CHARACTERIZATION OF LOW COST UHPFRC FOR STRUCTURAL APPLICATIONS

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Abstract

Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) are characterized by outstanding mechanical and durability properties. To reach such performances, their mixes generally require high amounts of cement, silica fume and steel fibres, a very low Water/Binder ratio thanks to a high-range water reducer, and a heat treatment. A research project has been carried out to develop of UHPFRC without heat treatment, using conventional mixer, in order to reduce both the energy applied during production process and the cost which currently limits their uses in construction industry. The mix criteria consist in incorporating local materials and less expensive and more available metakaolin in substitution of silica fume. The paper presents the comparative characterization of two of some tested mixes, a reference one with silica fume and an alternative one with metakaolin. The mechanical and durability results prove the ability of designing UHPFRC mix incorporating metakaolin without heat treatment of equivalent performances to those with silica fume.

Résumé

Les Bétons Fibrés Ultra Performants (BFUP) se caractérisent par des performances mécaniques et de durabilité exceptionnelles. Leurs formulations requièrent très souvent des quantités élevées de ciment, fumée de silice, fibres métalliques, un faible rapport Eau/Liant associé à l'ajout de superplastifiant haut réducteur d'eau, et l'application d'un traitement thermique. Le projet de recherche concerne la mise au point de BFUP dans des malaxeurs conventionnels, non traités thermiquement afin de réduire l'énergie nécessaire à leur production et leurs coûts qui actuellement limitent leur emploi dans le domaine de la construction. Les critères de formulations consistent à incorporer des matériaux locaux dont du métakaolin plus disponible et moins onéreux que la fumée de silice. Une étude de caractérisation comparative de deux des formulations testées, une de référence avec fumée de silice et une seconde avec métakaolin, démontre la faisabilité de formuler des BFUP, sans traitement thermique, avec metakaolin, de propriétés équivalentes à ceux avec fumée de silice.

1. INTRODUCTION

The UHPFRC are cementitious materials of highest mechanical properties characterized by a compressive strength over 150MPa [1, 2] and a high durability [2]. Their matrixes are composed by a high amount of cement, silica fume, fine sand, steel fibres, and high-range water reducer (HRWR). The cement content can be often superior to 1000 kg/m^3 [3]. Among the indispensable ultrafines which can be incorporated in addition or as partial cement replacement, the silica fume is the most used because of its high pozzolanic effect. Its content generally corresponds to 15 % to 25 % by weight of cement [4]. Traditional coarse aggregates are replaced by fine sand in order to improve compactness. Special heat treatment is often required in order to reach compressive strength over 150MPa [1]. All these specific mixes characteristics, high contents of cement, silica fume, superplasticizer, steel fibres, and fine sand, associated with heat treatment lead to a high cost of UHPFRC and restrain its wider applications. A research work in association with a prefabricated concrete enterprise has been led in order to design original UHPFRC mixes of lower cost with a limitation of energy consumption during production process. The design mix is based on the use of ordinary and available local materials, ordinary sand and metakaolin, without heat treatment and using a conventional mixer, as a previous researchers' approach [5]. As silica fume is becoming economically less appropriate because of the progressive disappearance of silicon-alloy manufacturers, it is replaced in this research project, by the metakaolin. This ultrafine is characterized by a less total cost resulting from the availability and the production process [6]. Some researchers have shown that metakaolin is promising addition which can gives equivalent mechanical properties in comparison with silica fume in this type of concretes [7]. In the same objective of reduction ecological impact and cost, the amount of fibres is limited to 2 % by volume which corresponds to the lowest proportion defined by the French UHPFRC material standard [8]. Optimization methods are also applied in order to ensure higher compactness and workability criteria [9].

This paper presents a part of this experimental program led to provide UHPFRC mixes of lower cost and environmental impact with a view of structural applications. It focuses on two mixes, a reference one incorporating silica fume and a second one with metakaolin. The results at fresh and hardened states with mechanical and durability properties are presented and compared. The values are also discussed in relation with French standard for UHPFRC materials [8], based on the previous French recommendations of the Civil Engineering French Association [2]. The first structural application of one the two UHPFRCs is then presented.

2. MATERIALS

2.1 Raw materials and concrete mixes

The cement is an Ordinary Portland Cement (OPC) CEM I 52.5 PMES according to the European 197-1 Standard [10]. This cement is chosen for its mechanical performance and its low C_3A content which limits the water demand and benefits fresh and hardened properties. The silica fume is an industrial by-product of silica obtained by a filtering process during the production of silicon. Their very fine rounded vitreous particles contains up to 95 % of SiO_2. A more economical and eco-friendly alternative solution consists in replacing silica fume by metakaolin. This other pozzolanic addition is produced from the flash calcination of kaolinite clay which is an abundant natural mineral. Its advantages are to be less expensive than silica fume and to be a local material reducing the CO_2 emission due to transport. Only one local coarse silica sand with particles size from 0 to 2 mm, without high fine particles proportion, was selected with the same lowering cost objective. No silica powder is added as this material is expensive. Short straight steel fibres, length of 13 mm and cross-section diameter of 0.2 mm, were incorporated in the designed mixtures. They are characterized by a tensile strength of 3000 MPa and a modulus of elasticity of 200 GPa. Fibres content was fixed at 2 % by volume corresponding to 160 kg/m^3. According to French standard for UHPFRC [8], the use of steel fibres contributing to non-brittleness allows to classify these UHPFRC as type M. A high-range water reducer superplasticizer was used to adjust the workability of concrete. It is noted that the maximum amount of superplasticizer is fixed at 6% by weight of binder.

The two concretes mixes are presented in Table 1. The reference mixture with silica fume and the second one with metakaolin are respectively named UHPFRC-SF and UHPFRC-MK. The comparison of the relevance of silica fume replacement by metakaolin was carried out by maintaining almost constant the other parameters of the mixtures as cement, sand and fibres contents. The metakaolin/binder ratio has been optimized using a wet packing method. The water/binder ratios are then equal to 0.25 and 0.30 for UHPFRC-SF and UHPFRC-MK respectively. Furthermore, the water content has been optimized by taking into account the water absorbed by metakaolin. This absorbed water is not taken into account by European standard [11]. The application of these two optimization methods for the metakaolin UHPFRC-MK is explained and detailed in [9]. A polycarboxylic superplasticizer is used to adjust the workability of concrete and a flow diameter of 300 mm is targeted in order to ensure the self-compacting ability. The estimated materials costs are rather low and the substitution of silica fume by metakaolin leads to a reduction of 13.4 %.

Table 1: Proportions of materials by weight of cement for the two UHPFRCs

Materials	UHPFRC-SF	UHPFRC-MK
Cement CEM I 52.5 (C)	1	1
Silica fume (SF)	0.25	-
Metakaolin (MK)	-	0.30
Sand 0/2 mm (S)	1.07	1.02
Superplasticizer (% of binder weight)	0.046	0.047
Steel fibres (% of concrete volume)	2 %	2 %
Water/Binder	0.20	0.17
Estimated materials cost (€/m^3)	820	710

2.2 Fabrication of UHPFRC

As UHPFRC contains high amounts of fine particles, superplasticizer and fibres, a rigorous mixing process is needed to reach a good homogeneity. The mixing steps are the following:

- all materials were mixed during 2 mn,
- addition of water and superplasticizer, and mixing during 8 mn,
- addition of fibres and mixing during 2 mn.

The mixing has been carried out in a conventional mixer used for other type of concretes. All mixtures were self-compacting, as the slump results will prove it. Thus, no vibration was applied for casting. After demoulding at 1 day, all the samples were stored in a curing room at 20 °C and 95 % of relative humidity until the date of tests.

3. EXPERIMENTAL PROGRAM

The experimental program lies in workability, mechanical and durability tests in order to characterize the two UHPFRCs, to assess the influence of mineral admixture type and to compare with values from French standard for UHPFRC material [8].

3.1 Workability

The workability and flow ability of UHPFRC have been studied through the mini slump test and the mini L-Box The mini slump cone is based on the Abrams cone, used for measuring the workability of concrete according to the French standard [12]. The dimensions of the mini cone respect 1/2 of those of the Abrams cone. The slump value corresponds to the average of diameters measured in two perpendicular directions. The mini L box consists in measuring the flow time needed for the concrete front to reaches the end edge of the L box.

3.2 Mechanical behaviour

The presented results concern a part of the mechanical tests program. 6 samples have been tested for each type of test. The samples were previously stored in a 20°C and 95 % RH room from the demoulding to the date of tests. The compressive strengths, the Young's modulus and the Poisson coefficient have been assessed at 28 days on cylinder of nominal dimensions Ø110 mm x 220 mm. The applied procedure for tensile characterization behaviour corresponds to thick elements [8] with tests on prisms according to the geometry of the project members described further. The samples are 7 x 7 x 28 cm prisms since the fibres length is lower than 15 mm. The four-points and three-points bending tests have been performed in accordance with Annex D of French standard [8]. The four-points bending tests is led on un-notched prism to assess the average limit of elasticity $f_{ctm,el}$ from the force-deflection curve recorded with a rate of 0.1 mm/mn. The three-points bending test is necessary to identify the tensile constitutive law and the contribution of fibres as reinforcement of a cracked section. The notch is 7mm high, corresponding to 10 % of the prism height, and 4mm wide. The test rate is 0.025 mm/mn. The crack width w is recorded in order to obtain the moment-crack law M-w. An inverse analysis is then applied to determinate the equivalent response under direct tension through stress-crack width law σ-w. From these results, the mean value of the post-cracking strength f_{ctfm} is assessed.

3.3 Durability characterization

The concretes durability properties have been characterized during this research program. The presented are the porosity, the diffusivity and carbonation. All the tests have been performed after 90 days of moist curing. The porosity tests have been carried out following French standard [13]. Three cut-out slices Ø110mm x 30mm were first saturated in water under vacuum. To limit the thermal damage caused by heat gradients, the drying was done at 50°C and 80°C for 24 hours at each temperature before the drying at 105°C. The weight loss was then measured until stabilization (weight variation less 0.05 % between two successive measurements within one day). The diffusion coefficient is the parameter which characterizes the transfer of ionic species through the materials due to concentration gradient. The evaluation of the chloride migration from non-steady state migration experiments have been performed on three samples Ø 110 mm x 50 mm [14]. The carbonation test consists in storing 7 x 7 x 28 cm prisms with 50% of CO_2. The prisms were previously submitted to 90 days of moist curing (20°C and 95 % HR) and dried during 2 days at 40°C. The samples are then sprayed of phenolphthalein to assess the depth of carbonation.

4. RESULTS AND DISCUSSION

4.1 Slump and L box flow time

The results of slump and L box flow time measurements performed after mixing are presented in Figure 1. Slump values are equivalent and greater or equal to 30 cm. The concrete can be considered as self-compacting, even if the test procedure is not exactly the same that recommended by the French standard [8]. The L box flow time of UHPFRC-MK is lower than UHPFRC-SF. This reveals the higher viscosity of the concrete with metakaolin. This difference in fresh state behaviour could be by the rounded shape of the silica fume grains facilitates flow compared to the platelet form of metakaolin [15]. However, taking into account the absorbed water by metakaolin using the method explained in [9] and adjusting the superplasticizer content allow a good workability.

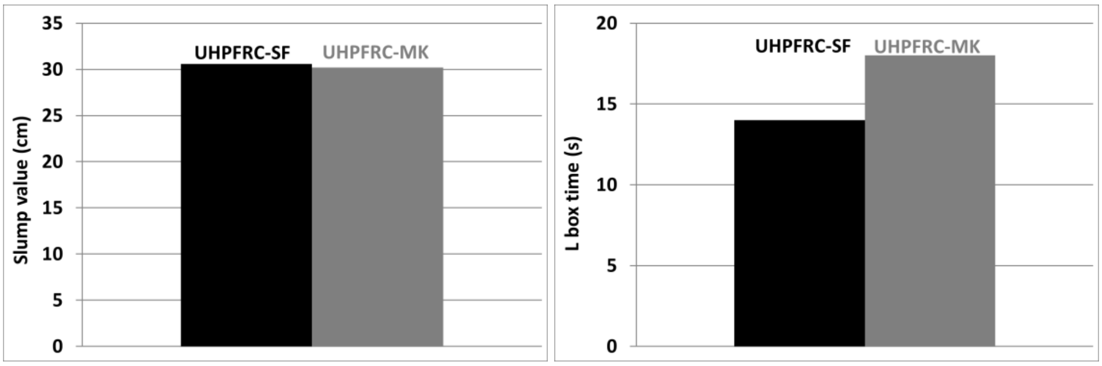

Figure 1: Slump value and L box flow time value

4.2 Mechanical properties

The Table 2 presents the mechanical properties results and the comparison with French UHPFRC material standard criteria for considering concretes as UHPFRC.

Table 2: Mechanical properties of the two UHPFRC at 28 days

Mechanical characteristic	UHPFRC-SF	UHPFRC-MK	French standard criteria [8]
f_{ck} (MPa)	150	152	≥ 150MPa
Young's modulus (GPa)	47	45	-
Poisson's coefficient	0.21	0.21	-
$f_{ctm.el}$ (MPa)	8.4	8.9	-
$f_{ctk,el}$ (MPa)	8.0	8.0	≥ 6MPa
f_{ctfm} (MPa)	11.6	10.4	-
f_{ctfk} (MPa)	7.0	6.6	-

Following the Annex B of French standard, the characteristic value (f_{ck}, $f_{ctk,el}$, f_{ctfk}) are calculated form the mean value respectively (f_{cm}, $f_{ctm,el}$, f_{ctfm}) using Student's law taking into account the number of experimental results and the standard deviation for results of each test [8]. Figure 2 presents the mean curve of σ-w constitutive law obtained from the inverse analysis of the three-points bending tests. This result allows to assess the mean value of the post-cracking strength f_{ctfm}. The results of characteristic compressive strengths and characteristic tensile strengths demonstrate that the two concretes can be graded as S-class and can be called UHPFRC-S. Thus, they can be used for structural application since only this class of UHPFRC is covered by French standard for design of concrete structures with UHPFRC [16]. The overall values prove that the mechanical behaviour of the two UHPFRC are equivalent and the relevance of silica fume substitution by metakaolin coupled with application of optimisation mixing methods.

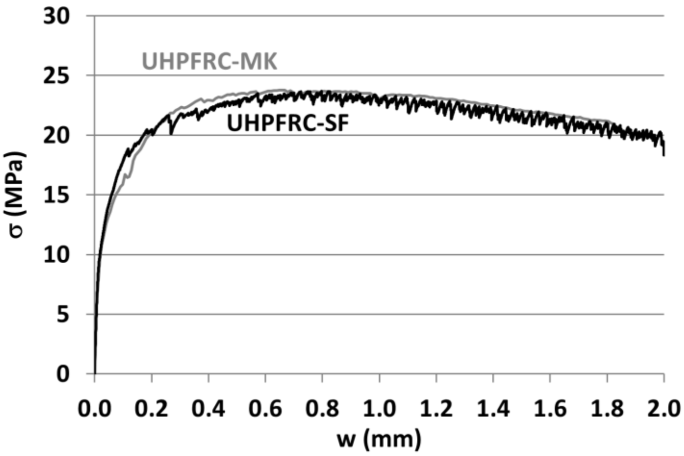

Figure 2: Stress-crack width curves of the two UHPFRCs from three-points bending test

The tensile behaviour class has to be assessed since it conditions the structural design method according to French standard for UHPFRC structures [16]. First, the post-cracking phase of σ-w is divided by the value of orientation factor K_{global} which expresses the effect of the fibres placement. A fixed postulated value of 1.25 can be taken for this parameter. Then, the class is obtained by comparing the limit of elasticity $f_{ct,el}$ and the post-cracking strength f_{ctf} for the mean curve and for the characteristic curve. In case of the concretes, as $f_{ctfm}/1.25 > f_{ctm,el}$ for the average curve and $f_{ctfk}/1.25 < f_{ctk,el}$ for the characteristic curve, the two concretes are of class T2, ie limited strain hardening materials.

4.3 Durability properties

The results of the various test of durability are presented in the Table 3.

Table 3: Values of durability indicators

Durability indicators	UHPFRC-SF	UHPFRC-MK	French standard criteria [9]
Water porosity (%)	7.1 ± 0.2	6.4 ± 0.3	≤ 9.0
Carbonation after 1 year	None	None	-
Apparent diffusion coefficient of chloride ions D_{eff} (m²/s)	$2.5x10^{-14}$ $\pm 1.4x10^{-14}$	$2.7x10^{-14}$ $\pm 1.2x10^{-14}$	$\leq 0.5x10^{-12}$

Globally, the results are similar for the two concretes. The water porosity is lower for UHPFRC-MK with metakaolin probably thanks to the optimization mix method. These values could be reduced by the addition of a second fine sand by optimizing the granular skeleton compactness. However, this solution has not been retained since it could significantly increase the cost and affect the environmental impact associated to sand production and transport. No carbonation is detected. The values of the apparent diffusion coefficient are similar for the two concretes. The values are lower than the values criteria of French standard [8].

5. STRUCTURAL APPLICATION

The producer of prefabricated elements involved in the project has been tasked the rehabilitation of a river bridge. It consisted in the realization of precast bridge deck panel to replace the ancient one. The use of UHPFRC is relevant since it allows a necessary lighter precast slab, an easier and a faster construction process without scaffolding during casting. The UHPFRC slab acts as a lost formwork for concrete casting of the superior reinforced concrete slab (Figure 3). From a preliminary design, the thickness is taken equal to 4 cm. As this thickness is greater than three times the fibres length, the slab has to be considered as a thick element. This explains the applied procedure of tensile behaviour characterization presented before. The concrete chosen is the UHPFRC-MK with metakaolin since it is of S-class and of lower cost. The slabs have been designed following the French standard for UHPFRC structures [16], considering its tensile behaviour of class T2, and taking into account the guide of special technical specifications of this construction. The application of this method is not presented in this paper. No difficulties during concrete production and the casting of these large panels have been encountered. This proves the robustness of the concrete mix.

Figure 3: Inferior face view of the precast UHPFRC slabs of the bridge

6. CONCLUSIONS

A research project has been led with the aim of proposing lower cost and limited energy UHPFRC mixes with a view of industrial application. To achieve this objective, the criteria of design mixture were to use local materials, coarse sand and lower cost and higher available metakaolin in substitution of silica fume, a conventional mixer, to limit steel fibres content, and also to avoid heat treatment and the addition of any other expensive materials such as silica powder or fine sands.

The presented results concern two UHPFRC of type M with steel fibres, a reference one with silica fume and a second optimized mix with metakaolin in replacement of silica fume. At fresh state, they present similar slump and a self-compacting ability. However, the L Box test reveals that metakaolin concrete seems more viscous, probably due to the platelet form of its particles compared to round shape ones of silica fume. Their mechanical performances are similar with characteristic compressive strengths over or equal to 150MPa. According to French UHPFRC materials standard, the two concretes can be classified as UHPFRC-S which means that they are deemed usable for designing structures in accordance with French standard for UHPFRC structures. The analysis of tensile behaviour proves that the two concretes are of class T2, limited strain hardening materials. Some results of the durability indicators are presented. The porosity is slightly lower for UHPFRC with metakaolin which can be explained by the mix optimization method applied for this concrete. No carbonation is observed after 1 year. The diffusion coefficient is similar for the two mixes. The values of these durability indicators respect the French standard for UHPFRC material.

This research has led on a first structural application with the replacement of an ancient bridge deck by a UHPFRC lighter precast slab of 4cm thick. This solution represents an easier and a faster construction process without scaffolding during casting. The design of this lost formwork slab has been carried out following the French standard for design of UHPFRC structures. The UHPFRC with metakaolin has been used. No difficulties during concrete production and the casting of these large panels have been encountered. This proves the robustness of the concrete mix.

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