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Effect of supplementary cementitious materials on autogenous shrinkage of ultra-high performance concrete

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HIGHLIGHTS

- The amount of fine pores in UHPC can highly affect the autogenous shrinkage.
- A strong correlation between the autogenous shrinkage and the porosity of UHPC was established.
- Reducing the fine pores in FA/GGBS samples leads to a reduction of the autogenous shrinkage.

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ABSTRACT

Ultra-high performance concrete (UHPC) not only presents ultra-high compressive strength but also exhibits ultra-high durability, due to its extremely dense structure and consequently highly reduced porosity. However, high dosages of silica fume (SF), typically adopted in UHPC, also lead to high autogenous shrinkage. This phenomenon, occurring at early ages, induces high internal stresses that, in turn, cause microcracking and increase permeability and, therefore, reduce the durability of concrete structures. The experimental study was conducted aiming to replace SF by another fine supplementary cementitious materials (SCMs), such as fly ash (FA) or ground granulated blast furnace slag (GGBS), in order to reduce the amount of autogenous shrinkage. The adopted approach involved partial or total replacement of SF by SCMs. Results indicate that the amount of fine pores in UHPC is a predominant factor that can highly affect the autogenous shrinkage. A strong correlation between the natural logarithm of autogenous shrinkage and the total porosity of UHPC mixtures was established. It was found that reducing the amount of fine pores in specimens containing FA or GGBS leads to a reduction of the autogenous shrinkage.

1. Introduction

Ultra-high performance concrete (UHPC) concept was developed in the last decade. This concrete type presents not only ultra-high compressive strength but also ultra-high durability [1], because of its extremely 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 [2]. Several types of fine size powders have been used as microfiller in this scope to meet the need for high degree of compactness and high compressive strength [3–5]. SF 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 UHPC. 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 additional C-S-H gel [2,6]. A wide-range of dosage from 10 up to 30% of SF in UHPC mixture has been reported in different investigations [7,8]. However, the optimum dosage has been recommended to be 25% in cement weight [2]. Besides of these advantages, SF presents some disadvantages, such as cost and scarcity if large quantities are requested. In addition, SF also presents some limitation in terms of aesthetic application due to its dark gray color. Although SF improves the rheology of concrete, the high specific surface of its particles results in an increased water

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demand [9] and it affects the fluidity of the mixtures depending on carbon content [10]. In general, higher percentages of SF lead to higher dosages of superplasticizer and therefore, the mixtures become sticky [10,11]. For a low water to cement ratio (W/C) concrete, particularly in UHPC, SF 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 that, in turn, provoke microcracking [12]. The latter increases permeability and, thus, reduces durability. It is also known that autogenous shrinkage, due to self-desiccation, is mostly related to fine pore structures [13]. Thus, mineral additions 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 SF. Igarashi et al. [14] found that the presence of larger amounts of fine capillary pores in concrete containing SF is responsible for higher autogenous shrinkage at early ages. Mazloom et al. [15] performed an experimental study on the autogenous shrinkage of high strength concrete. The results indicated that, as the proportion of SF increased, the autogenous shrinkage also increased. Zhang et al. [16] reported two factors, SF content and W/C ratio, as having a significant effect on the autogenous shrinkage of concrete. As mentioned above, SF 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 FA and GGBS, as a replacement of SF. It is well known that the inclusion of SCMs in concrete mixtures enhances durability, decreases the heat of hydration, and generally improves concrete properties [17–19]. SCMs enhance concrete properties by two primary means. The first is by reaction with cement hydration products 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 ultra high performance fiber reinforced concrete (UHPFRC) has already been studied. Rougeau et al. [10] investigated the mechanical properties as well as the durability of very high performance concrete and UHPC with some ultra-fine particles instead of SF, such as limestone microfiller, pulverized FA, and metakaolin, and the results pointed out that these ultrafine particles are potentially promising to produce UHPC. Tafraoui et al. [20] replaced SF by metakaolin and obtained an UHPC with almost equivalent mechanical performance. Yazici [21] reported that cement and SF content can be replaced by FA and/or GGBS keeping satisfactory mechanical properties. Based on the state of the art, the following two main objectives were defined for the present study: (1) to replace SF by other fine supplementary cementitious materials (SCMs), in order to reduce the amount of autogenous shrinkage, but without experiencing a significant reduction in UHPC mechanical properties, and (2) to establish the correlation between the pore structures and the autogenous shrinkage of UHPC, adopting the nitrogen gas adsorption technique to study the fine pore distribution of the specimens.

2. Experimental

2.1. Materials and mixture proportions

The UHPC mixtures were prepared with the following main constituents: Portland cement type 1 (52.5 R); 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, FA class C and GGBS obtained by grinding method were used as binders to replace SF in the mixture of UHPC. A new type of steel micro-fibers with 60 mm length and 0.15 mm diameter was also used. The mixing procedure includes the following steps: (1) First, in order to prevent agglomeration, and also to promote uniform distribution of the very fine particles, all powder and silica sand were mixed in dry state for 5 min at low speed; (2) Afterwards, water and the superplasticizer were added gradually in two steps; after 5 min, the mixtures became fluid; (3) Subsequently, fibers were added and additional mixing was applied for about 2 min at high speed; (4) After mixing, concrete was poured in a mold; and (5) 24 h later, specimens were removed from the mold. In order to investigate the effect of curing, half of the specimens were cured in water at 20 °C, and the remainders were cured at 90 °C and 95% relative humidity (RH) for 48 h, including 1-h ramp-up and ramp-down.

Table 1 shows five different types of mixtures, where ‘SFS’ sample is a reference mixture that includes 24% of SF by weight of cement. This amount of SF was totally replaced by GGBS (GBS) and FA (FAS) in the mixtures and also partially replaced in binary blends of GGBS-SF (GBSF) and FA-SF (FASF). SF has a lower density than FA and GGBS. As a consequence, replacement of SF leads to a reduction of the paste volume. Hence, the amount of SF was replaced volumetrically, keeping the paste/aggregate ratio constant. Moreover, since both autogenous shrinkage and porosity are highly affected by water to binder (W/B) ratio, this ratio was also kept constant in volume. Keeping the aforementioned parameters constant enabled measuring the autogenous shrinkage, as well as porosity, in the same condition.

2.2. Experimental tests

Experimental testing included three main parts: i) porosity assessment of the samples; ii) measurement of autogenous shrinkage; and iii) evaluation of UHPC mechanical properties.

Measurements of cumulative pores’ volume and pores’ size distribution of UHPC specimens were performed using the nitrogen gas adsorption method, considered as the most appropriate test for evaluating fine pore structures [22]. Autogenous shrinkage can be calculated by two methods, namely linear and volumetric measurements. It has been proven that autogenous shrinkage values obtained with linear methods are considerably lower than those measured with volumetric methods [23]. In the scope of the study herein described, a vertical test setup was developed and used in order to measure the composite cement paste autogenous shrinkage. The fresh concrete was cast in the molds, sealed with plastic, and placed between two support heads. Moreover, a plastic sheet was embedded in the mold, in order to reduce the friction between concrete and the mold. The whole setup was then placed in a moisture room for 24 h. Therefore, the autogenous shrinkage was measured for all types of mixtures under isothermal conditions. The measurements started at early ages and shrinkage was recorded based on the dial gauge values. The temperature was kept constant in order to eliminate the effect of thermodynamic heat

Table 1
Mixture proportions, in kg/dm^3.

Mixture	SFS	GBS	GBSF	FAS	FASF
Cement	692	692	692	692	692
Sand	899.6	899.6	899.6	899.6	899.6
SF	166.1	0	99.7	0	99.7
FA	0	0	0	196	78.4
GGBS	0	206.7	82.7	0	0
Quartz	200.1	200.1	200.1	200.1	200.1
Water	190.5	190.5	190.5	190.5	190.5
SP	36	36	36	36	36
Fibers	194	194	194	194	194