DEVELOPMENT AND APPLICATION OF A HIGH PERFORMANCE FIBRE REINFORCED SELF-COMPACTING CONCRETE IN POST-TENSIONING ANCHORAGE ZONES

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Keywords: steel fibres, high-performance fibre reinforced concrete, self-compactability, anchorage zones.

Summary: One of the most critical aspects in post-tensioned structures is the anchorage zones. Despite research works that have been published on this subject, problems during construction and throughout the life of these structures, such as cracking or local failures in anchorage zones, still occur. Apart from issues related to the design and safety assessment, the high density of steel reinforcement is the most common reason for problems with concrete cast in situ, resulting in sections with low compacity, hence leading to crush failures under the anchor plates. The solution of this problem may involve the reduction of reinforcement by improving the concrete compression and tensile strength.

Due to these requirements, a study was carried out to optimize a high-performance fibre reinforced self-compacting mortar mixture. The mixes were prepared with CEM I 42.5R, limestone filler, silica fume, natural sand (d_{max}=1 mm), superplasticizer, fibres (d=0.175 mm; l=6, 9, 12 mm) and tap water. The packing density was evaluated indirectly through the flow cone and V-funnel tests. For each tested mixture the indirect tensile and compressive strength tests were carried out on prismatic specimens (40 x 40 x 160 mm³). Compressive and splitting tensile strengths up to 127 MPa and 13 MPa, respectively, were achieved at 7 days, in current curing conditions. Since the efficiency of this solution also depends on the ability to penetrate voids between reinforcement bars the workability loss was also studied. The workability behaviour was characterized by the rheological parameter yield stress, as well as the procedures of mini slump flow. In order to assess both ultimate capacity and adequate serviceability of the local anchorage zone after reducing not only the minimum concrete cross-section but also the confining reinforcement, both specified by the anchorage device supplier for the particular tendon, an experimental program was carried out.

1 INTRODUCTION

High performance fibre reinforced concrete (HPFRC) is a cementitious material that can be seen as an extension of ordinary fibre concretes and high performance concretes. The main feature of these materials is the optimum combination of strength and toughness, but also substantially higher durability. In fact, most HPFRC studies available in the technical literature use a mixture with
maximum particle sizes less than 1 mm, thus qualifying the mixture as a mortar mixture not concrete [1]. HPFRC also can offer the advantage of belonging to the family of self compacting concretes, thus allowing a simple placement of the material in forms, even in complicated shapes [2]. The performance of fibre reinforced mixtures changes with varying paste formulation, as well as, the fibre material type, fibre geometry, fibre distribution, fibre orientation and fibre concentration. The basic HPFRC mix consists of cement, silica fume (and/or other supplementary cementitious materials), fine sand and often a high percentage of short steel fibres. The key concept is to obtain a dense packing of the reactive components. The binder content of HPFRC is about 4 times higher compared to a standard concrete, which leads to an increased admixture content of up to 15 times [3], [4]. It is also common to use heat treatment to accelerate the hydration processes by enhancement of the pozzolanic reaction of silica fume and supplementary cementitious materials.

The high unit cost of HPFRC makes it difficult to apply HPFRC in ordinary structures. Nevertheless, it has been used in numerous applications, either as stand-alone or in combination with reinforcing bars and prestressed tendons; it has also been used as support material in repair and rehabilitation work. The typical way to use HPFRC is to produce precast elements which are then assembled on the building site. However, its use in real-life structures remains rare, mainly because economically competitive solutions require the optimisation of aspects like the shape of structural elements, production process, storage and transportation. Because of its high strength, the volume of HPFRC is about 1/3 to 1/2 that of conventional concrete for comparable structural elements. This makes HPFRC also of interest in terms of sustainability and CO₂ footprint [5]. The use of HPFRC may not be necessary throughout the structure; only a small part (selected zone) of the structure may be in need of strengthening or toughening. In such a case their use is often competitive and economically justifiable [3]. Nevertheless, there is a lack of experience with the material in terms of design, practical application and actual performance of structures.

The aim of this study was to develop a high-performance fibre reinforced self-compacting mixture to be used in anchorage zones of post-tensioning tendons. With the use of a high performance concrete including a high percentage of steel fibres it was intended to reduce the concrete cross-section and decrease the amount of reinforcement needed. Target tensile and compressive strengths were 10 and 60 MPa, respectively. In addition, a self-compacting mixture was required to ensure a complete filling of the moulds and the involvement of prestressing reinforcement, without the need for vibration.

An experimental program, based on testing recommended by the European Organisation for Technical Approvals (EOTA) [6], was carried out in order to assess both ultimate capacity and adequate serviceability of the local anchorage zone after reducing not only the minimum concrete cross-section but also the confining reinforcement, both specified by the anchorage device supplier for the particular tendon.

2 HPFRC MIXTURE DEVELOPMENT

2.1 Materials characterization

The mortars investigated in this study were prepared with ternary mixtures of cement (CEM I 42.5 R, provided by Secil-Outão), limestone filler (P1 BETOCARB – OR, provided by Comital) and silica fume (Cenriliti Fume SX, in suspension with 50% solids content, provided by MC-Bauchemie) with a specific gravity of 3.10, 2.68 and 1.38, respectively. The average particle size of cement and limestone filler was 14.6 and 5.36 μm, respectively. The particles of silica fume have a size 50 to 100 times lower than that of cement particles. The superplasticizer used (Viscocrete 20HE, supplied by Sika) consists of modified carboxylates and has a specific gravity of 1.08 and 40% solid content. The sand used was provided by CONCREMAT, having a specific gravity of 2630 kg/m³ (dry material) and 0.3% absorption (the size distribution is given in Table 1). With regard to fibres three types of metallic microfibres were studied having circular cross section and different lengths, supplied by KrampeHarex from Germany. Table 2 summarizes the properties (mean values) of the different types of steel fibres used.
2.2 Mixing sequence and testing methods

The mixes were prepared in the laboratory in 1.4 l batches and mixed in a two-speed mixer complying to NP EN 196-1 1996. The mixing sequence consisted of mixing sand and powder materials with 0.8 of the mixing water during 150 s; stopping the mixer to scrape material adhering to the mixing bowl; mixing for another 150 s; adding the rest of the water with the 0.75 of the superplasticizer; mixing for 150 s; stopping the mixer again to scrape material adhering to the bowl; adding the rest of the superplasticizer; mixing for another 90 s; adding the fibres and finally mixing mortar during a further 120 s. The mixer was always set at low speed. Note that the mixing times were increased, relative to what is usually used with conventional self-compacting mortars, in order to achieve a good dispersion of the silica fume particles. Mortar tests using the flow cone and the V-funnel were then carried out to characterize the fresh state (see [2] for details on equipment and test procedures). The mortar flow test was used to assess deformability by calculating the flow diameter \(D_{\text{flow}}\) as the mean of two diameters of the spread area. The V-funnel test was used to assess the viscosity and passing ability of the mortar. Test flow time was recorded \(T_{\text{funnel}}\).

After fresh tests, three prismatic moulds (40\(\times\)40\(\times\)160 mm\(^3\)) were filled to evaluate the indirect tensile and compressive strengths, at 7 days (and at 28 days in one case). In addition, for the selected mixture the tensile strength was assessed by the splitting test performed on cylindrical specimens \((h=100\ \text{mm}, \ O=100\ \text{mm})\). Mortar specimens were demoulded one day after casting and kept under water in a chamber under controlled environmental conditions \((\text{Temp.}=20^\circ\text{C} \ \text{and} \ HR=95-98\%)\) until testing. It should be noted that the flexural tensile and splitting tests are not conventional tests to characterize the tensile strength of HPFRC. The uniaxial tensile test and the flexural test on thin plates are recommended to characterize the full pre- and post-peak response behaviour of HPFRC. The results of tensile strength presented here cannot be considered as the “true” tensile strength but are expected to follow the same trend as would be observed on the results of the uniaxial tensile test and flexural test on plates.

2.3 Experimental programme and test results

Based on previous studies, initially the mixture of a reference mortar (without fibres) was adjusted to achieve the lowest possible water to cement ratio \((\text{w/c})\) while maintaining the spread value of around 300 mm, which ensures the properties of self-compactability. In a similar study, Naaman and Wille [1] adopted a reference mortar with a spread value of 320 mm, though the cone used by these authors presents slightly different dimensions. Table 3 presents the mix proportions of the reference mortar having a \(\text{w/c}=0.25\), a silica fume to cement weight ratio of 5\% and a sand content of 40\%. Note that the quantity of water is corrected taking into account the water present in the suspension of silica and in the superplasticizer, and the water needed to saturate the sand, since this was used dry.

In a first phase, fibres DM 9/0.175 ranging in volume from 1.5\% to 4.5\% were integrated in the reference mix by replacing an equivalent volume of sand. The key test results are shown in Table 3. It is generally observed that an increase in volume fraction of the same fibre, leads to a decrease in spread diameter; however the decrease is not drastic; for instance, doubling the volume fraction of fibres from 1.5\% to 3\% leads to a decrease in the spread diameter from 298 to 284 mm or about 5\%.
A sudden loss of workability was found from a dosage of 3.75% DM 9/0.175 fibres. Figure 1 shows pictures of the spread areas for two mixtures with a fibre volume fraction of 1.5% and 4.5%, respectively. It can be observed that the mixture with the highest fibre content had significant fibre agglomeration within the spread area, while the other mixture had no such effect. In addition, the shape of the spread area ceases to be circular and assumes an irregular shape.

Table 3: Mix proportions and test results of investigated mixes

| Constituent materials |  |  |  |  |  |  |  |  |  |
|-----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $V_f$ (DM 6/0.175)    | 0               | 0               | 0               | 0               | 0               | 0               | 3.0%            | 0               |
| $V_f$ (DM 9/0.175)    | 0               | 1.5%            | 2.25%           | 3.0%            | 3.75%           | 4.5%            | 0               | 0               |
| $V_f$ (DM 12/0.175)   | 0               | 0               | 0               | 0               | 0               | 0               | 3.0%            | 0               |
| sand (kg/m³)          | 1040.00         | 1000.55         | 980.82          | 961.10          | 941.38          | 921.65          | 961.10          | 961.10          |
| cement (kg/m³)        | 810.60          | 810.60          | 810.60          | 810.60          | 810.60          | 810.60          | 810.60          | 810.60          |
| silica fume (kg/m³)   | 317.58          | 317.58          | 317.58          | 317.58          | 317.58          | 317.58          | 317.58          | 317.58          |
| limestone filler (kg/m³) | 317.58        | 317.58          | 317.58          | 317.58          | 317.58          | 317.58          | 317.58          | 317.58          |
| water (kg/m³)         | 156.80          | 156.80          | 156.80          | 156.80          | 156.80          | 156.80          | 156.80          | 156.80          |
| superplasticizer (kg/m³) | 11.16          | 11.16           | 11.16           | 11.16           | 11.16           | 11.16           | 11.16           | 11.16           |

| Test results          |  |  |  |  |  |  |  |  |  |
|-----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $D_{flow}$ (mm)       | 298.50           | 298.50           | 294.50           | 284.50           | 279.00           | 217.00           | 304.50           | 251.50           |
| $T_{funnel}$ (s)      | 15.98            | 16.94            | 17.00            | 23.02            | 33.34            | 20.32            | --              | --              |
| $f_{cm,fl}$ (MPa)     | 17.28            | 24.76            | 26.96            | 41.1             | 43.7             | 44.4             | 21.41            | 52.71            |
| (C.O.V.)              | (18.85%)         | (17.6%)          | (10.5%)          | (4.5%)           | (23.1%)          | (24.3%)          | (14.7%)          | (14.6%)          |
| $f_{cm}$ (MPa)        | 99.09            | 116.0            | 120.0            | 126.8            | 137.0            | 145.0            | 120.53           | 137.6            |
| (C.O.V.)              | (3.60%)          | (1.1%)           | (2.2%)           | (2.2%)           | (1.2%)           | (3.2%)           | (1.2%)           | (2.4%)           |

Figure 1: Final spread area: no fibre agglomeration (left) and visible fibre agglomeration (right)

In order to evaluate the influence of the aspect ratio ($l_f/d_f$) on the behaviour of HPFRC, in the fresh and hardened states, two additional mixes were studied by changing the type of fibre, while maintaining the fibres dosage ($V_f$=3%). Key test results are shown in Table 3. The results show that the aspect ratio (in this case only fibre length varied, diameter remained constant) also has a significant influence on the behaviour of this material. An increase of $l_f/d_f$ resulted in a loss of workability and improved mechanical properties, particularly, tensile strength. Unlike what was observed with DM 9/0.175 fibres, with only 3% of DM 12/0.175 fibres there was a drastic loss of workability. These results indicate that the use of a combination of fibres of different sizes can potentially improve the overall behaviour of the mixture.

In order to account for the combined influence of a fibres’ aspect ratio and volume fraction, a parameter called the fibre factor can be used; it is defined as follows [4].

$$\chi = V_f \times \frac{l_f}{d_f}$$
The variation of spread diameter results from the Table 3 with the fibre factor is presented in Figure 2. It can be generally observed that, everything else being equal, the spread decreases with an increase in fibre factor. In addition, a small value of fibre factor seems to have little influence on final spread diameter. It was observed that an increase in fibre factor increases the risk of fibre agglomeration during the mixing process and decreases workability. In Figure 2 we can identify three distinct zones:

- $0 \leq \chi < 1$: there is not a big difference in workability;
- $1 \leq \chi < 2$: there is an approximately linear decrease of $D_{flow}$ with $\chi$;
- $2 \leq \chi$: drastic reduction of $D_{flow}$ with increasing $\chi$ and the formation of clumps of fibres.

For the mixture including 3% DM 9/0.175 fibres, the tensile and compression strengths at 28 days (evaluated in prisms $40\times40\times160$ mm$^3$) were: $f_{ctm,fl}=44.62$ MPa (C.O.V.=11%) and $f_{cm}=154.9$ MPa (C.O.V.=3%), i.e., from 7 to 28 days, there was an increase of 8.5% and 22% in the results of tensile and compression, respectively. The tensile strength at 7 days of the mixture including 3% DM 9/0.175 fibres was also assessed through the splitting test, using larger cylinders ($h=100$ mm, $\phi=100$ mm), and the obtained results were: 14.4, 16.7 and 8.4 MPa, whose average value is 13.2 MPa ($f_{ct} \approx 0.9 f_{ct, spl}$). To sum up, besides ensuring self-compactability, at 7 days both the tensile and compression strength requirements ($f_{ctm} \geq 10$ MPa and $f_{cm} > 60$ MPa) were fulfilled; therefore, this mixture was selected to cast larger scale elements representing the anchorage zones.

### 3 RHEOLOGICAL CHARACTERIZATION OF SELECTED MIXTURE

As this mixture was designed to be self-compacting, flow properties of the grout were studied, using rheology. To analyse the HPFRC workability several tests were carried out, namely: mini-slump [7], [8], stability tests and rheological measurements using a rotational rheometer, in a plate/plate geometry [9]. Some results are presented here.

#### 3.1 Stability test

Workability loss is a challenge, particularly if HPFRC placing occurs during summer, where environmental temperature is higher. During the structural build-up of the concrete, diffusion and thermal motion control the process which leads to a long build-up time, since they lead to very small effects compared to the shear rate effect [10], [11], [12].

A new test procedure - the stability test (Figure 3) - was developed, based on the test proposed by Van Rickstal [13] aimed to check the density variation of a grout in resting conditions (which are unfavourable as far as stability is concerned). The procedure was adopted for this specific HPFRC.
Figure 3: Stability test device adopted

For this test, 500 ml of freshly mixed mortar (without fibres) was poured into a 500 ml glass graduated cylinder placed under a balance. A cylindrical object suspended from the balance was placed inside the cup with concrete. The mass variation was recorded with time. The results of the stability tests are plotted in Figure 4 as density variation versus time (for an environmental temperature of 25ºC).

Figure 4: Paste density versus time, according to the proposed stability test.

In general terms, the density of a fluid is determined as an average for a given volume. This does not mean that, within the several layers of the fluid, the density remains constant. In fact, the density of the analysed layers differs as a consequence of the different levels of stability of the mortars. If density variations are small the concrete is stable, the bleeding effect is negligible and the flocculation rate is small.

Since this HPFRC is tested during its resting time, the thixotropic effect becomes important and flocculation plays a major role here, especially until 30 minutes after what the HPFRC workability loss becomes relevant, probably due to significant hydration effects.

3.2 Mini-slump test

The mini-slump test is used to determine the “workability” of fresh HPFRC, when the yield stress value is low when compared to that of concrete. In this case, a cylindrical geometry with 50 mm height and 34 mm diameter was adopted and the spread was measured for the optimum HPFRC composition, for different resting times. After that, an attempt to estimate the yield stress was made. The spread seems to be a more relevant parameter for estimating the material yield stress [7], [8].

The spread diameter was measured for different HPFRC resting times, until 30 minutes. The test was made for the HPFRC produced in laboratory and on field conditions (Figure 5 (a)).

As it can be observed, the HPFRC workability is higher for lab environment than for on field production. On the first 15 min the workability loss is higher for both situations. On field measurements shows that the HPFRC workability tends to become constant, but smaller than in lab environment, between 15-30 min. Thus, this HPFRC presents a life time equal to 30 minutes, which should be improved in following research works.
3.3 Rheological measurements

The fresh HPC (without fibres) was also tested at different temperatures (from 20 to 30ºC). Considering that the application of a concrete may begin early in the morning and continue throughout the day during several days, the variations of temperature and relative humidity become self evident, namely in the increasing of materials hydration reactions. Thus, yield stress was calculated for each temperature. The modified Bingham equation was chosen for yield stress and plastic viscosity determination. Figure 5 (b) presents the values of yield stress for different mortar temperatures, confirming that, for a HPFRC temperature higher than 25ºC can lead to workability loss.

4 LOAD TRANSFER TESTS IN POST-TENSIONING ANCHORAGE ZONES

Since one of the purposes of using HPFRC in anchorage zones is to reduce not only the minimum concrete cross-section but also the confining reinforcement, both specified by the anchorage device supplier for the particular tendon, an experimental program to assess both ultimate capacity and adequate serviceability of the local anchorage zone was carried out. Thus, the load transfer test recommended by the European Organisation for Technical Approvals (EOTA) [6] was performed.

4.1 Load transfer tests according to EOTA [6]

The load transfer test is performed to verify the transfer of the prestressing force from the mechanical anchorage and its components to the concrete. The test recommended by EOTA [6] consists of loading a prismatic concrete block containing the anchorage components and confinement reinforcement which will be embedded in the structural concrete. The compression load is applied directly to the bearing plate by means of an anchor head. The load should be increased in steps of 0.2Fpk, up to 0.8Fpk, where Fpk is the characteristic ultimate resisting force of prestressing steel of tendon. Then, at least ten slow load cycles should be performed between 0.8Fpk and 0.12Fpk. Cyclic loading should be continued until stabilization of strain readings and crack widths. Following cyclic loading, the specimen should be loaded continuously to failure. The maximum allowed crack width is 0.15 mm upon first attainment of 0.8Fpk and upon last attainment of 0.12Fpk. The maximum allowed crack width at 0.8Fpk after the conclusion of the cyclic loading is 0.25 mm. The measured failure load must exceed 1.1Fpk.

4.2 Specimen geometry

The experimental program included four prisms of ordinary reinforced concrete (ORC), shown in Figure 6 and defined in Table 4 (specimens P1, P2, P1A and P2A), and three prisms (specimens P3, P5 and P6) of HPFRC and specimen P4 of high performance concrete without steel fibres (HPC), shown in Figure 7 and defined on Table 5.
Table 4: Characteristics of the ORC test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dimensions (mm$^3$)</th>
<th>Concrete type</th>
<th>Type of reinforcement</th>
<th>Spiral</th>
<th>Stirrups</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>305×305×650$^{(a)}$</td>
<td>ORC 1</td>
<td>Spiral+Stirrups$^{(a)}$</td>
<td>12 60 6</td>
<td>12 60 6</td>
</tr>
<tr>
<td>P1A</td>
<td>305×305×650$^{(a)}$</td>
<td>ORC 2</td>
<td>Spiral+Stirrups$^{(a)}$</td>
<td>12 60 6</td>
<td>12 60 6</td>
</tr>
<tr>
<td>P2</td>
<td>305×305×650$^{(a)}$</td>
<td>ORC 1</td>
<td>Spiral</td>
<td>10 60 6</td>
<td></td>
</tr>
<tr>
<td>P2A</td>
<td>305×305×650$^{(a)}$</td>
<td>ORC 2</td>
<td>Spiral</td>
<td>10 60 6</td>
<td></td>
</tr>
</tbody>
</table>

$^{(a)}$ Specified by the anchorage device supplier (VSL International [14])

It is worth to mention that the pitch of the spiral or spacing of the stirrups $s$ refers to the distance measured from centre to centre of the bars.

Figure 6: Test specimens of ordinary reinforced concrete (dimensions in m)

In specimens P1, P2, P1A and P2A, as additional reinforcement, 4∅8 longitudinal reinforcing bars, as well as ∅6 stirrups uniformly distributed along the height or half height of the specimen were adopted. The reinforcing steel grade was A500NR SD.

Table 5: Characteristics of the HPFRC test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dimensions (mm$^3$)</th>
<th>Concrete type</th>
<th>Type of reinforcement</th>
<th>Stirrups</th>
<th>φ (mm)</th>
<th>s (mm)</th>
<th>Number of stirrups</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3</td>
<td>305×305×650</td>
<td>HPFRC</td>
<td>-</td>
<td>Stirrups</td>
<td>6</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>P4</td>
<td>210×210×420</td>
<td>HPC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P5</td>
<td>210×210×420</td>
<td>HPFRC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P6</td>
<td>210×210×420</td>
<td>HPFRC</td>
<td>Stirrups</td>
<td>6</td>
<td>50</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
In specimen P6, the additional reinforcement consisted of 4\( \phi \)6 longitudinal reinforcing bars and \( \phi \)6 stirrups uniformly distributed along the half height of the specimen. The reinforcing steel grade was A500NR SD.

![Diagram](image)

Figure 7: Test specimens of high performance self-compacting concrete (dimensions in m)

The stressing anchorage used in the specimens was a VSL anchorage Type GC for seven strands of 0.6", with a 180\( \times \)180 mm\(^2\) bearing plate. Corrugated steel ducts with internal and external diameters of 60 mm and 67 mm, respectively, were also adopted.

4.3 Test procedure and measurements

The equipment used for testing was a servo-controlled compression testing machine with a load capacity up to 3000 kN and displacement capacity up to 50 mm. Figure 8 presents a typical setup for the testing of a square prism.

A total of sixteen strain gauges in specimens P1, P1A and P6, and eight strain gauges in specimens P2 and P2A, were affixed to diametrically opposite sides of selected reinforcing bars. In specimens P1, P2, P1A, P2A and P3, the vertical surface strains were measured with displacement transducers on two faces of the block. Demec locating discs for mechanical extensometer measurement of concrete horizontal surface strains were placed on two faces of the specimens. In specimens P4, P5 and P6, the vertical and horizontal surface strains were both measured with displacement transducers on two faces of the block. The strain gauges and the displacement transducers were connected to a computerized data acquisition system.

Each block was loaded through a 135 mm diameter and 60 mm height anchor head which was placed on top of the stressing anchorage. The anchorage used in the tests is intended for a maximum of seven strands type 0.6", each strand with a nominal area of 1.5 cm\(^2\) and a tensile strength of 1860 MPa.

During the load transfer test ten load cycles were carried out between 234.4 kN (0.12\( F_{pk} \)) and 1562.4 kN (0.8\( F_{pk} \)). The measured breaking load should be superior to 2148.3 kN (1.1\( F_{pk} \)).
4.4 Experimental results

Ordinary reinforced concrete specimens

In the reinforced specimens (P1, P1A, P2 and P2A), all the cracks developed during the load cycles were located in the upper half of the specimens. The first cracks to appear were vertical in the half-width of the specimen and horizontal cracks at a distance of approximately 70 mm from the top of the specimens. As shown in Figure 9, at failure, cracks propagated to the bottom half and also developed at the top surface of the specimen. The test results are presented in Table 6.

Table 6: Concrete characteristics, crack widths and ultimate load capacity of the test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete characteristics</th>
<th>Crack widths w (mm)</th>
<th>P_u (kN)</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f_cm (MPa)</td>
<td>f_ctepl (MPa)</td>
<td>First 0.8F.pk</td>
<td>Last 0.12F.pk</td>
</tr>
<tr>
<td>P1</td>
<td>65.2</td>
<td>4.7</td>
<td>0.02</td>
<td>0</td>
</tr>
<tr>
<td>P2</td>
<td>65.2</td>
<td>4.7</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>P1A</td>
<td>36.7</td>
<td>3.2</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>P2A</td>
<td>36.7</td>
<td>3.2</td>
<td>0.20</td>
<td>0.30</td>
</tr>
</tbody>
</table>

The concrete characteristics were evaluated at the date of the tests of the specimens. The concrete mean compressive strength was obtained using three and six cubic specimens with 150 mm width. The splitting cylinder tensile strength was assessed using six cylindrical specimens (h=300 mm, Ø=150 mm).

High performance concrete specimens

During load cycles, specimen P3 developed a single vertical crack with a very small opening in the half-width of the specimen, centred, with about half the height of the piece. The specimen was loaded until the maximum capacity of the compression testing machine and did not fail.
The failure of specimen P4 (cast with HPC) occurred suddenly with bursting and spalling of concrete. The failure was brittle and explosive. In specimen P5, during the application of the first load, a vertical crack developed in the half-width of the specimen along the full height, in two opposite faces. As shown in Figure 10 (a), the presence of fibres prevented the increase of the crack width and helped to maintain the integrity of the specimen, despite having exceeded the maximum allowed crack width. However, it was found that the fibres showed a preferential orientation, so that the only cracked faces were the two opposite faces parallel to the direction of concrete pouring. Specimen P6 behaved far better than P5 throughout the test regarding crack width. As shown in Figure 10 (b), at failure, multiple vertical and horizontal cracks are visible. The test results are presented in Table 7.

![Specimen P5 and P6 after testing](image)

Table 7 : Concrete characteristics, crack widths and ultimate load capacity of the test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete characteristics</th>
<th>Crack widths w (mm)</th>
<th>$P_u$ (kN)</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{cm}$ (MPa)</td>
<td>$f_{ct,sp}$ (MPa)</td>
<td>First 0.8$F_{pk}$</td>
<td>Last 0.12$F_{pk}$</td>
</tr>
<tr>
<td>P3</td>
<td>118.5</td>
<td>9.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P4</td>
<td>114.1</td>
<td>3.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P5</td>
<td>134.0</td>
<td>13.6</td>
<td>0.35</td>
<td>0.25</td>
</tr>
<tr>
<td>P6</td>
<td>118.5</td>
<td>9.6</td>
<td>0</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<sup>(a)</sup> The specimen did not fail

The concrete characteristics were evaluated at the date of the tests of the specimens. The concrete mean compressive strength was obtained using three cubic specimens with 100 mm width. The splitting cylinder tensile strength was assessed using three and six cylindrical specimens ($h=300$ mm, $\varnothing=150$ mm) for specimens P3 and P6, and for specimens P4 and P5, respectively.

5 CONCLUSIONS

The performance of HPFRC mixtures was studied with varying fibres concentration and fibre geometry (varying length). As reported in the literature, it was found that the addition of short needle-like discontinuous fibres ($l=9$ mm, $d=0.175$ mm), which occupy less than 5% of the mixture by volume, may lead to a drastic change in the properties of an otherwise self-compacting mortar mixture. Besides the concentration of fibres in the mixture, also its aspect ratio was found to significantly influence the mixtures behaviour, in both the fresh and hardened states. In the present work a tailor-made HPFRC mixture was developed achieving about 13 MPa of tensile strength at 7 days, with no recourse to heat or pressure, while maintaining excellent flowability in the fresh state.
From the analysis of the test results in anchorage zones it can be concluded that for specimens of ordinary reinforced concrete with identical type and amount of reinforcement, the failure load of the specimen increases and the crack width decreases with increasing concrete compressive strengths. For the same concrete section, the use of HPFRC allows the suppression of the confining reinforcement for the type of anchorage utilised.

In anchorage zones, the use of HPFRC allows not only the reduction of the concrete cross-section but also of the confining reinforcement. The suppression of all the confining reinforcement is not advisable, since the non-randomness of fibre orientation can lead to formation of cracks with unacceptable width.

With the testing, research and implementation carried out under the current work one hope to contribute to increase the knowledge on these materials, in Portugal, and to obtain a wider acceptance in order to quickly increase the number and variety of applications; and thus increasing the competitiveness of Portuguese companies in external markets.

ACKNOWLEDGEMENTS

Collaboration and materials supplying by VSL, Concremat, Secil, Comital, MC-Bauchemie, Sika, and KrampeHarex is gratefully acknowledged.

REFERENCES