ENHANCED DURABILITY OF ULTRA HIGH PERFORMANCE CONCRETE BY INCORPORATING SUPPLEMENTARY CEMENTITIOUS MATERIALS

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Abstract

Most aspects of concrete durability are directly related with its porous structure, since capillary pores are responsible for fluids’ migration in the concrete matrix. Ultra high performance concrete (UHPC) not only presents ultra-high compressive strength but also exhibits ultra-high durability, due to its ultra-dense structure and consequently highly reduced porosity. However, high dosages of silica fume, commonly adopted in UHPC, also lead to high autogenous shrinkage. This deformation, occurring at early ages, induces high internal stresses which, in turn, cause microcracking, increasing permeability and, therefore, reduces the durability of concrete structures.

The experimental study herein described was conducted aiming to replace silica fume by another fine supplementary cementitious materials (SCMs), such as fly ash (FA) and ground granulated blast furnace slag (GGBS), in order to reduce the amount of autogenous shrinkage, without changing concrete mechanical properties and porosity. The adopted approach involved partial or complete replacement of silica fume by SCMs. Autogenous shrinkage and compressive strength were assessed. Pores size distribution and pores volume were measured using nitrogen gas adsorption test. Total volume of permeable voids (VPV) of specimens was determined through boiling procedure. Results showed a good correlation between the refinement of UHPC fines pore structure and the reduction of autogenous shrinkage. It was concluded that incorporating GGBS, in either binary or ternary blends, does not change concrete mechanical properties or porosity but reduces autogenous shrinkage due to a refined fine pore structure.

Key words: UHPC; SCM; Porosity; Durability; Autogenous Shrinkage
1. INTRODUCTION

Ultra-high performance concrete (UHPC) was developed in the last decade. It presents not only ultra-high compressive strength but also ultra-high durability, because of its ultra dense structure and, thus, highly reduced porosity. To produce UHPC, it is mandatory to minimize the aggregate size and simultaneously to increase the paste/aggregate ratio [1]. Several types of fine size powders have been used as micro filler in this scope to meet the need for high degree of compactness and high compressive strength. Silica fume is known as a main constituent of a typical UHPC mixture and reactive powder concrete. It plays a significant role in improving both rheological and mechanical properties of UHPFRC. These prominent effects are divided into three main functions: i) filling effect, which improves the particle packing density; ii) lubricating effect, which results in an enhancement of rheological properties due to sphericity of particle shape; and iii) pozzolanic reaction, which leads to the production of more C-S-H gel [1]. A wide-range of dosage from 10 up to 30 % of silica fume in UHPC mixture has been reported in different investigations [2, 3]. However, the optimum dosage has been recommended to be 25 % in cement weight [1].

Besides the above mentioned advantages, silica fume also presents some disadvantages, such as unavailability in large quantities and being expensive. In addition, silica fume has some limitation in terms of aesthetics application due to its grey colour. Although silica fume improves the rheology of concrete, the high specific surface of its particles results in increased water demand [4] and it affects the fluidity of the mixtures depending on carbon content [5]. In general, higher percentages of silica fume lead to higher dosages of superplasticizer and, therefore, the mixtures become sticky [5, 6]. In low W/C ratio concrete, particularly in UHPC, silica fume presents the additional disadvantage of affecting durability. It is now well understood that autogenous shrinkage, caused by self-desiccation at early ages, induces high internal stresses which, in turn, provoke microcracking. This increases permeability and, thus, reduces durability. It is also known that autogenous shrinkage due to self-desiccation is mostly related to fine pore structures [7]. Thus, mineral additives containing more fine pores are more susceptible to self desiccation and consequently to autogenous shrinkage. Up to now, several researchers have reported high autogenous shrinkage of concrete specimens containing silica fume. Igarashi et al. [8] found that the presence of larger amounts of fine capillary pores in concrete containing silica fume is responsible for higher autogenous shrinkage at early ages. Mazloom et al. [9] performed an experimental study on the autogenous shrinkage of high strength concrete. The results indicated that, as the proportion of silica fume increased, the autogenous shrinkage also increased. Zhang et al. [10] reported two factors, silica fume content and W/C ratio, as having a significant effect on autogenous shrinkage of concrete. As mentioned above, silica fume has been used in high percentage in UHPC typical mixtures. Therefore, autogenous shrinkage can be more critical in the case of UHPC.

The study herein described focused on evaluating the potential use of fine supplementary cementitious materials (SCMs), such as fly ash (FA) and ground granulated blast furnace slag (GGBS), as a replacement of silica fume. It is well known that inclusion of SCMs in concrete mixtures enhances durability, decreases the heat of hydration and generally improves concrete properties [11]. SCMs enhance the concrete properties by two primary means. The first is by...
reaction with by-products of cement hydration and the other by increasing particle packing efficiency. The effect of different SCMs as an alternative powder in the composition of reactive powder concrete and UHPFRC has already been studied. Rougeau et al. [5] investigated the mechanical properties as well as the durability of very high performance concrete (VHPC) and UHPC with some ultra-fine particles instead of silica fume, such as limestone microfiller (LM), pulverized fly ash (PFA) and metakaolin (MK) and results pointed out that these ultrafine particles are potentially interesting to produce UHPC. Tafraoui et al. [12] replaced silica fume with metakaolin and obtained an UHPC with almost equivalent mechanical performance. Yazichi [13] reported that cement and silica fume content can be replaced by FA and/or GGBS keeping satisfactory mechanical properties.

Taking into account the state of the art, the following main objective was defined for the present study: to replace silica fume with other fine supplementary cementitious materials (SCMs), in order to reduce the amount of autogenous shrinkage, without having a significant change in concrete mechanical properties and porosity. In addition to mechanical and porosity tests, nitrogen gas adsorption technique was used to study the fine pore distribution of the specimens.

2. EXPERIMENTAL PROGRAM

2.1 Materials and mixture proportion

The UHPC mixtures were prepared with the following main constituents: ordinary Portland cement type I(52.5 R); silica fume (SF); a new type of quartz flour (P600) used as a micro filler (particle size less than 10 µm); silica sand with maximum aggregate size of 0.6 mm; and polycarboxylate ether based superplasticizers. In addition, fly ash class C and ground granulated blast furnace slag (GGBS) were used as binders to replace silica fume in the mixture of UHPC. A new type of steel micro fibers with length of 60 mm and 0.15 mm diameter was used.

The mixing procedure includes the following steps: (1) First, in order to prevent agglomeration, and also to promote uniform distribution of very fine particles, all powder and silica sand were mixed dry for 5 minutes at low speed; (2) Afterwards, water and superplasticizer were added gradually in two steps; after 5 minutes, the mixtures became fluid; (3) Subsequently, fibers were added and additional mixing was applied for about 2 minutes at high speed; (4) After mixing, concrete was poured in a mold; and (5) 24 hours later, specimens were removed from the mold.

In order to investigate the effect of curing, half of the specimens was cured in water at 20 °C and the rest was cured at 90 °C, for 48 hours, including one hour ramp up and down and, finally, cooled in ambient air. Table 1 shows five different types of mixtures, where ‘SQ’ is a reference mixture which includes 24 % of silica fume by weight of cement. This amount of silica fume was totally replaced in binary blends of GGBS-quartz flour (GQ) and FA-quartz flour (FQ) mixtures and also partially replaced in ternary blends of GGBS-SF-quartz (GSQ) and FA-SF-quartz (FSQ).

Silica fume has a lower density than fly ash and GGBS. As a consequence, replacement of silica fume leads to a reduction of the paste volume. Hence, the amount of silica fume was replaced volumetrically, keeping the paste/aggregate ratio constant. Moreover, since both autogenous shrinkage and porosity are highly affected by W/B, this ratio was also kept
constant in volume. Keeping the mentioned parameters constant enabled to measure the autogenous shrinkage as well as porosity, in the same condition.

Table 1: Mixture proportions, in kg/dm$^3$

<table>
<thead>
<tr>
<th>Mixture</th>
<th>SQ</th>
<th>GQ</th>
<th>GSQ</th>
<th>FQ</th>
<th>FSQ</th>
</tr>
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<tbody>
<tr>
<td>cement</td>
<td>692</td>
<td>692</td>
<td>692</td>
<td>692</td>
<td>692</td>
</tr>
<tr>
<td>sand</td>
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<td>899.6</td>
<td>899.6</td>
<td>899.6</td>
<td>899.6</td>
</tr>
<tr>
<td>SF</td>
<td>166.1</td>
<td>0</td>
<td>99.7</td>
<td>0</td>
<td>99.7</td>
</tr>
<tr>
<td>FA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>196</td>
<td>78.4</td>
</tr>
<tr>
<td>GGBS</td>
<td>0</td>
<td>206.7</td>
<td>82.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>QF</td>
<td>200.1</td>
<td>200.1</td>
<td>200.1</td>
<td>200.1</td>
<td>200.1</td>
</tr>
<tr>
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<td>190.5</td>
<td>190.5</td>
<td>190.5</td>
<td>190.5</td>
</tr>
<tr>
<td>SP</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
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<tr>
<td>fibers</td>
<td>194</td>
<td>194</td>
<td>194</td>
<td>194</td>
<td>194</td>
</tr>
</tbody>
</table>

2.2 Experimental test

Experimental testing included three main parts: i) evaluation of concrete mechanical properties; ii) assessment of water absorption and porosity; and iii) measurement of autogenous shrinkage.

Prismatic (40 × 40 × 160 mm$^3$) and cubic (40 × 40 × 40 mm$^3$) specimens were used to determine concrete flexural and compressive strengths, respectively. Water absorption was measured according to the ASTM C-642 standard [14]. After conditioning the specimens to (105 ± 5) °C (mass A), the specimens were soaked to constant mass in water (mass B), and water absorption was measured considered as a mass difference, expressed as a percentage of the mass of the dry specimen. Thus, the absorption after immersion, in %, is given by (B-A)/(A)×100.

The volume of permeable voids (VPV), expressed as a percentage of the volume of the solid, was determined according to ASTM C-642 standard [14]. In this procedure, after boiling the specimens for 5 hours, these were allowed to cool with natural loss of heat for 14 hours until a final temperature of 20 to 25°C was reached. Then, the moisture of the specimen’s surface was removed with a towel and the mass of the specimen was determined (mass C). Placing the specimen suspended in water, the apparent mass in water was determined (mass D). The volume of permeable voids is obtained from Equation (1):

$$\text{VPV} \%=\left(\frac{C-A}{C-D}\right) \times 100 \quad (1)$$

Measurements of cumulative pore volume and pores size distribution of UHPC specimens were performed using the nitrogen gas adsorption method, considered the most appropriate test for evaluating fine pore structures [15]. The autogenous shrinkage was measured for all types of mixtures under isothermal condition. After casting, the concrete specimens were immediately sealed to avoid moisture dissipation. Moreover, a plastic sheet was inserted in the mold, in order to reduce the friction between concrete and the mould. Then, shrinkage deformation was continuously monitored for each specimen.
3. RESULT AND DISCUSSION

3.1 Gas adsorption test

The obtained pore size distribution for SQ, GQ, and FQ mixtures from nitrogen gas adsorption test is shown in Fig. 1. The obtained plots cover the pore size distribution range from 1nm to 100nm.

Fig. 1: Pore size distribution obtained by nitrogen gas adsorption test

The pore size distributions show the existence of much finer pores distribution in the range of 1nm to 10 nm (10-100 Å) for UHPC specimens containing binary blends of SQ. The achieved results indicate that all the mixtures have a maximum peak of pore volume in the range of 2 to 3 nm. However, in this critical interval, SQ represents more cumulative volume of the fine pores, whereas FQ mixtures have the lowest amount of pore volume in the mentioned range. In general, it is clearly observed that the incorporation of both GGBS and FA resulted in refined fine pores structures of UHPC.

3.2 Compressive and flexural strengths

Results for compressive strength in both heat treatment and ambient temperature conditions are shown in Fig 2. Generally, thermal treatment contributed to enhance compressive strength, regardless of mixture proportion. Although binary blend of SQ shows the highest compressive strength, it does not have the same efficiency in ambient temperature condition. The incorporation of fly ash in both binary and ternary blends led to a decrease of concrete compressive strength, up to 16 %, for heat treated specimens, and up to 10 %, for specimens cured in ambient temperature. In addition, the ternary blend of GSQ shows the highest compressive strength for specimens cured in ambient temperature and exhibits a slight reduction in heat treated specimens. It has to be mentioned that the incorporation of both FA and GGBS increased the fluidity of the mixtures, with the same W/B ratio. As mentioned before, the adopted strategy aimed to measure the autogenous shrinkage and porosity of all mixtures in the same conditions. Therefore, it was expected that the compressive strength of mixtures with GGBS and FA would be increased with the reduction in water content by designing the mixtures to have the same consistency instead of the same water content. As it
can be seen in Fig. 3, results show that binary and ternary blends containing GGBS have a higher flexural strength. The results of flexural strength showed a large deviation from the average which may be due to the effect of fiber orientation, which has been proved that has great influence on the mechanical properties of UHPC [17]. It seems that the improvement of the flexural strength of GGBS blends is related to their better fluidity which can convey the steel fibers in the more effective direction[18].

3.3 Autogenous shrinkage

The measured autogenous shrinkage is shown in Fig. 4 for all mixtures. Since the W/B ratio is very low in UHPFRC, this concrete is more susceptible to self-desiccation and consequently to autogenous shrinkage. As expected, results show very high autogenous shrinkage in early ages for mixtures containing only SF. The results corroborate the results of previous studies [7, 19].

Recalling the discussion regarding the fine pore distribution and pore volume in Fig. 1, it can be concluded that the combination of these two parameters accelerated the self-desiccation process, resulting into high autogenous shrinkage. The obtained values yielded the lowest and approximately equal deformation for specimens with binary blends of GQ and FQ.
However, distinction significant difference was observed for binary blend of SQ, particularly at early ages. Due to intimate relation between refined fine pores structure and autogenous shrinkage, it can be expected that refining the fine pores structure with FA and GGBS lead to a reducing of autogenous shrinkage.

3.4 Water absorption and volume of permeable voids (VPV)

Results from water absorption and volume of permeable voids are presented in Table 2. The binary blends of SQ and GQ showed the lowest and approximate equal value of the water absorption and VPV. Heat treated specimens gave the lowest values of both water absorption and VPV when compared with specimens cured in ambient temperature. This is due to the discontinuity of capillary pores by formation of more C-S-H gel. The binary and ternary blends with FA presented the highest values of VPV and water absorption.

Table 2: Water absorption and volume of permeable voids (%)

<table>
<thead>
<tr>
<th>Mixture type</th>
<th>Curing</th>
<th>SQ</th>
<th>GQ</th>
<th>FQ</th>
<th>GSQ</th>
<th>FSQ</th>
</tr>
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<tr>
<td>Water absorption (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>steam</td>
<td>0.75</td>
<td>0.76</td>
<td>0.82</td>
<td>0.90</td>
<td>1.20</td>
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<tr>
<td>water</td>
<td>1.10</td>
<td>1.42</td>
<td>1.72</td>
<td>0.96</td>
<td>1.46</td>
<td></td>
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<tr>
<td>VPV (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>steam</td>
<td>2.01</td>
<td>2.15</td>
<td>2.30</td>
<td>2.17</td>
<td>2.50</td>
<td></td>
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<tr>
<td>water</td>
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<td>3.58</td>
<td>4.15</td>
<td>2.50</td>
<td>3.72</td>
<td></td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

In this study, the potential use of fine types of SCMs, such as fly ash (FA) and ground granulated blast furnace slag (GGBS), was evaluated as a replacement of silica fume in UHPC. All the mixtures showed reasonable results, in relation to UHPC characteristics. Comparing these UHPC mixtures with the reference mixture (containing SF), it was concluded that the incorporation of GGBS, in either binary or ternary blends, gives similar results, in terms of both mechanical properties and in volume of permeable voids. Although incorporating FA into the mixtures resulted in a slight decrease of the mechanical properties and in an increase of the volume of permeable pores and water absorption, these mixtures show much lower autogenous shrinkage. A close relation between the fine pores structure refinement of UHPC and the reduction of autogenous shrinkage was observed. The results showed that FA and/or GGBS can reduce the UHPC autogenous shrinkage, due to a refined fine pores structure.

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