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Characterization of heat-treated self-compacting concrete containing mineral admixtures at early age and in the long term

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HIGHLIGHTS

- Valorization of local mineral admixtures and reduction of the final cost of SCC.
- Improvement of SCC characteristics in both fresh and hardened states.
- Minimization of the losses of strengths of heat-treated SCC in the long term.

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ABSTRACT

Self-compacting concretes (SCCs) are increasingly used in the field of prefabrication, although the final strength of the heat-treated concrete is less than that of reference samples that have been cured in normal conditions. The aim of this work is to contribute to the improvement of the mechanical behavior of this kind of SCC. This paper presents the effect of the incorporation of local mineral admixtures on the behavior of heat-treated SCC at an early age (1 day) and in the long term (28 and 180 days). The characteristics of the SCC in the fresh and hardened states were also studied. The adopted heat-treatment cycle attained a maximum temperature of 60 °C and a total duration of 24 h. Three additions to the cement at the levels of 20% and 40% were used. They were fine limestone (LF), granulated slag (GS), and crystallized slag (CS). The fresh states characteristics of SCC are affected by the nature and dosage of the mineral admixture. In the hardened state, the comparison between the elaborated SCC and the control SCC without addition and without heat treatment showed an overall gain in strength at early age and minimal loss in the long term. The CS with a dosage of 40% allowed to the heat-treated SCC to be the less porous and the more resistant one compared to the elaborated SCCs. The use of LF appears to be more favorable if its incorporation is limited to below 20%. The GS is also favorable with 20% and it can be more beneficial if its fineness exceed that of the cement powder.

1. Introduction

Self-compacting concrete (SCC) is currently widely used in the production of prefabricated elements with simple or complex geometry. This has several advantages, such as downsizing, reduced noise and vibration, and improved finished characteristics and life of moulds. However, the kinetics of hardening of SCC is not always equivalent to that of traditional concrete, because the adjuvants which are necessary to obtain SCC generally have a secondary retarder effect. The decreased hardening time of the concrete allows the precast concrete industry to meet its productivity challenge and to extend the field of application of these materials. Indeed, the reduction of the time between the mixing of fresh concrete and the unmoulding of the concrete products is a key factor for a quicker rotation of the equipment and reduces the overall cost of production [1]. The application of an optimized heat treatment to a mixture of SCC containing conventional components and appropriate additions makes it possible to produce a concrete which reaches a substantial compressive strength after a few hours of treatment and allows the losses of strength of hardened concrete to be minimized in the long term. The gain in compressive strength at early ages of the heat-treated concrete is affected by the composition of the mixture and the parameters of the treatment process [2,3].

Knowing that SCC is a sensitive mixture that is highly dependent on the composition and characteristics of its constituents, it must have incompatible properties of high fluidity with high

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resistance to segregation. One of its disadvantages is its high cost. An alternative for reducing the cost of SCC is the use of fine mineral additions which replace a part of the Portland cement. Further, many studies have confirmed the benefits of the incorporation of these fine materials. Limestone filler (LF), marble powder (MP), and fly ash (FA) were evaluated by researchers [4–6], and granulated slag (GS) and metakaolin (MK) have been used and studied [7,8], proving their contributions to the characteristics and durability of SCC. These fine materials can improve the granulometry and the arrangement of the particles, thus ensuring a greater cohesion in fresh state. In hardened state, they can significantly improve the microstructure of the concrete and reduce the interconnected capillary pores in concrete.

If concrete undergoes an acceleration of its hardening by heat treatment, according to some researchers [9] this would lead to a change of the distribution of the SCC pore size to coarse pores but would not increase the total pore volume of the concrete. The effectiveness of the use of additions in this area has been proven by several studies: Researches [10,11] have shown that with GS and FA it is possible to obtain more efficient SCC, while according to another work [12], a high steam-curing temperature can significantly improve the reactivity of GS and FA in the concrete, and therefore the action of hydration of these mineral admixtures. Other research [13] studied the effect of several cycles of treatment of SCC and found that the use of FA and silica fume (SF) has a positive effect on the mechanical strength of the SCC, while another study [14] showed that the use of MK helps to obtain pores with small average diameters, reducing the porosity and water absorption of the heat-treated concrete. These mineral admixtures can also be used as binary, ternary or quaternary blended concrete. The main advantage of this combination is to eliminate the drawbacks of the particular supplementary cementitious materials through combining with other superior quality material and reduce the overall cost of the concrete production. It is also useful to enhance the structural properties of concrete. The influence of supplementary materials such as GS, MK and LF in steam-cured ternary and quaternary cement blends was studied in the research [15] which revealed that it is possible to replace up to 40% cement to exhibited superior mechanical properties.

This experimental work aimed to investigate the effect of the incorporation of local mineral admixtures and the effect of different dosages on the performance of heat-treated SCC. A reference SCC (without addition and without heat treatment) was prepared to assess the results of the studied SCC.

2. Materials and methods

2.1. Materials

The cement used in this work is a Portland cement compound, CPJ CEM II 42.5, produced by Hdjar-Soud cement factory (Department of Skikda, northern Algeria). Its mineralogical composition is C_3S = 55–65%, C_2S = 10–18%, C_3A = 10–12%, and C_4AF = 10–12%.

The limestone filler (LF) used is a calcium carbonate powder ($CaCO_3$ = 98%) from the crushing quarry of the National Company of Aggregates d'El-Khroub (Department of Constantine, northern Algeria).

The granulated slag (GS) and the crystallized slag (CS) used were recovered from the blast furnaces of the steel complex of El Hadjar (Department of Annaba, northern Algeria). They were ground to obtain a fine powder similar to that of common cements.

The chemical composition of the various cementitious materials is given in Table 1. The chemical composition of LF indicate that is inert product, and the chemical composition of GS and CS is near to that of the cement which indicate that are reactive products.

The physical characteristics of the admixtures: absolute density, specific surface of Blaine (SSB) (EN 196-6), and specific surface by laser diffraction (SSDL) (NF X11-666), are shown in Table 2 and their particle size distribution is illustrated in Fig. 1.

Two sands and two gravels were used for making self-compacting concrete: a 0.1 mm siliceous sand (denoted S1) from the region of Oued Zhor (Department of Skikda), a 0.4 mm crushed limestone sand (denoted S2) from the quarry of Boucelba (Department of Guelma, northern Algeria), a 3–8 mm gravel (denoted G1), and a 8–15 mm gravel (denoted G2) from the crushing quarry of Guerbeze (Department of Skikda).

The physical characteristics of the aggregates are summarized in Table 3. The results of particle size analysis conducted in accordance with Standard NF P 18-560 are shown in Fig. 2 is continue and indicates that the granulometric curves of aggregates are current and the aggregates can be used in the composition of concrete. The results of the chemical analysis of sands are given in Table 1.

2.2. Casting, curing and testing procedure

The SCC mixes were prepared in a laboratory mixer. The components of SCC mixture were batched by weight. Cement and mineral admixture were premixed with coarse aggregates and fine aggregate for 1 min, then the amount of 60% of mixing water and mixed for 1 min, then the remainder amount of mixing water (40%) with the dissolved superplasticizer was added in 0.5 min. Finally, the SCC mixture was mixed for an additional 1.5 min, resulting in a total mixing period of 4 min.

Before casting, a variety of tests were conducted to determine properties of fresh SCC, i.e. Slump flow diameter, V-funnel, L-box, Sieve stability, Occluded air and absolute density.

Specimens were then cast in cube moulds with the dimension of 150 mm and were not subjected to any compaction other than their own self weights. For one batch, half of the test specimens were cured in laboratory conditions for 24 h until demoulding.

The other half were kept wet in molds for 3 h and then were exposed to steam curing at 60 °C in the steam chamber (laboratory oven) to accelerate the hardening of SCC.

The acceleration of hardening of SCC was carried through the heat-treatment process according to the cycle schematized in Fig. 3. The cycle used in this work (which is very similar to those used in precast plants) takes into account the specification of EN 13369 [16].

The treatment temperature is 60 °C and the total duration is 24 h. It comprises 3 h of pretreatment (pre-set at 20 °C), a phase of temperature rise of 16 °C/h, isothermal bearing at 60 °C for 16 h, and finally a phase of ambient cooling for 2.5 h. The demoulding of the specimens was carried out just at the end of the cycle. At this moment, the specimens were weighed to determine the quantity of evaporated water (EW) under the effect of the heating.

Forty-two specimens were tested in compression at early age (CS_1) and 126 others were stored in water at ambient temperature for long-term tests; these are the tests for determination of the porosity (P), the water absorption capacity (WAC), and the compressive strength at 28 days (CS_{28}) and 180 days (CS_{180}).

The effect of the composition of the concrete is studied well in order to assess its influence in parallel with the acceleration of hardening using the heat-treatment process. For this, three additions of two different types with levels of 20% and 40% were used: LF, GS and CS. The percentages of mineral additives 20 and 40 selected in this work are within the actual rates usually adopted in the manufacture of Algerian composite cements: such as CPJ-CEM II/A (6–20% of mineral additives) and CPJ-CEM II/B (21–35% of mineral additives). The cement was substituted by the mineral admixture by weight to obtain a self-compact paste for each SSC mixture as recommended by the French Association of Civil Engineering (AFGC) [17]. For this, 7 different SCC mixtures were prepared (Table 4), i.e. SCC(R), SCC20LF, SCC40LF, SCC20GS, SCC40GS, SCC20CS and SCC40CS.

The characterization of SCC in fresh state was carried out using the tests recommended by the AFGC [17]:

- Flow test using an Abrams cone, which allows the fluidity and mobility of unconfined concrete to be characterized. It involves measuring the diameter (D) of the wafer after lifting the concrete cone and T_{500}, the time it takes to reach a spread diameter of 500 mm.
- V-funnel test, which aims to evaluate the fluidity and the stability of the SCC. The time $T_{\text{V-Funnel}}$ is the flow time in seconds between the opening of the bottom outlet and when the light is visible from the bottom when viewed from above. For an SCC it is permissible to have a time between 6 and 12 s [18].
- L-box test, which enables the risk of blockage and the filling capacity of the concrete in a confined space to be evaluated. We measure the filling rate, defined as the ratio of the heights H_2/H_1, which must be greater than 0.8.
- Sieve stability test, which is used to describe SCC with respect to the risk of segregation. It complements the tests for assessing the mobility in confined or unconfined space by characterizing the stability.
- Other tests were carried out on different fresh mixtures: the occluded air (OA) test and the determination of the absolute density of fresh concrete (ρ_{fc}).

A calculation of the plastic viscosity was undertaken. This parameter has a correlation with T_{500} known as the rheology–workability, which can be highlighted according to [19] by the Formula (1):