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Mechanical properties of high performance self-compacting concretes at room and high temperature

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HIGHLIGHTS

- Mechanical properties of 11 self-compacting concretes studied up to 600 °C.
- Evolution of f_c and E as a function of paste volume and water/binder ratio.
- Modified and extended Eurocode 2 law proposed for E(f_c).
- Thermal strain, compressive strength and modulus of elasticity up to 600 °C.

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ABSTRACT

The composition of Self-compacting concretes (SCCs) differs significantly from that of vibrated concretes (VCs). In particular, SCCs generally contain higher paste volumes, larger contents of mineral admixtures and often lower binder to water ratios than VCs. These specific composition parameters allow fulfilling the hard-to-please fresh state requirements of SCCs. However they could also modify significantly their mechanical behavior when concrete is submitted to high temperatures. The main objective of this paper is to study the mechanical behavior of SCCs at room and high temperature. Compressive strength, modulus of elasticity and free thermal strain of 11 self-compacting concretes (SCCs) have been studied at room and high temperature (up to 600 °C). Two series of SCCs are studied: a series in which the mixture proportions of a given concrete are changed in order to vary independently the water/binder ratio and the paste volume and a series with compositions similar to those employed in the precast industry. The variations of compressive strength and modulus of elasticity as a function of the two composition parameters studied are in good agreement with those obtained in the literature for vibrated and self compacting concretes. A relation is given to link the modulus of elasticity of SCC to its compressive strength, which is close to that proposed by ACI 363-2010. The free thermal strain of SCCs is then studied as a function of temperature. Below 300 °C, the free thermal strain of SCCs is larger than that proposed by Eurocode 2 rules for vibrated concrete. Above 300 °C, free thermal strain of SCCs lies between the values proposed by Eurocode 2 for siliceous and calcareous aggregates. The relative compressive strength determined at elevated temperature is generally lower than that proposed by Eurocode 2 for traditional vibrated concrete. The comparison of our results with those determined on several vibrated concretes shows that the obtained relative modulus of elasticity is in the same range. The influence of water to binder ratio and paste volume on these results is discussed.

1. Introduction

Self-compacting concretes (SCCs) emerged in the late 80's in Japan. These concretes can be poured into formwork and compacted purely by means of their own weight without the need of vibration. They have therefore to be fluid enough to fill correctly the formworks but also to exhibit a high resistance to static and dynamic segregation. In order to meet these requirements at fresh state, SCCs contain higher paste volumes, larger contents of mineral admixtures and often lower binder to water ratios than vibrated concretes (VCs). However these differences may modify

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significantly their mechanical behavior. The specific composition and the characterization of fresh SCC are frequently discussed in the literature. However, their mechanical properties at room and especially at high temperatures are less studied and only a few papers can be found on this subject [1–3]. The work presented here is an experimental study on the mechanical properties of SCCs in the hardened state at room temperature and at high temperature (up to 600 °C).

Studies on the mechanical behavior of SCC in the hardened state show on one hand that for the same water/binder ratio, the SCC has generally lower mechanical strengths than traditional vibrated concrete (VC) [4–7]. The modulus of elasticity of SCC has also lower values than for VC [4,5], due to the higher volume of cement paste in SCCs, but some studies show relatively small differences between the modulus of the SCC and of the VC [8–10]. Domone [11] shows that the decrease of modulus of elasticity of SCC compared to VC is 5% for SCCs with high compressive strength (90–100 MPa) and up to 40% for the SCCs with the lowest strength (20 MPa). The relationship between tensile strength and compressive strength of SCC is similar to that of VC.

Finally, the mechanical behavior at high temperatures of SCCs has been poorly studied. According to Persson [12], the compressive strength of SCC at 100 and 200 °C are significantly higher for SCC than for VC. The modulus of elasticity seems rather to decrease more rapidly with temperature for SCC than for VC. Some other studies on the residual properties [13–15] also show an increase in strength of SCC compared to VC after heating in particular around 300 °C. At 600 °C, the results between SCC and VC are similar.

However, the various studies are often difficult to compare, especially because of the multitude of components used in the compositions of tested SCCs. In addition, within the same study, the concrete compositions are also often highly variable and conclusions are generally difficult to relate to the composition parameters of concrete.

The objective of this paper is twofold. First, we study systematically the influence of two important composition parameters (water/binder ratio and paste volume) on the main properties of hardened concrete at room and high temperature. Then, we examine the applicability, for SCC, of main regulatory equations, in particular those proposed by Eurocode 2 (NF EN 1992-1-2) [16] and we propose eventually more suitable relations.

In our work, two series of SCCs have been studied. In a first series (S_1, laboratory SCCs), the mixture proportions of a given SCC have been changed in order to vary independently two important composition parameters: the water/binder ratio and the cement paste volume. Then, a second series of SCCs (S_2, called industrial SCCs in the following) has been studied with varying materials and varying compositions, covering a wide range of mechanical properties. This series of concretes has been designed by CERIB (French Concrete Industry Study and Research Center) in collaboration with CSTB (French Scientific and Technical Center of Building), and corresponds to SCCs used in real applications in the precast industry. The compressive strength and the modulus of elasticity of the different concretes are determined at room temperature. Free thermal strain, compressive strength and modulus of elasticity are then determined at high temperatures up to 600 °C.

2. Concrete mixes

From a reference laboratory SCC called S_1-C_2, seven compositions were developed on one hand by varying the paste volume (3 concretes called S_1-C_1, S_1-C_3 and S_1-C_4) and on another hand the water/binder ratio (3 concretes called S_1-C_{2a}, S_1-C_{2b} and S_1-C_{2c}). A constant superplasticizer content was used for all these concretes as, despite varying compositions, the obtained slump flows always complied with SCC requirements. Four industrial SCCs (called S_2-C_1, S_2-C_2, S_2-C_3, and S_2-C_4) were also studied.

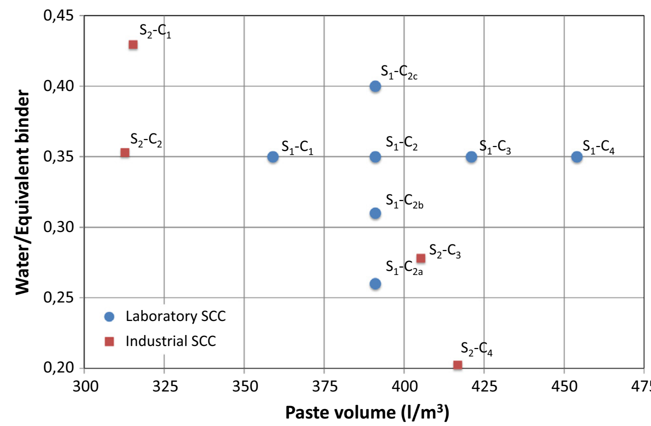

Fig. 1. Paste volume and W/B for studied concretes.

In Fig. 1, the paste volume and the water/equivalent binder ratio (W/B) of each concrete can be visualized. Equivalent binder is determined according to EN 206-1 (Eq. (1)):

$$\text{Equivalent Binder} = \text{Cement content} + k \times \text{Mineral Admixture content} \quad (1)$$

where k is the activity coefficient (0.25 for calcareous and siliceous filler and 2 for silica fume).

The paste volume corresponds to the sum of powder volumes (cement, silica fume, siliceous and calcareous fillers) and of effective water, considering that the volume of entrapped air is negligible. The powder volumes are calculated from their mass content and their specific densities (3190, 2270, 2650, and 2700 kg/m^3 for cement, silica fume, siliceous and calcareous fillers respectively).

This figure shows that the compositions cover a wide range of paste volume (V_p) and W/B corresponding to the field of industrial compositions. The compositions and some characteristics are given in Tables 1 and 2.The seven laboratory SCCs and the four industrial SCCs are studied and their mechanical behavior at room temperature and at high temperature is detailed.

3. Experimental procedures

3.1. Tests at room temperature

The compressive strength and the modulus of elasticity were determined at room temperature on cylindrical specimens 11 × 22 cm. For the modulus of elasticity, tests were performed on the basis of RILEM recommendations [17]. Cycles of loading/unloading were applied to the specimens at a speed of 0.5 MPa/s, with a stress comprised between 0.5 MPa and one third of the compressive strength of the material, determined on a preliminary test. After the last cycle, the specimens were loaded until failure. The specimens were stored in water at 20 °C and tested 28 ± 1 days after casting. For each composition, three specimens were tested. Strain measurements were performed using an extensometer [18]: the relative movement of two rings attached on the specimen (positioned at mid-height perpendicular to the loading direction) is measured using three displacement sensors positioned at 120 °C.

3.2. Tests at high temperature

Compressive tests were carried out at several temperatures: 20, 120, 250, 400 and 600 °C. For each test, the compressive strength, modulus of elasticity and free thermal strain were measured for concretes S_1-C_2, S_1-C_{2a}, S_1-C_{2c}, S_1-C_4, S_2-C_1, S_2-C_2, S_2-C_3 and S_2-C_4. For each temperature and for each concrete, two specimens were tested for industrial concretes (S_2-C_1, S_2-C_2, S_2-C_3 and S_2-C_4). However, for the specimens of series S_1 (S_1-C_2, S_1-C_{2a}, S_1-C_{2c}, S_1-C_4) only one specimen was tested for