DESIGN OF UHPFRC WITH ENHANCED DUCTILITY AND FLOWABILITY

E. Ghafari *, H. Costa **, E. Júlio ***

* ICIST & Dep. Civil Eng., Faculty of Sciences and Technology, University of Coimbra
  Rua Luis Reis Santos (Polo II), 3030-788 Coimbra, Portugal
  e-mail: ghafari@dec.uc.pt
** ICIST & Polytechnic Institute of Coimbra – ISEC, Coimbra, Portugal
  Rua Pedro Nunes, Quinta da Nora 3030-100 Coimbra, Portugal
  e-mail: hcosta@isec.pt
*** ICIST & DECivil IST, Technical University of Lisbon, Portugal
  ejulio@civil.ist.utl.pt

Keywords: UHPFRC, steel fibers, aspect ratio, flowability.

Summary: The experimental study herein described was conducted aiming to design UHPFRC with enhanced ductility and flowability. The influence of different type and dosage of steel fibres on the behaviour of UHPFRC was analysed. Steel fibers with different aspect ratio (l/d) were added, individually and blended, to the mixtures. The flexural strengths of all UHPFRC mixtures were measured. The concrete flowability was assessed using both the slump flow test and the V-funnel test. Conclusions are drawn in relation to the optimal addition of steel fibres, i.e., the one leading to the highest flexural strength and simultaneously ensuring self-compacting properties of the mixtures.

1 INTRODUCTION

Ultra high performance concrete (UHPC) presents both ultra-high compressive strength and durability. The major drawback is the reduction in ductility, since this parameter decreases with the increase of the compressive strength. The addition of steel micro fibers to UHPC mixtures improves its ductility, as well as other mechanical properties, due to the crack bridging effect of the fibers. In fact, interlocking effect between the fibers and the binding matrix is responsible for transferring stress from the matrix to the fibers. Thus, after the matrix cracking, all stresses are transferred to the fibers [1]. For this reason, quality enhancement of the matrix-fiber interface is a key issue. In addition, other factors affect the mechanical properties of steel fibers reinforced concrete as well, such as: the fiber type; the volume fraction; and the aspect ratio (length to diameter ratio). Among all the variables mentioned above, the latter has a significant role to improve the fiber-matrix bond, since a higher aspect ratio results in higher pull-out strength of the fiber [1], which finally enhances the mechanical properties of hardened concrete. Nevertheless, higher aspect ratio raised the problem of insufficient workability in the fresh state. On the other hand, the orientation and the uniform distribution of steel fibers in the mixtures, the two most influential parameters on the mechanical properties, are mainly governed by fresh state properties. In fact, orientation and alignment of the fibers is highly dependent on the flowability [2], whereas uniformly dispersed steel fibers can be achieved through the high degree of the mixture’s stability, in which the risk of segregation drops significantly. P. Stähli et al. [3] showed that the alignment of the fibers increases with the increase of the flowability of the mixtures regardless of fiber's aspect ratio.

Self-compacting concrete with high degree of flowability and stability during the placement would be the ideal situation to govern both fiber orientation and dispersion. Markovic [4] expressed that the self-compacting hybrid fiber concrete achieved a much better performance in the mechanical properties as well as pull-out strength, when compared to those of ordinary fiber reinforced concrete.
Fibers can be added to the mixtures either individually or blended, the latter also known as hybrid-fibers. The superior performance of hybrid fibers concrete is gained due to a synergy that has been widely reported [4-7].

The synergetic effect of the hybrid fiber concrete is better categorized by Banthia [6], based on: (i) fiber constitutive response, noting that one type of fiber is stiffer, which provides higher ultimate strength, while the other one is more flexible, leading to an improvement in toughness and ductility; (ii) combination of different dimension and aspect ratio, where small fibers bridges micro cracks, control their growth and lead to a higher tensile strength of the concrete, while larger fibers control macro cracks, resulting in an improvement of the fracture toughness of concrete; (iii) fiber function, which involves the combination of synthetic and steel fibers, where one type of fiber is intended to improve the fresh state properties and to control the effect of plastic shrinkage, while the second type leads to the enhancement of the mechanical properties.

Several works have been performed to study the synergetic effect of steel fibers in UHPC. However, the optimum volume fraction of steel fibers, to ensure an acceptable range of flowability as well as the stability of the mixture, remains to be determined. Therefore, the experimental study herein described was conducted aiming to design UHPFRC with enhanced ductility and flowability, through evaluating the possibility of producing self-compacting UHPFRC. Steel fibers with different aspect ratio (l/d) were added, individually and blended, to the mixtures. The mechanical properties of all UHPFRC mixtures were characterized in terms of flexural strength. The concrete flowability was measured using the slump flow test and the V-funnel test.

2 EXPERIMENTAL PROGRAM

The UHPC mixtures were prepared with the following main constituents: ordinary Portland cement type I 52.5 R, from Secil; silica fume (SF), from SIKA; quartz flour (P600), from “Sibelco”, used as a micro filler (particle size less than 10 µm); silica sand, with maximum aggregate size of 0.6 mm; polycarboxylate ether based superplasticizers, from BASF. In this study, two types of micro steel fibers, with different aspect ratio of 65 and 83, were used. The diameter and length of the fibers were 0.2, 0.15 mm and 13, 10 mm, respectively. The mixture proportions of UHPC specimens are shown in Table 1.

Table 2 shows a series of 20 mixtures of UHPC, with the fiber factors ranged from 0.9 to 2.5, which were arranged both single and hybrid blend. In this study, five fiber ratios of 1-0, 2-1, 1-1, 1-2 and 0-1 were adopted, where the numbers correspond to the proportion of fibers with aspect ratio of 65 and 83, respectively. For instance, 1-0 means that the mixture contains 100 % of fibers with aspect ratio of 65 and fiber ratio of 1-1 means that the mixture has 50% of fibers with aspect ratio of 83 and 50% of fibers with aspect ratio of 83. In order to evaluate the effect of different volume fraction, four values were considered: 1.5, 2.0, 2.5 and 3.0%. Table 2 shows the mixture proportion for the UHPFRC mixtures investigated.

<table>
<thead>
<tr>
<th>Cement</th>
<th>Crushed quartz</th>
<th>Silica fume</th>
<th>Sand</th>
<th>W/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.18</td>
<td>1.3-1.4</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The mixture process involved several steps. First, all powders and silica sand were mixed dry for 5 minutes at low speed. Afterwards, water and superplasticizers were added gradually in two steps. After 5 minutes, the mixtures became fluid. Subsequently, fibers were added and additional mixing was applied for about 2 minutes at high speed. In order to prevent clumping effect, and also to provide the same condition, the fibers were already separated and added to the mixture in the same period of time. After the mixing was completed, tests were conducted immediately, still on fresh state, to determine mini slump flow diameter and mini V-funnel flow time. After mixing, concrete was poured in a mold and, 24 hours later, specimens were removed from the mold. The total experimental campaign
for hardened state characterization consisted of three tests for flexural strength, using prismatic (40×40×160 mm$^3$) specimens. The self-compactability of the mixtures was evaluated according to the standards of Self-Compacting Concrete Committee of EFNARC [8]. The spread cone and the V-funnel were used, having the internal dimensions shown in Fig. 1[9].

Table 2. A series of twenty mixtures based on different volume fraction and fiber ratio

<table>
<thead>
<tr>
<th>Mixture</th>
<th>$V_f$ (%)</th>
<th>$F_r$</th>
<th>$F_{fib}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 1</td>
<td>1.0</td>
<td>0.970</td>
<td>1.050</td>
</tr>
<tr>
<td>M 2</td>
<td>2.1</td>
<td>1.100</td>
<td>1.164</td>
</tr>
<tr>
<td>M 3</td>
<td>1.1</td>
<td>1.245</td>
<td>1.300</td>
</tr>
<tr>
<td>M 4</td>
<td>1.2</td>
<td>1.660</td>
<td>1.408</td>
</tr>
<tr>
<td>M 5</td>
<td>0.1</td>
<td>1.552</td>
<td>1.625</td>
</tr>
<tr>
<td>M 6</td>
<td>2.0</td>
<td>1.050</td>
<td>1.480</td>
</tr>
<tr>
<td>M 7</td>
<td>2.1</td>
<td>1.245</td>
<td>1.480</td>
</tr>
<tr>
<td>M 8</td>
<td>1.1</td>
<td>1.660</td>
<td>1.552</td>
</tr>
<tr>
<td>M 9</td>
<td>1.2</td>
<td>1.625</td>
<td>1.760</td>
</tr>
<tr>
<td>M 10</td>
<td>0.1</td>
<td>1.552</td>
<td>1.850</td>
</tr>
<tr>
<td>M 11</td>
<td>1.0</td>
<td>1.625</td>
<td>1.940</td>
</tr>
<tr>
<td>M 12</td>
<td>2.1</td>
<td>2.075</td>
<td>2.075</td>
</tr>
<tr>
<td>M 13</td>
<td>1.1</td>
<td>2.075</td>
<td>2.112</td>
</tr>
<tr>
<td>M 14</td>
<td>1.2</td>
<td>2.075</td>
<td>2.220</td>
</tr>
<tr>
<td>M 15</td>
<td>0.1</td>
<td>2.075</td>
<td>2.328</td>
</tr>
<tr>
<td>M 16</td>
<td>1.0</td>
<td>2.075</td>
<td>2.500</td>
</tr>
<tr>
<td>M 17</td>
<td>2.1</td>
<td>2.075</td>
<td>2.500</td>
</tr>
<tr>
<td>M 18</td>
<td>1.1</td>
<td>2.075</td>
<td>2.500</td>
</tr>
<tr>
<td>M 19</td>
<td>1.2</td>
<td>2.075</td>
<td>2.500</td>
</tr>
<tr>
<td>M 20</td>
<td>0.1</td>
<td>2.075</td>
<td>2.500</td>
</tr>
</tbody>
</table>

Fig 1: (a) relative slump flow test; (b) mini V-funnel flow test
3 METHODOLOGY

The methodology used in this study involved two main steps: (i) the design of mixtures proportion for plain UHPC-SCC; and (ii) the evaluation of the behavior of SCC-UHPFRC. All the effort in the first step of experimental program was focused on how to design the mixture proportion to produce self-compacting UHPC without fibers. In this regard, the method proposed by Okamura [9] was adopted.

First, the best type and optimum dosage of superplasticizers was selected based on the two main criteria of the best spread value of paste and of the least air content, which has been suggested by Wille et al. [10]. After performing preliminary tests, the optimum dosage of superplasticizers was determined and fixed at 2.5% (by mass of binder). The total amount of aggregate was fixed at 45% of the total volume of concrete, and then the slump test performed on pastes with the following volumetric water to powder ratios (Vwp/Vp): 0.46, 0.48, 0.50, and 0.52. Finally, the obtained values of relative slump Lm corresponding to each Vwp/Vp were plotted. The value of Vwp/Vp ratio for zero flow was determined in the paste. According to Okamura, this value corresponds to βp which is the minimum amount of water requirement to assure a fluid cement paste. The low value of 0.4 for βp was achieved, which implied a high packing density of the mixtures. Afterwards, some tests were performed on fresh state, in order to achieve the acceptable requirement of SCC rheology, which is defined by EFNARC [8], and then the Vwp/Vp ratio was adjusted. Considering the limitation on aggregate size in the mixtures, less than 0.6 mm, the behavior of UHPC in fresh state is similar to self-compacting mortar mixtures, which has been studied before [11].

Afterwards, steel fibers were introduced into the mixtures, aiming to develop self-compacting UHPFRC. This approach was conducted based on the standard range of variation, defined for the two non-dimensional parameters, including the relative slump (Lm) and the relative flow velocity (Rm) [8, 9]. The relative slump flow gives an indication of the potential deformability and the relative flow velocity is a measure for viscosity of the mixtures. In fact, high deformability enables the mixtures to flow under its own weight and adequate viscosity is required to ensure the segregation resistance of the mixtures. In this study, the effort comprised the development of the self-compacting-UHPFRC mixtures with an optimum deformability and viscosity. The Lm parameter is measured on spread test and calculated according to the Eq. (1), while Rm is measured on the V-funnel test and calculated according to Eq. (2), in which: d is the mean value of the two perpendicular diameters, in mm; d0 is a constant value and is defined as the bottom diameter of the truncated slump cone, which was 100 mm: and t represents the time of flow in the V-funnel, measured in seconds.

\[ L_m = \left( \frac{d}{d_0} \right)^2 - 1 \quad \text{where} \quad d = \frac{1}{2} (d_1 + d_2) \]  
\[ R_m = \left( \frac{10}{t} \right) \]

Self Compacting Concrete Committee of EFNARC [8] recommends the target values for slump flow of 24 to 26 cm and of 7 to 11 seconds, respectively for slump test and for V-funnel test. It is noteworthy that this interval has been defined for plain SCC. However, in this research, the lower and upper threshold of this interval, respectively for slump flow and for V-funnel time, was studied in the case of self-compacting UHPFRC containing steel fibers. The fiber factor (Ffib) was used as a parameter to evaluate the workability of the hybrid fiber UHPC[2]. This parameter is calculated according to Eq. (3), in which: Vf is the volume fraction of each type of fiber; Lf is the length of the fiber; and d0 is the diameter of the fiber. Moreover, in order to compare different mixtures with different fiber ratio, the fiber ratio (Fv) was used. Five different ratios were supposed for this study to evaluate the synergy effect, as well as the single effect, of the fibers in the mixtures. (Table1).
4 RESULTS AND DISCUSSION

4.1 Fresh state behaviour

The two main rheological properties of concrete, relative slump and relative flow velocity, were measured to determine the maximum amount of fibers that can be introduced, while the mixtures retain the required workability. In general, high paste content in UHPC mixtures brings the possibility of introducing high amount of fibers in the mixtures. The effect of the fiber ratio and the volume fraction of the fibers on the relative slump is shown in Fig. 2. The results apparently showed that relative slump decreased with the increase of the volume fraction. However, the slump decrease did not follow the same trend for all the mixtures with different fiber ratio, particularly beyond the volume fraction of 2.5%, in volume. It was found that incorporating higher volume fraction of fibers with l/d ratio of 83 in the mixtures led to a significant reduction of flowability, noting that a dramatic reduction in the value of relative slump for the mixtures with fiber ratio of 1-2 and 0-1 was observed. This effect can be observed better in Fig 3, being results presented in terms of fiber factor and relative slump. A lower value of $L_{m}$ indicates lower deformability of the mixtures. The results indicate that when the fiber factor is higher than 2, a poor deformability in the mixtures occurs. (See Fig. 4). In fact, the mixture with the highest volume fraction of fibers with l/d ratio of 83, tended to be more clustered in the mixture, which significantly led to a decrease of the workability.

In general, steel fiber reinforced mixtures showed higher stiffness than plain concrete. It seems that the different flow behavior of self-compacting UHPFRC mixtures from plain-SCC can reduce the threshold defined by EFNARC for plain-SCC. According to Eq. (1), the relative slump corresponding to the lowest value of the slump flow brings us to 4. However, it was observed that this threshold can be lowered, due to the high flowability and stability of the mixtures. Almost all the mixtures with fiber factor below 2, (except the one including only the fibers with the aspect ratio of 83), showed an acceptable range of relative slump. It is relevant that the mixture with relative slump below 3.2 showed poor deformability. The results of V-funnel time according to Vf and l/d ratio are given in Fig 5. The inclusion of steel fibers resulted in a higher viscosity of the mixtures and, as a consequence, the V-funnel time increased with the increase of Vf and l/d.

According to the obtained results from V-funnel test and relative slump, three different zones for the mixtures were specified, which are shown in Fig. 5. The self-compacting zone corresponded to the mixtures having a medium viscosity and high flowability, while the low deformability threshold was determined according to the average value of V-funnel time for the mixtures with acceptable and non acceptable relative slump value, previously discussed in section 3. The segregation zone was specified based on the value of the relative slump for plain–SCC which has already been defined by EFNARC[8]. It should be kept in mind that these three zones were specified at the same constant SP dosage (2.5%) and $V_{w}/V_{p}$ (0.18). It was observed that for all mixtures, except the one with fiber ratio of 1-0, the maximum possible fiber content which assured the self-compactability of the mixtures was 2.5%. A liner correlation between $L_{m}$ and $R_{m}$ parameters for self-compacting UHPFRC mixtures can be seen in Fig 6, and a similar relation has been presented by Okamura for plain SCC [9].
Fig 2: Influence of volume fraction and fiber ratio on relative slump

Fig 3: Influence of fiber factor and fiber ratio on relative slump

Fig 4: Self compacting-UHPFRC slump flow (left); mixture with low deformability (right)

Fig 5: Three specific zones for the mixtures according to V-funnel time and relative slump.
Fig 6: linear correlation between $L_m$ and $R_m$ for SCC-UHPFRC mixtures

4.2 Flexural strength

Results for flexural strength, obtained according to $V_f$ and to fiber ratio are shown in Fig. 7. Both the volume fraction and the aspect ratio were found to be highly effective for flexural strength enhancement. Additionally, results indicated that the flexural strength is influenced by fiber ratio factor. In fact, all mixtures containing steel fibers up to 2.5 vol. (%), higher percentage of fibers, with aspect ratio of 83, led to higher values of flexural strength. When the volume fraction exceeded 2.5 vol.-%, the increasing trend was also observed for the mixtures with fiber ratio of 1-0, 2-1 and 1-1, while for the mixtures with fiber ratio of 1-2 and 0-1 an increase in the volume fraction of fibers did not show any improvement in flexural strength. The distinction in flexural strength behavior of the mixtures with different fiber ratio might be correlated to the rheology parameters of these mixtures in the fresh state, which were categorized in low deformability and self-compactable zone. Therefore, it might be concluded that the mixtures with self-compactability properties showed better performance in improving the flexural strength. In fact, both problems of non-uniform dispersion and bad alignment of the fibers were covered by high stability and flowability of these mixtures.
In addition, the hybrid-fiber mixtures showed better flexural strength than mixtures containing only one fiber type. It can be concluded that, the synergetic effect of self-compactability and of using hybrid fiber allowed to achieve a higher value of flexural strength up to 45 MPa for the mixtures with 1:1 fiber ratio, and 3.0 vol.-% of fiber content.

5 CONCLUSIONS

The aim of the experimental study herein described was to develop and characterize UHPFRC mixtures with self-compactability properties. The following major conclusions can be drawn: (i) UHPFRC-SCC showed a distinct flow behavior from plain-SCC, so that only in the mixtures with relative slump lower than 3.2, low deformability was observed; (ii) The 3 vol.-% was determined as the highest possible fiber content to achieve self-compactability in fresh concrete; (iii) The effect of the volume fraction and fiber ratio on flexural strength is highly dependent on the rheological behavior of mixtures. In the case of self-compacting mixtures, inclusion of higher volume fraction of fibers with l/d ratio of 83 led to an increase of flexural strength, while for the mixture with low deformability, increasing the volume fraction did not improve flexural strength; and (iv) Hybrid fibers exhibited better performance in both fresh and hardened states than mixtures contained only one fiber type. In fact, the synergetic effect of fibers with different aspect ratio led to self-compacting mixtures with high percentage of fibers, which finally led to considerable value of flexural strength.

ACKNOWLEDGEMENT

The authors thank the financial support of the Portuguese Science and Technology Foundation (FCT) for the project PTDC/ECM/098497/2008 entitled Intelligent Super Skin (ISS).
REFERENCES

[4] MARKOVIĆ, I., High-Performance Hybrid-Fibre Concrete.- Development and Utilisation -. 2006, Delft University