 at Bourg-lès-Valence in South-Eastern France are the world's oldest road bridges made of ultra-high performance fibre-reinforced concrete (UHPFRC). They were completed in 2001. From opening to traffic in 2002, no significant maintenance operation has been done. After a decade, the bridges have deserved a detailed survey, deflections were measured and cores were drilled from end transverse zones of one of the bridges spans for long-term performance investigation. Although surface corrosion of the fibres is visible for lower ends of the beams lower flanges, where the surrounding atmosphere is rather humid, fibres are sound in the whole volume of the drilled cylinders, which confirms the high potential durability of the material. Based on characteristics measured on the drilled specimens, the paper details the performance obtained from the tests carried out on the twelve-year old material as compared to the data identified during control of the construction, and concludes on the experience gained.

Résumé

Les passages supérieurs OA4 et OA6 sur la déviation de Bourg-lès-Valence dans le Sud-est de la France sont les plus anciens ponts routiers du monde en béton fibré à ultra-hautes performances (BFUP). Ils ont été construits en 2001. Depuis leur mise en service en 2002, aucune opération de maintenance importante n'a été effectuée. A 10 ans, les ouvrages ont fait l'objet d'une inspection détaillée, leur flèche a été mesurée et des carottes ont été prélevées dans l'entretoise d'about d'un des ponts pour évaluer leur état à long terme. Malgré la corrosion superficielle des fibres visible en sous-face des extrémités des talons des poutres, où l'environnement est humide, les fibres sont saines dans tout le volume des cylindres carottés, confirmant la durabilité potentielle élevée du BFUP. En se basant sur les mesures réalisées sur les carottes, l'article détaille les performances issues des essais réalisés sur le matériau âgé de 12 ans, par comparaison aux valeurs de contrôle lors de la construction, et conclut sur le retour d'expérience ainsi obtenu.

1. INTRODUCTION

Overpasses OA4 and OA6 at Bourg-lès-Valence [1] in South-Eastern France are the world's oldest road bridges made of ultra-high performance fiber-reinforced concrete (UHPFRC). They were completed in 2001 by Quille Company, presently merged within Eiffage. The deck has been made of BSI®-Ceracem. The material properties were established according to a prototype application of just issuing AFGC recommendations. A typical compressive strength of 180 MPa had been achieved [2]. Each span of the decks has been made of five precast parallel Pi-shaped pre-tensioned beams keyed on site longitudinally (Fig. 1). From opening to traffic in 2002, no significant maintenance operation had been done. After a decade, with the support of French Highways Authority and of the operator, it was decided to gain experience based on these structures in site-ageing of UHPFRC used in a typical bridge application.



Figure 1: UHPFRC bridges under completion at Bourg-lès-Valence

The bridges have thus deserved a detailed survey, deflections were measured and cores were drilled from end transverse zones of one of the bridges spans for long-term performance investigation. Mechanical and durability characteristics were measured on the drilled specimens. The paper details the performance obtained from the tests carried out on the twelve-year old material as compared to the data identified during control of the construction, and concludes on the experience gained, complementing lessons obtained from tests on ten-year old specimens from Cattenom power plant beams [3].

2. MAIN FEATURES OF THE DETAILED BRIDGES SURVEY

Both bridges exhibit similar visible features after the detailed survey carried out in April 2012, namely 11 years after the structures completion. They are in overall correct condition with no sign of deck damage (Fig. 2). Elegance of a thin crossing over the highway has been visibly kept. Lack of maintenance and non-corrected initial defects have led to local spalling and water-induced current minor damage on abutments made of ordinary concrete (Fig. 3-a). Persistent humidity or condensation in the lower ends of the beam flanges has led to surface visible corrosion of the fibers (Fig. 3-b). However this aesthetical defect is limited and most of UHPFRC facings have kept grey and glossy (Fig. 4). No significant cracks have appeared at cast-in-place UHPFRC joints between the precast beams.

The OA4 and OA6 bridge deflections have been recorded under favorable conditions (low thermal gradient) and compared to measures carried out in 2002. The evolutions are less than 6 mm while the deviation between measurements and computations was about 15 to 30 mm just after the bridges completion, mainly due to uncertainties concerning creep and temperature effects at the time of measurements.



Figure 2: General view of the bridges in operation.



Figure 3: a) Effect of water stagnations over abutments (left)
b) Limited surface corrosion of the fibres at beam edges and end of lower flange (right)



Figure 4: Pi-shaped UHPFRC beams facings

3. INVESTIGATIONS ON DRILLED CORES

The precast Pi-shaped beams which are the main resisting parts of the deck were not suitable for samples coring. Moreover, no remaining mock-up from the constructions phases remained available. Only cast-in-place parts of the cross-beams over supports could be used, since these parts do not include prestressing tendons and are only lightly reinforced.

3.1 Cores sampling

Cylindrical samples about 200 mm long, 94 mm in diameter have thus been drilled in cross-beams of the bridge OA6 at the end of the deck and above the central support (Fig. 5-6). Drilling direction goes from e to s in the symbols used to designate the parts of the samples (Fig. 7-8). All samples had to be dry-sawn at the ends. Moreover, as deviations were observed from the theoretical cylinder shape, samples #2, 4 and 5 had to be over-drilled for being suitable for mechanical testing. Fibers appear as sound (un-corroded) in the whole volume of the drilled cylinders, which confirms the high potential durability of the material.

The cores were to be used for confirmation of the physical / mechanical / chemical properties of the UHPFRC material used for this bridge, namely BSI®, and possible ageing of these characteristics. Based on the experience of characterization of samples from Cattenom power plant beams [3] and due to the limited material quantity, it was decided not to consider carbonation, which represents a very low-probability risk even for high performance concrete. For initial assessment during construction, bending tensile strength identified in four-point bending tests on un-notched prisms and bending tensile post-peak behaviour identified in three-point bending tests on notched specimens had been used after back analysis to provide the characteristic figures of the design tensile constitutive law. Extracting prisms for performing similar tests on the on-site aged UHPFRC was yet non feasible. Splitting tensile strength is not adapted for characterizing post-peak tensile capacity in fibre-reinforced concrete. Direct tensile tests on cylinders were thus chosen, after AFREM recommendations for fibre-reinforced concrete [4].



Figure 5: Cores drilled from OA6 bridge in the cross-beam above abutment

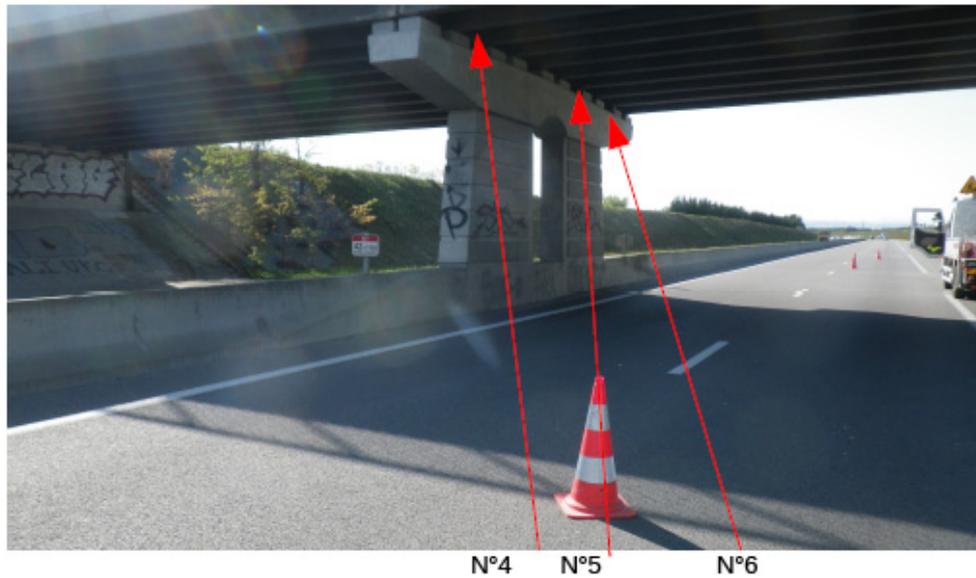


Figure 6: Cores drilled from OA6 bridge over the central support



Figure 7: Visual aspects of cores and coring zone. No fibres corrosion.

Since cores # 1, 3 and 6 had a regular cylinder shape they were used in compressive tests after sawing the ends for ensuring their axis to be orthogonal to the bases (Fig. 8). The available specimen height is about 150 mm for a diameter close to 94 mm. This aspect ratio tends to avoid end confinement during the tests and associated strength overestimation. The ends were kept for porosity measurement. Cores #2, 4 and 5 have been divided in two parts to get six cylinders with an aspect ratio close to 1, to be preferred for direct tensile tests in a rigid testing setup. Namely, the specimens' diameter was 74 mm and their nominal height 73 mm. The layers sawn from the "e" side of the cores were used for chlorides dosage, in order to identify a possible progression in the content of these aggressive ions. Remaining parts were kept for possible SEM observations or additional control measurements in case of unexpected results. Except dry-sawing of samples 2ee1 to 2ee3 and similar for #4 and #5 cores, other operations used water for cooling the sawing or drilling tools. After preparation, specimens were kept unprotected in the laboratory conditions.

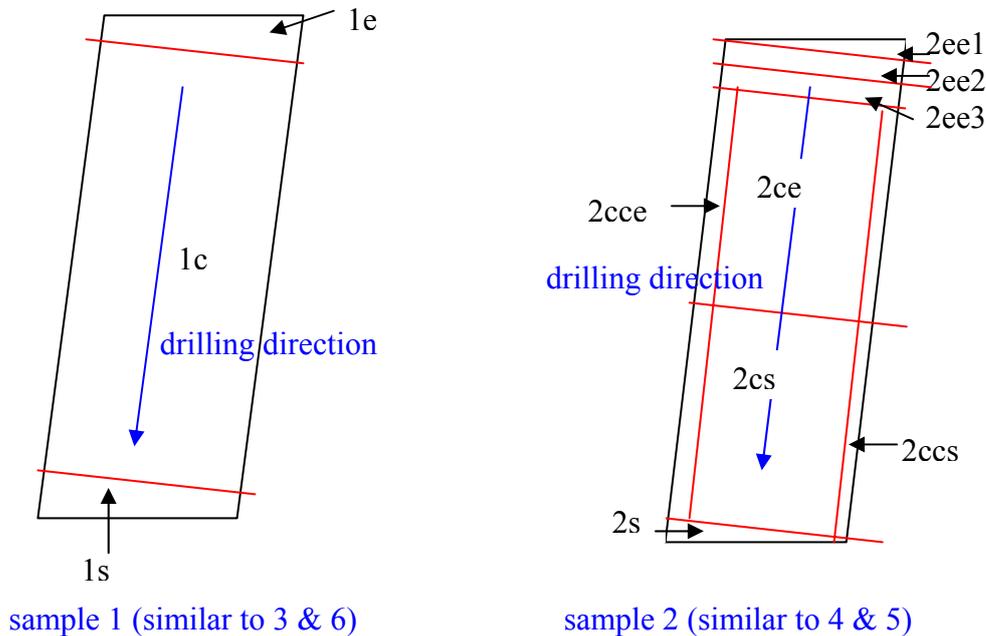


Figure 8: Cores preparation for mechanical, physical and chemical investigations

3.2 Porosity

The porosity accessible to water was measured according to the French standard [5], except the duration for re-saturation of the samples which was set to 72 hours instead of 48 hours. The results are given in Table 1. The mass of the samples was comprised between 390 g and 490 g, which allowed ensuring a deviation in porosity measurements (for repetitive measures on the same specimen) lower than 0.2 %.

Table 1: Physical characteristics at 12 years of age

Sample	Porosity (%)	Saturation degree	Initial specific gravity (kg/m ³)	App. specific gravity (kg/m ³)
1e	8.2	0.90	2813	2740
1s	7.8	0.89	2838	2769
3e	6.8	0.92	2862	2799
6s	7.6	0.91	2840	2771
4ccs (tube)	11.8	0.86	2875	2773
Average (w/o 4ccs)	7.6	0.91	2838	2770

Although specimens had been kept unprotected, the saturation degree is very high, which confirms the very low moisture transfer characteristics of UHPFRC. For the 20 mm disks and even for the tube-shaped specimen 4ccs with only 5 mm-thick walls, drying has remained limited. Mass stability is usually deemed as reached for relative mass variation lower than 0.05 % per day. Conversely to regular concrete, mass stability had not been reached for the UHPFRC specimens following the standard protocol [5]. This is illustrated in Fig. 9. It raises the question of quantitative well-foundedness of standard test protocols to UHPFRC.

It is also further confirmed that the density of the BSI® used in this project was very high. This should be related to the rather high fibre content and to the type of aggregate used. In terms of porosity, the average absolute value of 7.6 % is of the expected order of magnitude, taking into account the duration of the re-saturation period (which was only 24 hours for data documented in [2]). Only the measured value for the thin-walled tube-shaped specimen turns out significantly higher. Explanations may be related to the specimen geometry (surface to volume ratio significantly higher, which has favoured drying), micro-cracking due to drilling operations, and also to the location of the sample (other specimens may have been more compact due to wall effects during UHPFRC casting).

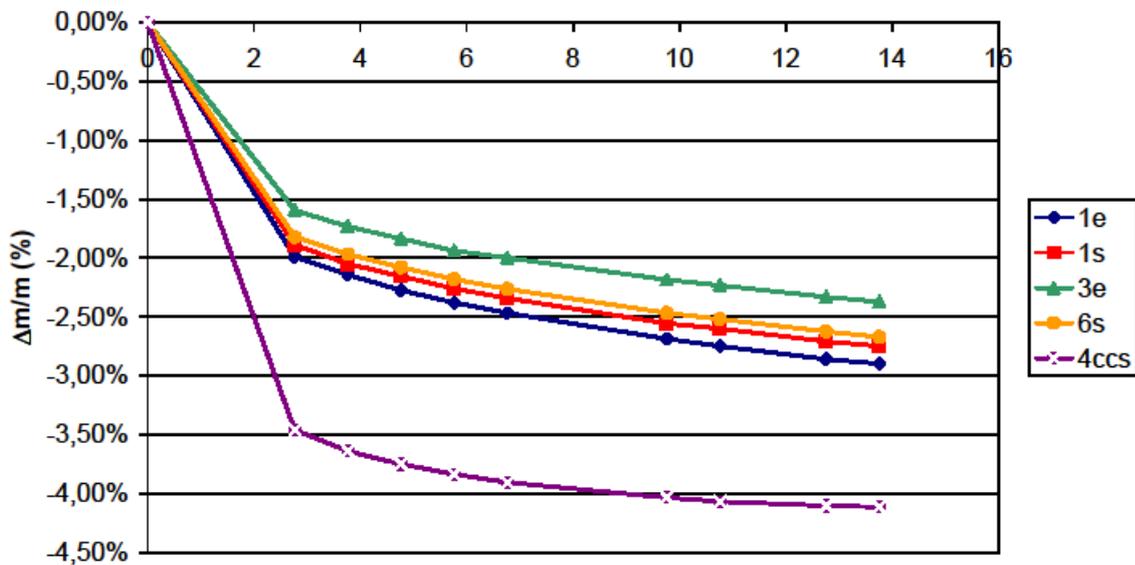


Figure 9: UHPFRC samples drying vs. time in days (specimens 20 mm-thick except 4ccs 5mm-thick)

3.3 Chlorides ingress

Free chloride content was determined according to the recommended protocol [6], on ground material from successive layers of the external wall over the central support (samples 4ee1 to 4ee3, 5ee1 to 5ee3, 94 mm in diameter, about 7 mm thick) and also on samples representative of the core of the crossbeams (2ccs, 5ccs). In all cases, the detected content (displayed in Table 2) is close to the precision of the method (less than 0.02). Although the use of de-icing salts is not intense in this region (probably less than 10 days per year, on average), such limited contents confirm that chlorides have not penetrated inside the UHPFRC and can not contribute to eventual fibre or strands corrosion.

Table 2: Results of the free chloride content dosage (in g of Cl⁻ ions per 100 g of UHPC without fibres)

Sample	4ee1	4ee2	4ee3	5ee1	5ee2	5ee3	2ccs	5ccs
Cl ⁻ content	<0.01	<0.01	0.02	<0.01	0.01	<0.01	0.01	<0.01

3.4 Compressive strength, Young's modulus and Poisson's ratio

Young's modulus was measured following the LPC protocol [7]. Three compressive loading cycles were applied at a 0.3 kN/s loading rate between 70 kN and 419 kN, corresponding to 5 and 30 % of the estimated compressive strength, respectively. Both longitudinal and transverse strains were measured. After having removed the measuring device, specimens were loaded up to failure (Fig. 10). Results are displayed in Table 3.

Poisson's ratio is very close to the expected and common 0.2 value. The measured Young's modulus is rather high, as compared to the generally admitted 65 GPa value for BSI®, generally measured at 28 days of age. Consistently with the high specific gravity, this may be due to ongoing hydration in ageing UHPFRC, provided water supply may be ensured, which is probably the case in the core of the crossbeams considered. The high saturation degree may also explain this result. Such an effective high modulus and ongoing hydration might also be related to the low creep effects observed, inducing prestressed beam geometry having kept a positive counter flexure due to prestressing losses lower as computed based on Young's modulus and creep coefficient measured in laboratory conditions (50 % relative humidity and 2 and 28 days-old material).

After 12 years on-site, the average compressive strength of BSI® is close to 20 % higher than the average 28-days strength generally considered for this material [2]. The cylinders aspect ratio may have had a favourable effect. Their diameter is also somewhat lower than the commonly used cast cylinders, 11 cm in diameter. In the case of cored cylinders, wall effects preventing fibres to be efficient for confinement in the outer part of the cylinder also does not exist (yet even in the present case fibres anchorage in the outer side of the cylinder may also be questioned). These favourable artefacts however hardly explain alone the observed strength increase, which seems also consistent with ongoing slow hydration, already observed for Ductal® after 10 years of age in Cattenom power plant. These results support the safety of AFGC provisions concerning α_{cc} and the UHPFRC design compressive strength [2, 8]



Figure 10: Compressive test, loading up to failure

Table 3: Mechanical characteristics of BSI® at 12 years of age

Sample	Young's modulus (GPa)	Poisson's ratio	Max. Load (kN)	Compressive Strength (MPa)
1c	73.6	0.192	1863.8	270.0
3c	73.9	0.201	1852.6	271.3
6c	72.5	0.195	1714.3	250.2
Average	73.3	0.196	1810.2	263.8

3.5 Tensile strength

Direct tensile tests were carried out on the six cylinders 2ce, 2cs, 4ce, 4cs, 5ce, 5cs obtained from the drilled samples. Since at least one of the ends was affected by wall effects during casting, and due to insufficiently careful gluing process, the un-notched cylinders all failed partly within the glue joint (Fig. 11), with an average tensile capacity ranging from about 6 to 7 MPa. Due to the non-homogeneous failure surface, a realistic evaluation of the tensile strength of the UHPFRC matrix is impossible. Fibre contribution also cannot be quantified. It has thus been decided to test the specimens again, after grinding once more the end surfaces, creating a notch at mid-height and providing a glue over-thickness to prevent weakness in the end sections where fibres are oriented parallel to the glue joint due to wall effect. Although the matrix limit may be not properly identified, a better estimation of the post-peak tensile response is expected from these further tests, which are currently under preparation.



Figure 11 : Direct tensile test specimen after failure within the glue joint.

4. CONCLUSIONS

After a decade, the OA4 and OA6 bridges of Bourg-lès-Valence bypass being the world's oldest road bridges made of UHPFRC have deserved a detailed survey. Deflections were measured and cores were drilled from end crossbeams of one of the bridges spans. Although surface corrosion of the fibres is visible for lower ends of the beams lower flanges, where the surrounding atmosphere is rather humid, fibres are sound in the whole volume of the drilled cylinders and even along most beams facings, which confirms the high potential durability of

the material. A very high saturation degree, absence of chlorides penetration and increase of Young's modulus and compressive strength as compared to 28-days characteristics also confirm the safe evolution of the material, with probable ongoing hydration. Further tensile tests on notched cylinders prepared from the drilled cores are expected to confirm the maintained post-peak tensile capacity of the material, which has been critical for the transverse bending assessment.

ACKNOWLEDGEMENTS

This detailed investigation has been made possible thanks to the help of the French State highways operator in charge of these bridges, represented by Didier Brazillier. Financial help of the Sétra, represented by Grégory Généreux, is also gratefully acknowledged. Support of Thierry Thibaux and Jacques Resplendino who were involved in the bridges project at time of their erection has been highly beneficial. Technical and organization help of Pierre Marchand and Florent Baby from Ifsttar has been greatly appreciated, as well as technical cooperation of Fabienne Ménessier, Serge Hamparian and Sylvie Arnaud from CETE de Lyon.

REFERENCES

- [1] Hajar, Z., Simon, A., *et al.*, 'Construction of the first road bridges made of UHPFRC', 3rd International Symposium on HPC, Orlando, 2003.
- [2] AFGC-Sétra, 'Ultra-high performance fibre-reinforced concretes. Interim Recommendations', 2002.
- [3] Toutlemonde, F., *et al.*, 'Field demonstration of UHPFRC Durability. Girders shown to perform well in a cooling tower', *Concrete International*, November 2010, 39-45.
- [4] Rossi, P., *et al.*, 'Les bétons de fibres métalliques. Recommandations sur les méthodes de dimensionnement, les essais de caractérisation, de convenance et de contrôle. Eléments de structures fonctionnant comme des poutres', AFREM, technical seminar, Dec. 1995.
- [5] NF P 18-459, French Standard, Concrete - Testing hardened concrete, testing porosity and density, March 2010.
- [6] Chaussadent, T., Arliguie, G., 'AFREM test procedures concerning chlorides in concrete: extraction and titration methods', *Materials and Structures* **32**, April 1999, 230-234.
- [7] Torrenti, J.-M., *et al.*, 'Projet de processus d'essai pour la détermination du module de déformation longitudinale du béton', *Bull. LPC*, **220**, 1999, 79-81.
- [8] AFGC, 'Ultra-high performance fibre-reinforced concretes. Recommendations', 2013.