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ULTRA-HIGH PERFORMANCE CONCRETE REINFORCED WITH STAINLESS STEEL FIBRES: FROM MATERIAL OPTIMIZATION TO STRUCTURAL COMPONENT RESPONSE

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Abstract

UHPFRC elements that are reinforced with stainless steel fibres can, after several years, suffer from unattractive, rusty surface points – although tests and publications have validated the material's mechanical integrity under aggressive conditions. For some architectural applications (especially those in white), it was necessary to develop specific solutions in order to cope with this aesthetic issue respecting AFGC/SETRA recommendations. Consequently, a test program of UHPFRC reinforced with stainless steel fibres has been performed at the material level (mechanical characteristics, aesthetical and durability) to verify the structural response was verified on concrete element level and at the project level the applicability of this solution was demonstrated.

Résumé

Les composants en BFUP à fibres métalliques peuvent présenter au fil des années des points de rouilles disgracieux en surface due à une corrosion superficielle des fibres. Des publications et tests ont démontrés l'intégrité structurale du matériau mais d'un point de vue architectural, et tout spécialement lorsque les couleurs requises sont blanches ou claires, il a été nécessaire de proposer des alternatives répondant aux recommandations AFGC/SETRA. Un programme a été lancé de l'échelle matériau (propriétés mécaniques, durabilité, esthétique) jusqu'à l'échelle de la réponse structure sur poutres et prototypes de projets pour valider la possibilité de proposer cette solution sur des projets.

1. INTRODUCTION

Why use stainless steel fibres? For more than 15 years, almost all structural Ultra-high performance fibre reinforced concrete (UHPFRC) projects have been completed with high tensile strength steel fibres for civil engineering and innovative building elements (e.g. MuCEM and Stade Jean Bouin [6]). Nevertheless, on white or light coloured panels, unattractive rusty points at the surface level could appear after several years, even if some publications [4] have demonstrated the mechanical integrity of UHPFRC in aggressive conditions. For "non structural" facade elements, the use of polyvinyl alcohol (PVA) fibres is allowed and this issue is solved. However, for structural applications (bridges/ footbridges), PVA fibres are not suitable to carry high cyclic loading at the ultimate limit state (ULS).

A complete test program has been launched with stainless steel fibres; to validate a suitable fibre content that will respect "AFGC/SETRA recommendations" on a ductility principle and an economical optimum. This work has been performed at three levels:

- First, at the material level, mechanical characteristics have been assessed considering fibre variation according to AFGC SETRA recommendations and using a back analysis method. A durability study was carried out in parallel with the LERM laboratory to validate aesthetic and durability performances.
- Then, at the structural level, UHPFRC beams reinforced with longitudinal steel bars (but no transverse bars) have been tested in shear and flexure at Lyon University with a fibre content variation.
- Last, at the "project level", prototypes of the future "Blandan Footbridge" and "Pont de la Republique", have been erected at 1/1 or 1/2 scales with the fibre content selected in the previous step in order to simulate industrial conditions (rheology) and the response of structural components subjected to combined external forces.

2. MATERIAL LEVEL

For structural applications like bridges and footbridges, the price per ton of UHPFRC premix is frequently more critical than facades where very thin thicknesses (2 cm) leads to a far lower ratio between premix price and component price. To be competitive (compared to steel solutions for instance), a shape optimization is necessary [9] to lower the amount of material. In the case of expensive fibres, a design study should be executed with characteristic values of the matrix.

2.1 Matrix optimization considering various fibre content

The "ductility" principle, in accordance with AFGC recommendations, was to be fulfilled:

AFGC ductility principle (1):

$$\frac{1}{w_0}\int_0^{w_0}\sigma(w)dw \geq \frac{f_{t28}}{2.5}$$

Therefore the following was considered: a matrix combining limestone and silica fume (Ductal B3) exhibiting high durability results with a minimal characteristic strength of 150 MPa, and a thermal treatment (minimal requirement of AFGC interim recommendations [1]) and 130 MPa (not strictly the range of AFGC recommendations; specific checking at structural levels should be performed to extend the existing rules) without thermal treatment. Four fibre contents have been performed in this material study (Table 1).

2.2 Fibre content selection using back analysis and ductility criteria

An inverse analysis on 70 x 70 x 280 mm^3 notched specimens under three-points bending was performed for the four materials. The method developed by Gilles Chanvillard, Pierre Rossi and Pascal Casanova is detailed in [2]. The "moment-crack opening" curve is then analysed to determine the post cracking tensile behaviour with fibre content of 0.5 %; 1 %, 1.5 % and 2 %. It has to be mentioned that stainless steel fibres have a higher elastic strength than steel fibres used in classical Ductal FM. The results are presented below:

Table 1: UHPFRC with and without thermal treatment

Mixes		**N° 3772 Formula Ductal B3 0,5% Fibres SS**	**N° 3773 Formula Ductal B3 1,0% Fibres SS**	**N° 3774 Formula Ductal B3 1,5% Fibres SS**	**N° 3775 Formula Ductal B3 2,0% Fibres SS**	**N°3650 Formula Ductal B3 0,5% Fibres SS**	**N° 3651 Formula Ductal B3 1,0% Fibres SS**	**N° 3652 Formula Ductal B3 1,5% Fibres SS**
Curing Conditions		**Curing: 28 days at 20°C 100% HR**				**Thermal Treated 48 Hrs at 90°C 100% HR**		
Compressive strength on 70 mm cylinders in MPa	Value	149,2	133,6	142,1	136,8	172,6	174,1	167,1
		146,4	135,9	140,9	134,5	163,1	171,6	145,2
		152,6	136,2	131,7	137,4	178,6	143,9	169,9
		131,6	134,5	142,0	134,3	173,0	165,6	150,5
						166,4	174	158,9
						167,2	169,4	160,9
	Mean	**145,0**	**135,1**	**139,2**	**135,8**	**170,2**	**166,4**	**158,8**
	S.D.	*9,3*	*1,2*	*5,0*	*1,6*	*5,6*	*11,5*	*9,5*
4 points flexural strength on 7x7x28 prisms in MPa	Value	15,7	17,7	23,7	27,3	10,0	20,5	25,3
		14,5	16,7	20,5	23,4	12,1	18,6	23,9
		15,4	17,3	23,2	24,4	13,2	21,1	22,2
	Mean	**15,2**	**17,2**	**22,5**	**25,0**	**11,7**	**20,1**	**23,8**
	S.D.	*0,6*	*0,5*	*1,7*	*2,0*	*1,6*	*1,3*	*1,5*

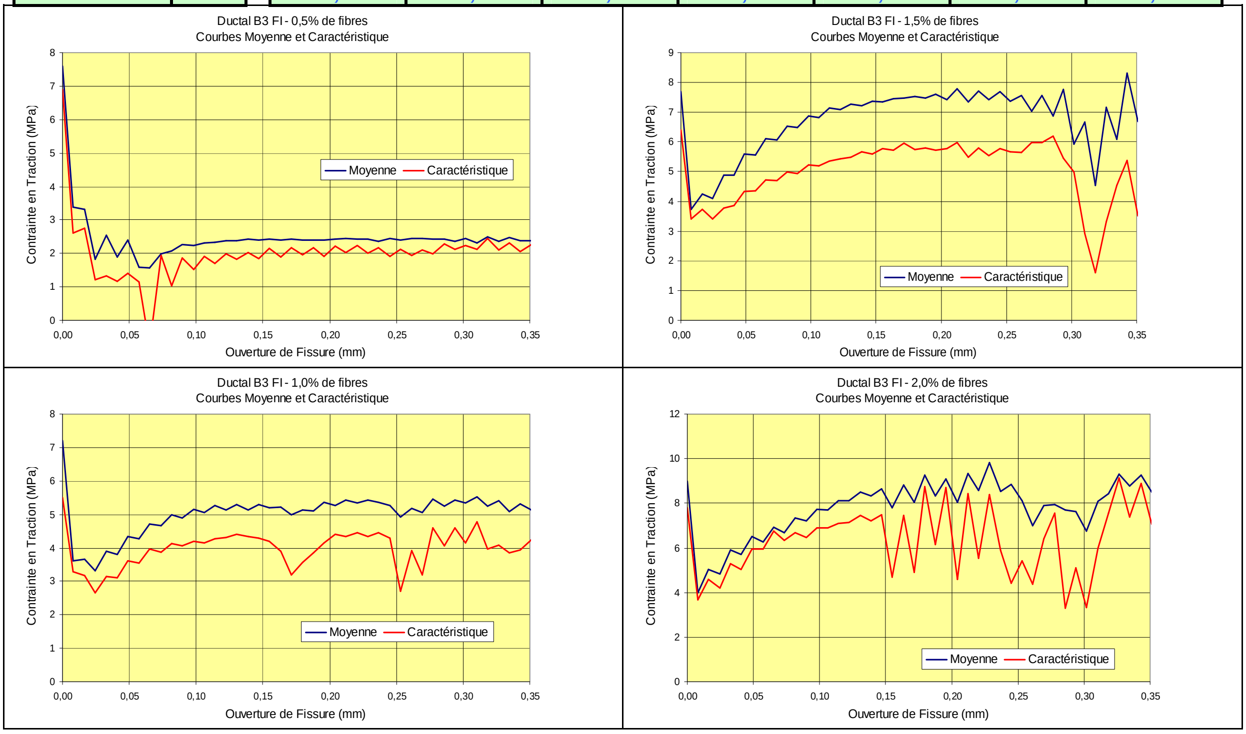


Figure 1: Reverse Analysis with 4 dosages without thermal treatment

Without thermal treatment, f_{tj} = 7 MPa (minimal value according to AFGC). Considering a maximal K factor of 1,75, relation (1) integrating K factor leads to $\sigma_{0,3mm}$ = 5 MPa and a fibre dosage of 1.25% without thermal treatment.

With thermal treatment, f_{tj} = 8.5 MPa. Considering a maximal K factor of 1,75, Equation (1) integrating K factor leads to $\sigma_{0,3mm}$ = 6 MPa and a fibre dosage of 1.5 % with thermal treatment. It is also possible to keep 1.25% but the acceptable K factor is reduced to 1.5 in all directions and for all locations.

2.3 Aesthetic Properties

This part of the program has been performed by LERM SETEC at Arles.

2.3.1 Experimental Program

The experimental study on aesthetical properties is based on visual and microscopic examinations of UHPFRC samples surfaces after exposure to an aggressive environment, simulated through an accelerated chloride penetration test. Two different series of UHPFRC samples – 2 % vol. fibres (dimensions 15x15x5 cm), have been manufactured with two types of fibres: brass-plated steel fibres and stainless steel fibres. Chloride penetration within the material was accelerated two ways:

- Exposure of the 15 x 15 x 5 cm samples to cycles of immersion in a chloride solution (35 g/l of NaCl) for one week, followed by drying at 20°C and 50 % RH, up to 13 cycles. The samples were followed after each period of drying, by visual and magnified counting of rust spots on the 15x15 cm² molded surfaces (Fig. 2). Three samples of each UHPFRC type were tested.
- Chloride migration testing was performed on cored Ø95 x 50 mm samples, according to the principle of the standard XP P 18-462. After immersion under vacuum in an NaOH (0.1 mol/l) solution, each sample is placed in the migration cell between the cathodic compartment containing NaCl (0.5 mol/l) + NaOH (0.1 mol/l) solution, and the anodic compartment containing only the NaOH (0.1 mol/l) solution; the molded surface being exposed to a chloride solution (cathodic compartment). Electrical potential in the range 11 - 14 V/cm is applied axially across the specimen. Three time durations are considered: 5, 14 and 28 days. Visual examinations of the surface have been performed after each period. The chloride penetration depth is also measured by spraying 0.1 M silver nitrate solution on freshly split sections.

2.3.2. Results

A) Immersion in chloride solution /drying cycles

Rust spots appeared on the surface of UHPFRC with brass-plated steel fibres, right after the first cycle (table 3). Their number increased significantly after the second cycle, beyond which the rate of evolution is very slow. Surface samples of UHPFRC containing stainless steel fibres did not show any sign of rust, even after 13 tests cycles (Fig. 3). In fact, a single spot of rust was observed on one sample.

It is important to note that, by this accelerated test, the dimension of the observed spots of rust does not exceed 1 to 2 mm^2, even after 13 cycles. Furthermore, examination of cross sections under magnification indicates that the rust spots are located near the surface sample, up to about 0.2 mm depth within the material, without associated micro-cracks (Fig. 4). Examination under the scanning electron microscope (SEM), coupled to energy dispersive X-ray analysis (EDXA), confirms the superficial extent of the corrosion (Fig. 5).

	brass-plated fiber				stainless fiber			
	Number of corrosion spots							
Nb of cycles/Sample Ref.	*12*	*13*	*19*	*Avr.*	*13*	*15*	*18*	*Avr.*
0	0	0	0	0	0	0	0	0
1	36	127	102	88	0	0	0	0
2	247	270	240	252	0	0	0	0
3	247	270	240	252	0	0	0	0
4	240	265	246	250	0	0	0	0
5	251	259	239	250	0	0	0	0
6	247	261	241	250	0	0	0	0
7	251	260	239	250	0	0	1	0
8	245	269	239	251	0	0	1	0
9	246	274	243	254	0	0	1	0
10	247	273	240	251	0	0	1	0
11	252	280	253	262	0	0	1	0
12	252	280	253	262	0	0	1	0
13	252	280	253	262	0	0	1	0

Table 2 – Results of corrosion spots counted during immersion in chloride solution/drying cycles

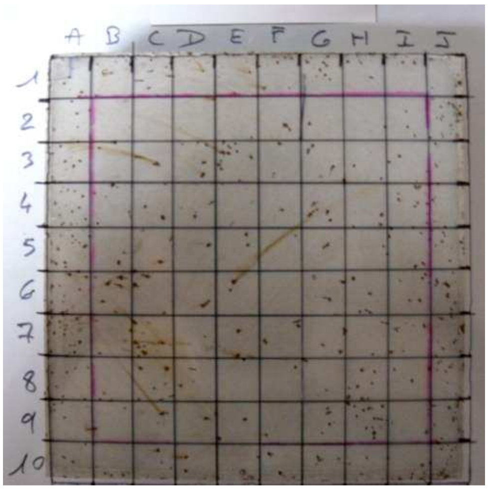


Figure. 2: Illustration of rust spots counted in UHPFRC – high tensile steel fibres, submitted (edge effects excluded)

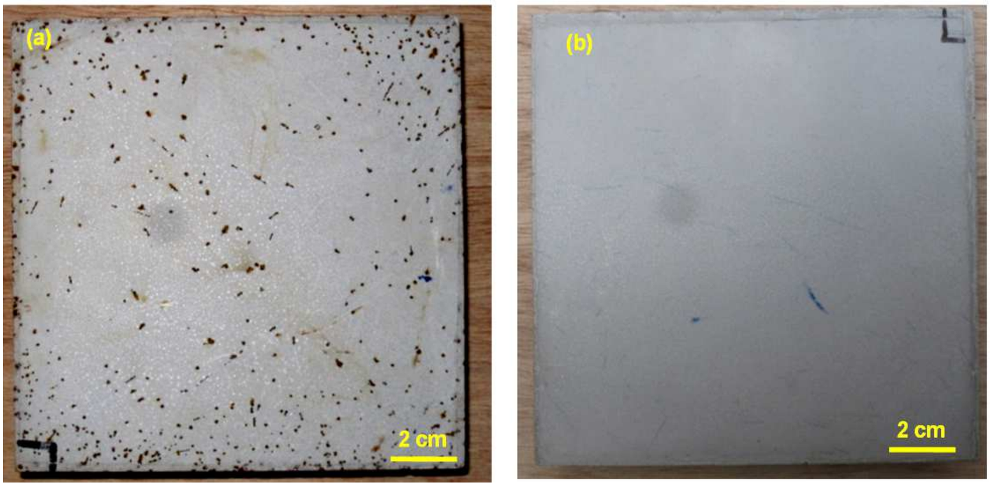


Figure 3: Photographs of UHPFRC samples after 13 cycles of immersion in chloride solution / drying (a) brass-plated steel fibres, (b) stainless steel fibres

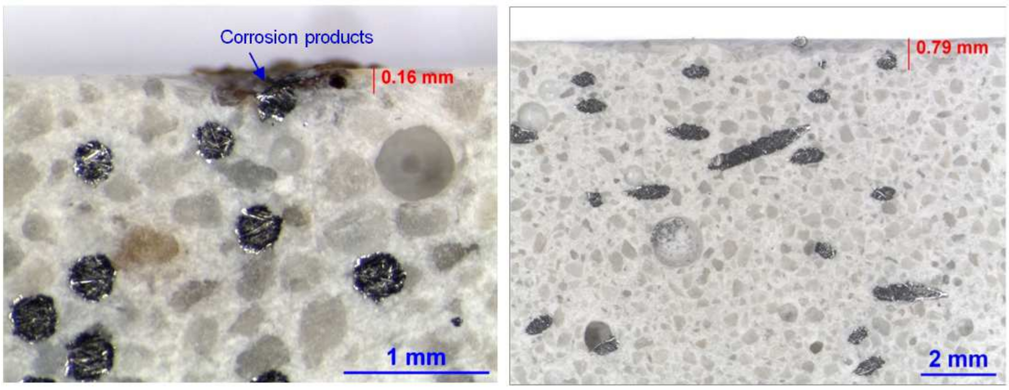


Figure 4: Photographs of UHPFRC samples after 13 cycles of immersion in chloride solution / drying (a) brass-plated steel fibres, (b) stainless steel fibres (no signs of rust spots)

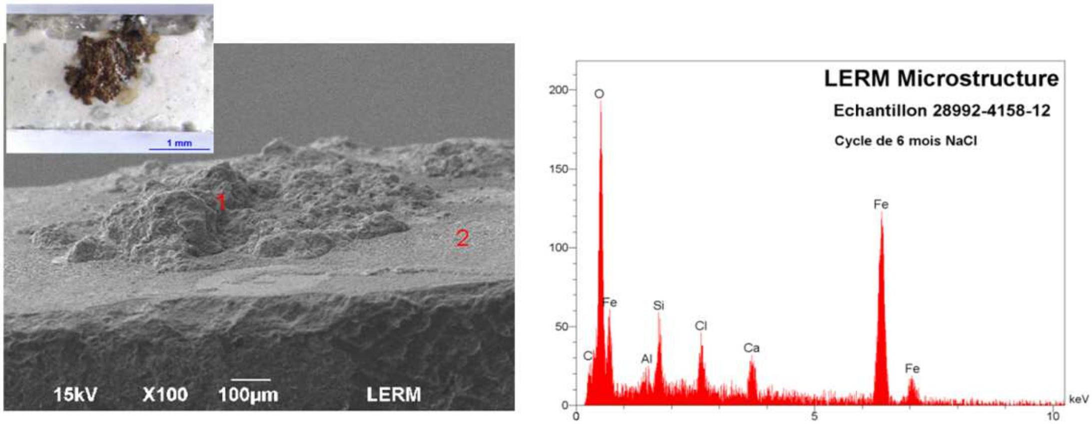


Figure 5: SEM photograph and EDX analysis of corrosion at the surface of a with UHPFRC brass-plated steel fibres after 13 cycles of immersion in chloride solution / drying

B) Migration Tests

In this configuration of experiments on smaller surfaces (Ø 95 mm), the development of corrosion of the fibres has been assessed only qualitatively. After 5 days of testing, a few rust spots (approximately 1 mm diameter) appeared on the surface of UHPFRC with brass-plated steel fibres; the samples containing stainless steel fibres which showed no visible signs of corrosion. The silver nitrate test showed no chloride penetration front within the material. After 14 days of testing, some rust spots with a small diameter (about 1 mm^2) appeared on the surface of the samples when dealing with stainless steel fibres, while rust stains became more frequent and larger (few millimeters squares) when dealing with steel fibres. Micro-cracks and small surface pop outs were also observed under a microscope, near corrosion spots. Since the chloride penetration front could not be clearly revealed, the test has been extended by 28 days.

The number and size of rust areas increased significantly between 14 and 28 days in the case of steel fibres, with more visible associated signs of micro-cracking and micro-scaling (Fig. 6a and 7a). With stainless steel fibres, rust spots are still few (Fig. 6b), but some of them have reached a few millimeters squares and present also scales (Fig. 7b). At this term, a non-uniform chloride penetration front could be observed, with a maximum penetration depth estimated in the range 4 – 7 mm. The apparent chloride diffusion coefficient estimated by this test is about 3 - 5 10^{-14} m^2/s. This coefficient is at least one order of magnitude lower than those of High Performance Concrete. Examinations of magnified cross sections lead to the following observations:

- The formation of expansive corrosion spots induces micro-cracks which are sub parallel to the surface of UHPFRC samples with steel fibres. These signs of damage are observed, however, only to a maximum depth of about 1 mm (Fig. 8a).
- The stainless steel fibres showing signs of corrosion are those turning red on the top of the samples. Indeed, the fibres covered with a thin layer of UHPFRC matrix show no sign of corrosion (Fig. 8b).

The results of this study show the conservation of the initial aspect of UHPFRC using stainless steel fibres after 6 months of exposure to chlorides through cycles of immersion / drying in even more severe conditions of the long-term (28 days) migration test, the surface appearance of UHPFRC samples with stainless steel fibres remains much better than with brass-plated steel fibres.

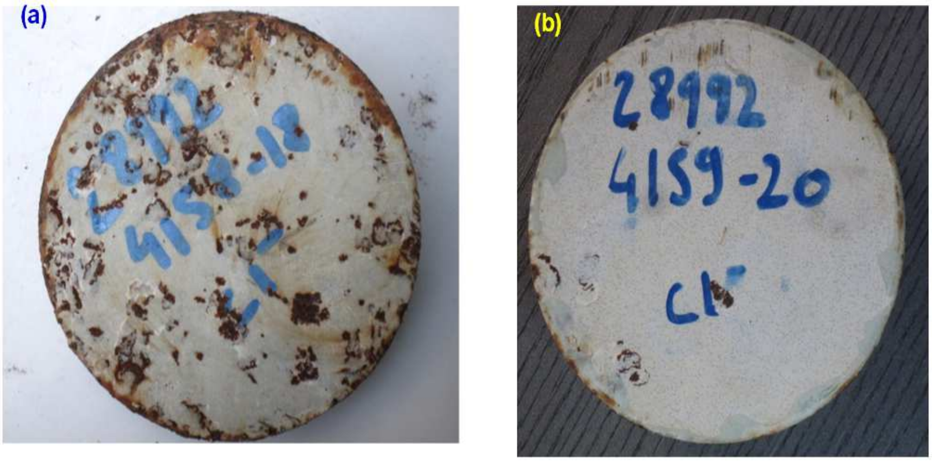


Figure: 6: Global view of UHPFRC surface sample after 28 days of chloride migration test.
(a) brass-plated steel fibre, (b) stainless steel fibre

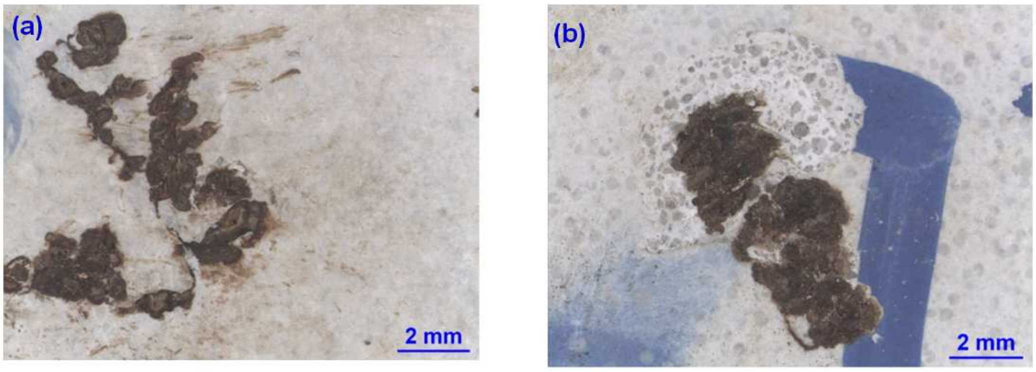


Figure 7: Detail view of surface sample of UHPFRC after 28 days of chloride migration testing.
(a) brass-plated steel fibre, (b) stainless steel fibre

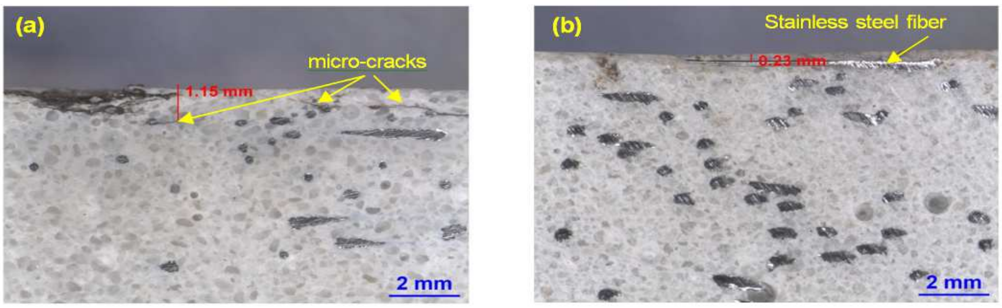


Figure 8: Detail view of a cross section of UHPFRC after 28 days of chloride migration testing.
(a) brass-plated steel fibre, (b) stainless steel fibre

3. STRUCTURAL PROPERTIES

This part of the program has been performed at University LYON 1

3.1 Testing protocol and specimens

Four 1 m length beams with four different fibres have been manufactured at Lafarge Research Centre (LCR). The rectangular section with a h/w=3 corresponds to a size already tested with steel fibres and organic fibres reinforced with and HA8 for comparison purposes [10]. Two 3 point bending flexural tests are performed with spans of 90 cm and 45 cm to reach respectively, flexural and shear failure. Measurement techniques included:

- Vertical displacement measured with an LVDT. Loading is displacement controlled.
- Strain gauges bonded on rebars to assess the steel deformation and identify the load corresponding to yielding of rebars.
- Image correlation to capture crack opening measurement.

Table 3: Geometrical properties and reinforcement (fibre content, rebars) of the beams tested.

N°	Reference	Depth [mm]	Width [mm]	Rebar diameter	Cover (> 1.5 Lf)	Fibres content (%)
1	Ductal beam F-Inox 3772	120	40	HA8	20	0.5
2	Ductal beam F-Inox 3773	120	40	HA8	20	1
3	Ductal beam F-Inox 3774	120	40	HA8	20	1.5
4	Ductal beam F-Inox 3775	120	40	HA8	20	2

3.2 Results and Discussion

Results are presented on the following page.

- It can be noted that, for this configuration and flexure, the benefit of fibres over 1.5% is relatively low. The failure remains non brittle.
- In shear, the fibre content has more impact. For this configuration (over 1.5%), there is no benefit to add more fibres. Nevertheless, below 1%, the failure is brittle, with a reduced capacity (showing the importance of fibres in the ultimate shear strength).
- Image correlation allows good prediction of crack and crack opening.

For this typical size used in ribs for reinforced ribbed panels (e.g. roof), 1.25% leads to an optimized flexural response relative to fibre amount and a good capacity/safety in shear. This is coherent to the non-brittleness criteria explored in part 1 that leads to 1.25% minimal amount with a K factor of 1.75.

4. PROTOTYPES

To assess feasibility, two prototypes programs were performed with two key industrial partners who have participated in several projects with UHPFRC.

4.1 Precast segment: Industrial approach

The “Pont de La République” bridge constructed in white UHPFRC will be erected in Montpellier, France in 2014. To reach specified colors criteria, a mix containing stainless steel fibres was tested under industrial conditions in November 2011 using a ready-mix truck. Molds were heated up to 40°C to allow a reasonable hardening period. No segregation was observed. To achieve a higher whiteness, testing was performed with Titanium dioxide (added to the premix).

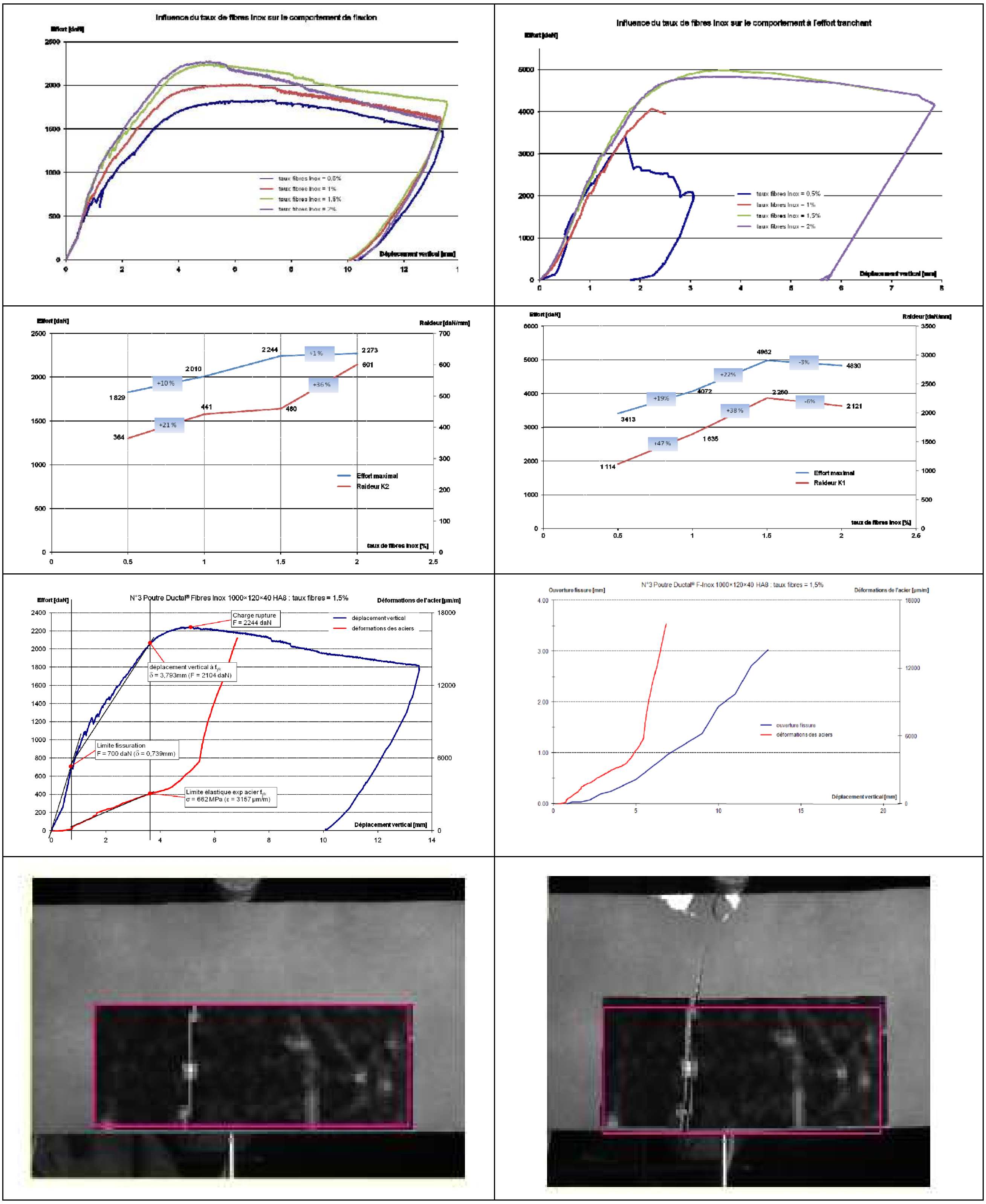
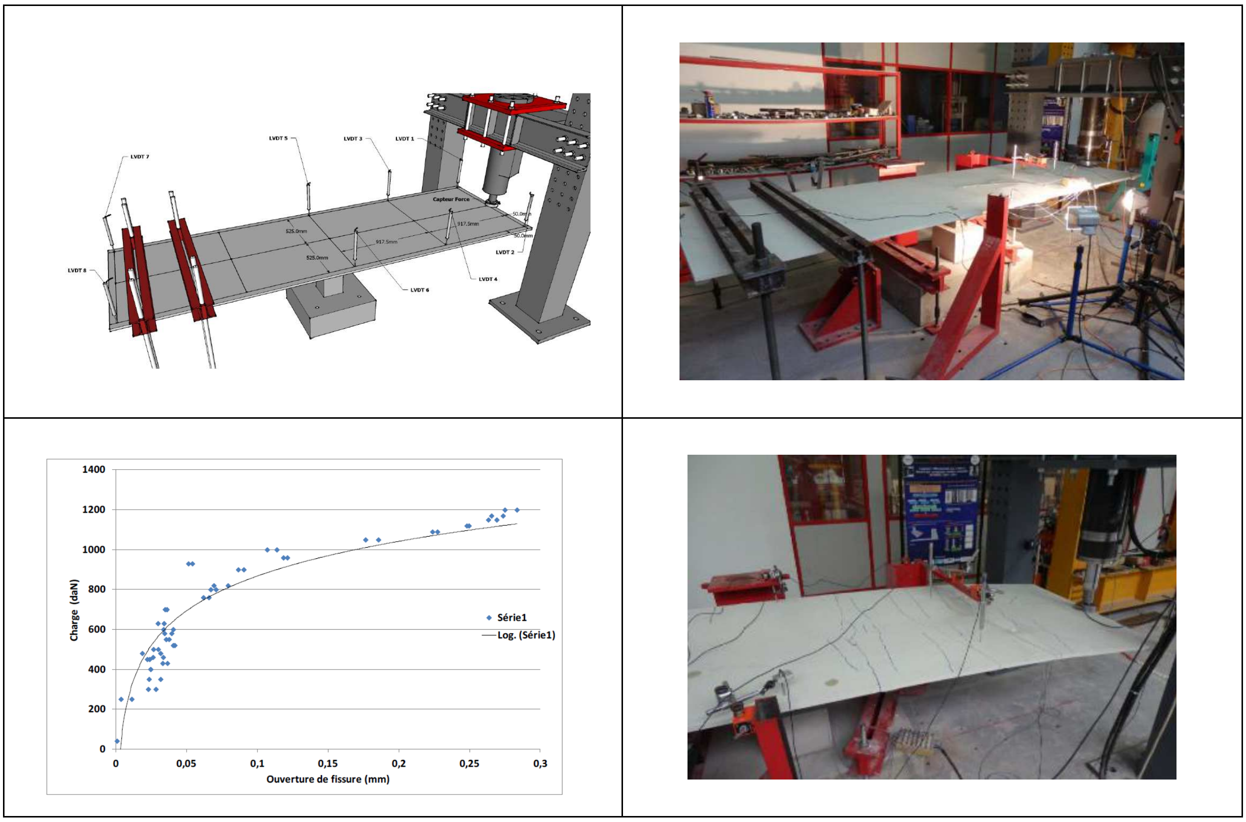


Figure 9: Results compilation (flexure and shear)

4.2 Cantilever deck

A white cantilever deck footbridge was originally planned for construction in the Blandan Park in Lyon, France. This footbridge is loaded in flexure, shear and torsion near the column. Three half-scale prototypes have been manufactured to demonstrate the feasibility of a white solution. One of the prototypes was tested under flexure; the second one in torsion combined to shear and the third is enduring a flexural creep assessment. Analysis of the results is presented in Figure 10 to 14. It was concluded that numerical assessment at the design stage, according to AFGC recommendations, corresponds to the results observed and predicts well the crack opening (key data for the deck at SLS).



Figures 10 to 14: Testing device and crack opening measurement.

5. CONCLUSIONS

To conclude, the UHPFRC presented in this contribution with a characteristic compressive strength of 130 MPa without thermal treatment and 150 MPa with thermal treatment, including stainless steel fibres, respects AFGC SETRA recommendations on ductility. Durability and aesthetic performances have been checked by an independent laboratory and are proved to be successful compared to the original mix design with steel fibres. This solution can be proposed for structural projects with bright colours, with longitudinal rebars as primary reinforcement on members combining local scale internal efforts (punching) and macro scale internal efforts (flexural bending, torsion). Without Thermal Treatment, prototype casting and full scale structural testing are necessary since the material presented is below 150 MPa. Capitalization of those experiments at 130 MPa would allow for future applications, an extension of AFGC Interim Recommendations between 130 MPa and 150 MPa.

ACKNOWLEDGEMENTS

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