TESTING THE FRESH AND HARDENED STATE PERFORMANCE OF STEEL FIBRE REINFORCED SELF-COMPACTING CONCRETE

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Summary: The fibre dispersing ability represents a key distinctive feature of the fresh state performance of a Steel Fibre Reinforced SCC (SFR-SCC) which has to be carefully assessed, also in the sight of its outcomes on the mechanical performance in the hardened state. In this paper, with reference to a typical SFR-SCC mix-composition, different methods to evaluate the resistance to static and dynamic segregation of fibres will be discussed and their results cross analyzed also in order to address a comprehensive testing methodology. Results obtained with reference to fresh state performance will be correlated to the fracture toughness properties in the hardened state, measured on specimens cast according to the same procedure employed for fresh state tests. This will allow a thorough evaluation of the correlation among fresh state performance, fibre dispersion and mechanical properties in the hardened state, furthermore enriching the meaningfulness, in a design oriented perspective, of material acceptance tests for quality control in the fresh state. The responsiveness and robustness of the proposed test methodologies will be finally widely assessed with reference to expected tolerances in the dosage of the mix constituents (water, cement, superplasticizer) which are mainly responsible of the performance in the fresh state.

1 INTRODUCTION

The use of Steel Fibre-Reinforced Self-Compacting Concrete (SFR-SCC) has received a tremendous impulse in the very last years in an attempt to push forward the boundaries of high end structural applications of both Steel Fibre-Reinforced Concrete (SFRC) and Self-Compacting Concrete (SCC) technologies. The synergy between fibre-reinforced and self-compacting concrete has rapidly become a challenge for the construction industry, mainly in the field of prefabrication, which is generally more innovation prone. Dedicated studies have clearly demonstrated that the main advantage of incorporating fibres into self-compacting concrete is the achievement of a more uniform dispersion of fibres within structural elements, thanks to the elimination of compaction and vibration and to the rheological stability of the SCC matrix [1,2]. This requisite is of paramount importance to guarantee a reliable structural performance in FRC members. In fact, any improper compaction and placement, made more complex by the negative effects that fibres have on workability [3], may hinder the random dispersion of the fibres within a structural member. Spots with a reduced fibre dosage or no fibres at all act as flaws and trigger early failures by activating unpredictable mechanisms, that affect the load-bearing capacity and the structural performance as a whole, e.g. in terms of stiffness, fracture toughness, ductility, etc.
Recently, it has also been recognized that fibres can be effectively aligned with the casting-flow direction [2,4,5] mainly by optimizing the viscosity of the fresh concrete. In so doing, the alignment of fibres - under suitable boundary conditions - can adhere to the stress pattern (i.e., to the direction of the principal tensile stresses) inside the structural member in question under the service loads. In this way, superior mechanical and structural properties may be obtained, with a number of benefits in terms of size optimization and self-weight reduction, time- and cost-effectiveness in the construction and transportation processes, something that is valuable particularly in the precast industry.

Transferring research achievements on advanced materials into construction practice and structural design requires simple and reliable procedures to be defined and validated, to measure materials performance in the framework of quality control and acceptance. This is also a smart way to increase the confidence of designers, contractors and end-users in the use of the new materials.

The assessment of SCC performance in the fresh state (including flowability, filling and passing ability, and resistance to static and dynamic segregation) is already well codified in numerous national and international recommendations, guidelines and design codes, and the same holds for FRC in the hardened state with reference – for instance - to the toughness in the cracked state. For example, with reference to the fresh state performance, slump-flow and V-funnel tests have been applied also to FR-SCC, employing either the same or some slightly modified tools as for plain SCC. The same target values adopted in plain SCC proved to be adequate for a quite broad range of fibre types and dosages, even if acceptance criteria based on the results of these tests alone have been recently questioned [6]. On the other hand, concerning the measurement of the performance in the hardened state (which is markedly affected by fibre dispersion and alignment with the applied stresses), the recently issued Model Code 2010 recommends the specimens to be manufactured according to the casting procedure to be used in the actual structure. As for the flow-induced alignment of the fibres, it should be the same as that expected in the actual structure subjected to the anticipated service loads.

In the case of FR-SCC, however, its peculiar features (like fibre dispersing and orienting abilities) should be considered. Some tests and performance indicators should be reconsidered, to adapt them to the peculiar features of the material at issue, and new dedicated test procedures, testing equipments and acceptance criteria should be introduced.

It clearly appears that fibres dispersing and orientating abilities are a key property of FR-SCC, and the chain link between the fresh- and hardened-state performance of the material.

In the present study the issue of performance-oriented testing in FR-SCC is investigated primarily with reference to the fibre-dispersing ability in the fresh state, as this property affects the performance in the hardened state. The effect on both the fresh and hardened state of the tolerances on water content, cement content and superplasticizer (SP) dosage is investigated as well, having in mind the tolerances typical of a precast factory [7].

The performance of FR-SCC in the fresh state has been assessed by means of the slump-flow and V-funnel tests. Different methods have been employed to evaluate (a) the resistance of the mix to fibres static and dynamic segregation, and (b) the fibre-dispersing ability of different FR-SCC mixes. Inspired by similar methodologies introduced for plain SCC [8], the “gradient” of fibre content has been evaluated both in the patties resulting from the slump-flow tests and in a 1.5 m-long beam. Static segregation of fibres in a number of cylinders (r, h = 80, 250 mm) has also been measured. Finally, the correlation between fibres dispersion and orientation (governed by the flow of the fluid mixture along a 1.5 m long beam) and the toughness of cracked concrete in the hardened state has been measured on three 0.5 m-long specimens cut from the same beam, for each of the seven mixes investigated in this project, as resulting from the aforementioned tolerances in mix constituents. The tests will be instrumental in defining the acceptance thresholds for fibres dynamic segregation, thanks to the information coming from the scattering of the toughness in the cracked state, which depends on the number of the fibres crossing the cracked interface and on the tensile strength of the plain matrix.

The comprehensive investigation presented in this study is meant to contribute to the definition of test methods aimed to assess the performance of FR-SCCs, through the correlation among fresh-state properties, fibre dispersion and hardened-state properties.
2 EXPERIMENTAL PROGRAMME

In this study reference is made to a fibre-reinforced self-consolidating concrete (see Table 1 for the mix design) suitable for precast applications [4]. Besides the reference mix, six other mixes were cast and tested, each characterized by different values of water content, cement content or superplasticizer (SP) dosage, always within the limits of the prescribed tolerances (Table 1).

The fresh-state properties of the FR-SCC mixes were determined by means of (a) the slump-flow to measure the slump-flow diameter, SFD, the time to a 500 mm spread (T50) and the time to the final spread (Tf); and (b) the V-funnel test to measure the flow time Tv.

Tests to evaluate the resistance of the mixes to static and dynamic segregation of the fibres were performed as well. For the former, Φ 80 mm cylinders with a h/Φ ratio equal to 3 were cast. Once hardened, the cylinders were cut into three parts and each part was crushed; the weight of the fibres, separated from the debris by means of a magnet, was measured to work out their specific dosage.

With reference to the resistance to dynamic segregation of the fibres, two different methodologies were adopted. Firstly, the slump-flow test and the resulting concrete patty were used. The patty was divided into three concentric circular regions, by means of suitably built steel rings, the inner with a diameter equal to 200 mm (= diameter of the slump cone); the middle with a diameter of 500 mm; and the outer up the final slump diameter. Concrete was extracted from each of the three regions and washed to separate the fibres, which were cleaned, dried and weighed, to evaluate their normalized specific weight in each region. (The volumes were calculated by measuring the slump-flow diameter and thickness of the patty at its centre and at the edges of each region, assuming the free surface of the patty to have a power-law profile). The gradient of the fibre content in the radial direction of the patty was assumed as a measure of the resistance to the dynamic segregation of the fibres in a free unconstrained flow [8]. In order to evaluate the resistance to dynamic segregation in the casting of long members, 2 beams for each mix were cast (length = 1.5 m; width = 15 cm; and depth = 6 cm).

During the casting process, a plexiglass cover was placed at the top of the mould in order to facilitate the filling of the mould and to avoid any spilling of the fluid concrete. The mix was cast into the moulds by means of a 1.5 m long chute inclined by 45°. The mould cover favoured the orientation of the fibres, because of the wall effect along the four sides of the mould [5]. Soon after mould filling, the plexiglass cover was removed and one of the two beams was divided into nine equal segments. Concrete was extracted from each segment and washed to separate the fibres, which were weighed to obtain information about their local concentration. This information was cross-examined with the one obtained from the slump-flow test, to check the reliability and representativeness of the latter test. After hardening, the second beam was cut into three 500 mm-long prismatic specimens, which were tested in 4-point bending to evaluate the fracture toughness, certainly affected by flow-induced fibre dispersion and orientation, that were checked by counting the fibres crossing the fracture surface.

The information given by the experimental program allows to correlate the fresh-state behaviour, the dispersion of the fibres and the hardened-state behaviour in FR-SCC. At the same time, the sensitivity of the material itself (in both the fresh and hardened state) and of the test methodology to the tolerances typical of any mix design can be assessed as well.

Table 1: Mix-design of reference FR-SCC and analyzed tolerances.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Dosage (kg/m³)</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type II 42.5</td>
<td>472</td>
<td>± 2%</td>
</tr>
<tr>
<td>Fly ash</td>
<td>45</td>
<td>=</td>
</tr>
<tr>
<td>Water</td>
<td>216 (w/b = 0.42)</td>
<td>± 5%</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>6 (l/lᵣ)</td>
<td>± 3%</td>
</tr>
<tr>
<td>Sand 0-4 mm</td>
<td>850</td>
<td>=</td>
</tr>
<tr>
<td>Gravel 4-8 mm</td>
<td>886</td>
<td>=</td>
</tr>
<tr>
<td>Fibers 65/35 (lf = 35 mm – lf/df = 35)</td>
<td>50</td>
<td>=</td>
</tr>
</tbody>
</table>

3 EXPERIMENTAL RESULTS: FR-SCC PERFORMANCE IN THE FRESH STATE

3.1 Slump-flow and V-funnel tests

The reference FR-SCC was proportioned for a target slump flow diameter of 650 ± 25 mm and a V-funnel flow time equal to 6 seconds. The performance in the fresh state of the reference mix and of the other investigated mixes is summarized in Table 2. The mix appears to be highly sensitive to the variation of the water content, and moderately sensitive to changes in the SP and cement dosage. For mix 3 and mix 7 manual compaction was needed when casting the 1.5m long beams.

Table 2: Fresh state performance and resistance to static segregation (FSSI) of investigated mixes

<table>
<thead>
<tr>
<th>Mix</th>
<th>W</th>
<th>C</th>
<th>SP</th>
<th>Slump flow test</th>
<th>FSSI</th>
<th>FDSI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SFD (mm)</td>
<td>T_f (s)</td>
<td>T_V (s)</td>
<td>Free</td>
<td>Channel</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>680</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>-5%</td>
<td>0</td>
<td>0</td>
<td>850</td>
<td>1 (?)</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>-5%</td>
<td>0</td>
<td>0</td>
<td>450</td>
<td>not applicable</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>+2%</td>
<td>0</td>
<td>600</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-2%</td>
<td>0</td>
<td>720</td>
<td>4.5</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>+3%</td>
<td>750</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>-3%</td>
<td>550</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

3.2 Resistance to static segregation of fibres

The fibre concentration along the height of the 250 mm-long cylinders is shown in Figure 1 for all mixes. The reference Mix1 showed a good segregation resistance; its response to the changes in the mix design was as expected: excessive water content increases the proneness to static segregation, that is still sizable (even if in more acceptable terms) in the case of excessive dosage of superplasticizer or of less cement in the mix.

The Fibre Static Segregation Index (FSSI) was calculated as the difference between the fibre content in the top and bottom regions of the cylinder, divided by the average fibre content in whole cylinder. In Figure 2 the FSSI has been plotted vs. the indicators of fresh state performance: any increase in the slump-flow diameter and any decrease in the V-funnel flow time tend to increase the proneness to segregation. With reference to T_50 and T_f, the higher meaningfulness of the latter clearly appears [8]. In Figure 2, the ranges of FSSI corresponding to the allowable ranges of the fresh-state performance indicators are indicated, as recommended for plain SCC. Also the resulting acceptable values of the time to the final spread are indicated (so far not considered in the standards).

![Figure 1: Effect of changes in water (a), cement (b) and SP (c) on static segregation of fibers](image-url)
3.3 Resistance to dynamic segregation of fibres: unconstrained flow

The fibre content in the different circular sectors of the patty was measured (as previously mentioned) at the end of the slump-flow test for all mixes. In order to evaluate fibre concentration, the volumes of each of the aforementioned sectors were calculated, assuming a power-law profile for the free surface of the patty, on the basis of the inner and outer diameters of each sector, and of the thickness of the patty itself measured at the edge of each sector by means of a digital calibre provided with shaft to be sunk into the concrete mass.

The results on the normalized fibre concentration versus the normalized radial-spread distance are plotted in Figure 3. The normalizing factors are the average value of the concentration in the whole patty and the final spread, respectively. The mid-point between the inner and the outer radius of each sector was assumed as a reference for the plots. In Mix 7 the outer circular sector (diameter between 500 and 550 mm) resulted of a dimension comparable to that of the fibre and, in the analysis, was merged together with the second one (which hence ranged from 200 to 550 mm).

As previously done in the case of static segregation, a fibre dynamic segregation index in free flow conditions, FDSI_{free flow} was computed as the gradient of the normalized fibre concentration vs. the normalized radial distance. FDSI_{free flow} was not computed for Mixes 3 and 7 for which only two data point were available (Figure 3). The index FDSI_{free flow} is plotted in Figures 4a-c as a function of various indicators of the fresh-state performance. The different roles that the tolerances of the mix constituents play on material’s performance are consistent with previous findings concerning the static segregation of the fibres. Slump-flow diameter, time to final spread and V-funnel flow time appear to be effective predictors of the mix resistance to the dynamic segregation of the fibres. The values of FDSI_{free flow} corresponding to the allowable range of fresh-state performance indicators are also consistent with previous findings on the resistance to fibre static segregation, mainly in terms of time to final spread.

3.4 Resistance to dynamic segregation of fibres: four-sided constrained channel flow

Figure 5 shows the concentration of the fibers as measured along the length of the 1.5 m-long beams. The sensitivity to mix constituents is once again confirmed. A Fibre Dynamic Segregation Index in constrained conditions for the channel flow, FDSI_{channel flow}, has been identified by fitting the trend lines of fiber concentration along the beam length (FDSI is normalized to the average value of fiber concentration). The correlation with the fresh-state performance (Figures 6a-c) confirms once again the reliability of the time-to-final slump spread as a predictor of the resistance to dynamic stability, irrespective of the distance travelled by the mix during the casting process. The consistency with previous results appears with reference to the expected values of FDSI_{channel flow} and to the allowable range of the performance indicators in the fresh-state.
The currently accepted ranges for such parameters as slump-flow diameter, TV and T50 correspond to acceptable values of the static segregation index ($\leq -0.5$) and of the dynamic index ($\leq -0.4$ and $\leq -0.9$ in constrained and unconstrained flow conditions, respectively). For $T_{final}$ the allowable range has been estimated between 5 and 17-22 second.

Figure 3: Effect of changes in water (a), cement (b) and SP (c) on dynamic fibre segregation - free flow

Figure 4: $FDS_{free\ flow}$ vs. indicators of fresh state performance: SFD (a), $T_V$ (b), $T_{SP}-T_{final}$ (c)

Figure 5: Effect of changes in water (a), cement (b) and SP (c) on dynamic fibre segregation four-side constrained channel flow
Figure 6: FDSI{\textsubscript{channel}} flow vs. indicators of fresh state performance: SFD (a), T{\textsubscript{V}} - T{\textsubscript{50}} - T{\textsubscript{final}} (b), V{\textsubscript{slump}} (c)

Figure 7: 4-point bending specimen geometry and test set-up(a); stress vs. COD curves for reference mix (b); mixes with ± 5% water (c,d); mixes with ± 2% cement (e,f) and mixes with ± 3% superplasticizer (g,h)
4 EXPERIMENTAL RESULTS: FR-SCC PERFORMANCE IN THE HARDENED STATE

Figures 7 a-h show the test set-up employed for 4-point bending tests and the nominal stress vs. crack opening curves measured for each of the investigated FR-SCC mixes by means of 4-point bending tests. These were performed over 60 mm thick and 500 mm long beams, tested over a 450 mm span, obtained by cutting into three pieces either 1.5 m long beam cast for each mix (the one not used for the evaluation of dynamic segregation resistance).

The degree of repeatability of the mechanical behaviour among specimens cast with the same material and extracted from the same structure is evidently correlated to the “rheological” stability of the mix, evaluated as above. In fact it clearly appears that the largest scattering has been always obtained for those mixes which also featured the highest tendency to dynamic segregation of fibres. Furthermore the farther the position of the specimen from the casting point, the poorer its fracture toughness. It is here worth remarking that the thickness of the specimens cast and tested in this study was dictated by a specific structural application within the framework of a rather general project focused on the use of FR-SCC in precast prestressed thin-webbed roof elements [4], which can highly benefit from the synergy between FRC and SCC. The former can lead to the elimination of the conventional welded wire-mesh reinforcement (commonly used against shear and lateral bending), which may lead to thicknesses as small as 50-60 mm, since minimum cover requirements do not hold any longer. On the other hand, thanks to SCC not only the construction process is facilitated, but also fibre dispersion can be significantly improved [2] (in vibrated concrete, vibrations favour fibre segregation, from the top to the bottom).

As a matter of fact, a pilot application of FR-SCC [1] was instrumental in starting this project, since it demonstrated the extreme sensitivity of FR-SCC to such factors as the daily fluctuation in aggregate moisture, the mass tolerances in the constituents and the little representativeness of the tests performed on plain SCC in the fresh state, whenever detecting possible flaws (due to the lack of homogeneity) is at issue. As currently performed, these tests (slump flow and V-funnel) provide no information about the fibre dispersing ability of the mixes, which – by governing the mechanical properties of the material (e.g. the post-cracking toughness) - is likely to affect, even dramatically, the structural performance, in terms of load bearing capacity and failure mechanism.

Within this framework and according to the Italian Guidelines on FRC-Structural Design CNR-DT204, the beams cast and tested in this study are “structural specimens”, whose size (mainly the thickness) and casting procedure should adhere - as closely as possible – to the intended application (roof elements), that implies also the mechanical characterization of the material. Furthermore, the length of the beams (1.5 m) is close to half the span (2.5 m) of the roof elements. The length of 1.5 m is also the distance along which the fluid mixture has to flow, according to the casting procedure adopted in this project. Moreover, the top and bottom formwork required by the casting of the roof elements has also been reproduced in each beam to be tested in this project, by covering the formwork with a plexiglass sheet.

In agreement with the aforementioned guidelines, the following stresses have been extracted from the nominal stress vs. crack opening curve, as “indicators” of the toughness of the material:

- the first cracking strength, \( f_{ik} \) (maximum stress in the COD range 0-0.1 mm);
- the equivalent SLS (Serviceability Limit State) stress, \( f_{eq,1} \) (equivalent stress in the crack-opening range 3-5 \( w_i \), where \( w_i \) is the COD value corresponding to \( f_{ik} \));
- the equivalent ULS (Ultimate Limit State) stress \( f_{eq,2} \) (equivalent stress in the crack-opening range 0.02\( h \) ± 20%, where \( h \) is the depth of the specimen; in this case \( h = 60 \text{ mm} \); 0.02 \( h = 1.2 \text{ mm} \)).

Due to the quite significant post-cracking resistance exhibited by the experimental results (Figure 7), the equivalent stress in the crack-opening range 3 mm ± 20% (denoted as \( f_{eq,3\text{mm}} \)) has been calculated as well \( f_{eq,3\text{mm}} \) is a further toughness indicator). A comprehensive list of the results is given in Table 3, together with the cube compressive strength \( f_{c,\text{cube}} \) (mean value from two specimens) and the splitting tensile strength \( f_{spl} \) (mean value from two specimens) measured on the respective plain concrete matrices.
Table 3: Mechanical properties in the hardened state of investigated FR-SCCs

<table>
<thead>
<tr>
<th>Mix</th>
<th>$f_{c,\text{cube}}$ N/mm$^2$</th>
<th>$f_{\text{eq}1}$ N/mm$^2$</th>
<th>$f_{\text{eq}2}$ N/mm$^2$</th>
<th>$f_{\text{eq}3}$ N/mm$^2$</th>
<th>$n^*$ fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59.3</td>
<td>4.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>49.2</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>58.7</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>62.2</td>
<td>5.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>56.8</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>57.7</td>
<td>4.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>59</td>
<td>4.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Influence of mixing tolerance on classification of FR-SCC (MC2010)

<table>
<thead>
<tr>
<th>Mix set</th>
<th>$f_{\text{eq}1}$ (N/mm$^2$)</th>
<th>$f_{\text{eq}2}$ (N/mm$^2$)</th>
<th>$f_{\text{eq}3}$ (N/mm$^2$)</th>
<th>$f_{\text{eq}1,k}$</th>
<th>$f_{\text{eq}2,k}$</th>
<th>$f_{\text{eq}3,k}$</th>
<th>class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-7</td>
<td>4.7</td>
<td>1.4</td>
<td>3.0</td>
<td></td>
<td>0.78</td>
<td>0.57</td>
<td>3.0 b/a</td>
</tr>
<tr>
<td>1-2-3</td>
<td>4.4</td>
<td>1.4</td>
<td>2.6</td>
<td></td>
<td>0.93</td>
<td>0.70</td>
<td>2.5 c/b</td>
</tr>
<tr>
<td>1-4-5</td>
<td>5.9</td>
<td>0.8</td>
<td>4.8</td>
<td></td>
<td>0.95</td>
<td>0.71</td>
<td>4.0 c/b</td>
</tr>
<tr>
<td>1-6-7</td>
<td>4.6</td>
<td>1.3</td>
<td>3.1</td>
<td></td>
<td>0.80</td>
<td>0.55</td>
<td>3.0 b/a</td>
</tr>
</tbody>
</table>

Figure 8 is about the effect that the tolerances in the dosage of the mix constituents have on the cracking strength and on the post-cracking toughness. The rather huge scattering is partly due to the “spatial” dispersion of the fibres and of the concrete properties in the fresh state inside each beam (1.5 m-long), from which the specimens tested for material characterization were extracted.

A first observation is about the bending strength at first cracking $f_{\text{fr}}$, which appears to be sensitive only to the increase in water content, similarly to the tensile strength by splitting in plain matrices. The scattering among the results from nominally-identical specimens appears to be quite insensitive to the variations in the mix constituents. With reference to post-cracking equivalent strengths at different values of the crack opening ($f_{\text{eq}1}$, $f_{\text{eq}2}$, $f_{\text{eq}3}$), it is interesting to observe that not only the average value of the aforementioned parameters is affected by any variation in the dosage of the mix constituent, but also their scattering (which is actually a spatial scattering inside the same structure) is highly affected by any increase in the content of water and/or SP or by any decrease in the cement content. It should be also observed that the mixes with both a lower water and SP content performed quite poorly in the post-cracking regime, even if with a rather limited scattering. A reasonable explanation is that the poorer performance in the fresh state required some manual filling and/or compaction to completely fill the formwork and consequently resulted in a “defective” material. Not
only fibre dispersion was poor (as observed during the mixing stage with the formation of fibre bundles and clusters), but even the bonding at the fibre-matrix interface was poor, due to the voids and macro-pores caused by improper compaction.

Obviously, the scattering in the measured values of material properties affects the material classification, a critical issue when any structural material, and particularly a “new” one such as FR-SCC, is prescribed. The classification of the FRC performance in the hardened state has been recently addressed in the new draft of Model Code 2010, is based on the characteristic value of the residual stress at SLS crack opening (f_{eq,1} as in MC2010), as well as on the ratio between the residual stress at ULS crack opening (f_{eq,3} as in MC2010) and that at SLS crack opening. As in MC2010, the aforementioned post-cracking stresses have to be calculated from the results of 3-point bending tests on notched specimens. Within the framework of this study, the MC2010 concepts have been adapted to the material’s characterization by means of the so-called “structural specimens”. Hence, reference will be made to the characteristic value of f_{eq,1} (f_{eq,1}) and to the ratios to it of either f_{eq,2} or f_{eq,3}mm, the choice depending on the ductility requirements dictated by the design needs.

The characteristic values of the properties related to material’s toughness can be calculated with reference to different sets of experimental results. In Table 4 the mixes are considered all together (from Mix 1 to Mix 7) or selectively (Mixes 1,2,3 – effect of change in water dosage; Mixes 1,4,5 – effect of change in cement dosage; Mixes 1,6,7 – effect of change in SP dosage). The spatial dispersion of the material properties (post-cracking equivalent strengths and “ductility” ratios) is in some way related to the fibre dynamic segregation index as well as to the indicators of fresh-state performance, as shown in Figures 9 a-f by the tentative correlations between the flow gradient and the slump-flow diameter, and the times T_f and T_final.

Figure 8: Effects of variation of mix constituents on toughness properties of FR-SCC: first cracking strength f_{FF} (a) and equivalent stresses f_{eq,1}, f_{eq,2}, f_{eq,3}mm (b-d) and ratios f_{eq,2}/f_{eq,1} and f_{eq,3}mm/f_{eq,1} (e,f).
Figure 9: “Spatial” coefficients of variation of FR-SCC toughness parameters (a-c) and ductility ratios (d-f) vs. indicators of fresh state performance (slump flow diameter, time to final spread, slump velocity)

This clearly shows that an effective control of the material performance in the fresh state, based on the concepts of “fibre dispersing ability”, could also be instrumental to achieve, inside a structural element, not only a more controlled dispersion of material toughness.

Tested specimens were finally broken into halves and fibres on the fracture surface were counted and correlated to both post-cracking equivalent stresses (Figure 10a). The performance in the fresh state is also (Figure 10b-c) responsible of the “rate of decay” of the fibre orientation factor along the casting flow, and hence of the spatial homogeneity of the material performance inside the element.
Figure 10: Post-cracking strength vs. n° fibres (a) and fibre orientation gradient vs. SFD(b) and T\textsubscript{final} (c)

5 CONCLUSIONS

The results presented in this paper and their correlations contribute to shed further light on the significance of fresh-state performance indicators in FR-SCC, and on the allowable ranges wherein the values of such indicators should be included. The allowable ranges valid for plain SCC should be modified in order to take into account the scattering of FR-SCC properties, with reference, e.g., to post-cracking toughness and to the implications ensuing from the intended application and from the requested material and structural performance level. The fresh-state performance should be optimized in order to guarantee the desired performance in the hardened state. The casting process - including the maximum distance that the fluid concrete has to travel from the pouring point - should be explicitly devised to take into account acceptable levels for the spatial dispersion of material’s properties, in order to avoid undesirable effects on the structural performance, because of lack of homogeneity inside the structural members. Coupling structural design with material’s mix design and the technological process used in the manufacture of the structural members is – in authors’ opinion - a cutting-edge topic which deserves further and deeper studies to favour and extend the applications of advanced cement-based materials, such as FR-SCC.

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