INFLUENCE OF MIXING AND CURING TEMPERATURES ON THE PROPERTIES OF FRESH AND HARDENED SELF-CONSOLIDATED CONCRETE IN HOT WEATHER CONDITIONS

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ABSTRACT

This paper describes an experimental investigation of the behavior of self-consolidating concrete (SCC) produced and cured under conditions of hot weather, in the context of manufacturing control specimens. Two different designs were tested, incorporating either OPC or slag cement. Mechanical properties and physical properties (porosity, water absorption) were quantified in the hardened state. Notably, in the case of SCC incorporating slag cement (CEMIII), results show that an increase in the mix temperature from 20°C to 50°C did not imply the use of extra water to keep the flow properties constant at the end of mixing. In addition, the increase in both mixing and curing temperatures did not have an adverse effect on the compressive strength or porosity for any of the concretes studied, but caused a significant increase in the total creep of concrete incorporating slag cement when it was mixed and cured under hot weather conditions.

Keywords: self-consolidating concrete; hot weather; fresh and hardened states; slag cement.

INTRODUCTION

Considerable developments are achieved for self-compacting concrete (SCC) during recent years. Practical application has been accompanied by much research into the physical and mechanical characteristics of this concrete capable of flowing under its own weight and without segregation. Such mixtures typically have a high paste volume, high mineral admixture content, less coarse aggregates and a high sand-to-coarse aggregate ratio linked to their specific self-compacting properties in the fresh state. Nevertheless, in the hardened state, they should show mechanical performance and durability very similar to those of traditional vibrated concrete. Many studies have shown that this requirement is almost achieved in mild weather conditions [1,2]. The question arises whether this requirement can be maintained under conditions of hot weather concreting in the context of the manufacturing of control specimens. Recommendations for hot weather concreting have been established [3,4] and justified for the vibrated concretes [5]: additions of water are prohibited, despite the occurrence of evaporation, in order to avoid an increase of the porosity of concrete both in the fresh and in the hardened state. Instead, the use of chemical admixtures, such as water reducers or high range water reducers, is promoted. An attempt to assess the characteristics of SCC mixed under simulated hot weather conditions was made at the Laboratory of Materials and Durability of Constructions (LMDC). Here, results are reported regarding some properties quantified on control specimens and "false" control specimens cured at elevated temperatures: compressive strength, bulk modulus of elasticity, porosity, absorption and creep.

EXPERIMENTAL PROGRAM

1. Materials

a. Cement (C1, C2)

The choice of cements was driven by the change of the production of cement and concrete, oriented towards a decrease in the clinker content. Hence, two cements were used. Main characteristics are given in Table 1: conventional OPC cement (CEM I) and slag cement (CEM III). Both cements comply with the European Standard EN 197-1.

b. Limestone filler (F)

A 0/90-µm limestone filler complying with the French standard NF P 18-508 was used (Blaine fineness = 6500 cm^2/g, specific gravity = 2.72 g/cm^3, strength activity index = 0.76, $CaCO_3$ content = 97.6% by weight).

c. Chemical admixture (SP)

A polycarboxylate-type HWRA was employed as a commercial solution (density =1.05, solid content = 21.6% by weight).

d. Aggregates (S, G)

Rounded siliceous aggregates were employed: sand (S) 0/4 mm (2670 kg/m^3, water absorption=1.5 %), and gravel (G) 4/10 mm (2670 kg/m^3, absorption = 1.1%).

e. Concrete mixture proportions

The concrete compositions tested in this investigation are presented in Table 2. They were defined by the use of a diphasic design approach, consisting in the combination of a paste (optimized flow) and a wet aggregate skeleton [6]. Both compositions had the same equivalent binder content, as defined in the EN 206-1 standard.

Table 1. Characteristics and composition of the cements used (C1, C2)

Name	Type	Specific gravity (g/cm^3)	Blaine fineness (cm^2/g)	Clinker (wt %)	Addition (wt %)
C1	CEM I 52.5 N	3.11	3750	98.5	1 (Limestone)
C2	CEM III 52.5N	3.01	3760	59.4	40 (Slag)

Table 2. Mix designs (kg/m^3) – dosages corresponding to entrapped air volume of 25 l/m^3

Constituents	C1	C2	F	S	G	SP	Added Water
SCC1-20	350.0	/	87.5	808.0	889.0	4.375	190.3
SCC1-50	350.0	/	87.5	808.0	889.0	4.375	190.3 ***+ 12.1****
SCC2-20	/	370.0	92.5	795.4	875.0	4.625	187.8
SCC2-50	/	370.0	92.5	795.4	875.0	4.625	187.8

* *Additions of water were needed to keep the fresh properties constant (see section 2b below)*

2. Procedures

a. Means to achieve the initial temperature of the mix

The initial temperature of the mix was varied between 20^{o}C and 50°C. A temperature of 50°C was considered as a sufficient upper limit, reached in hot weather when concrete is cast with aggregates exposed to solar radiation (a surface temperature of 80°C can be reached, especially when they are dark in color) and with warm cement (a temperature of 80°C is often observed, especially when it comes directly from the factory and is immediately used in a concrete plant). Accordingly, the cement, the limestone filler and the aggregates were heated to 80°C. Water and HRWA were stored at ambient temperature (20°C±1°C) so that the resulting temperature of the mix was 50°C (mixing under 20°C ± 1°C and 45% ± 5% RH).

b. Mixing procedure and workability tests

The mixing comprised, first, the introduction of gravel, cement, limestone filler and sand followed by 60 s mixing; second, the introduction of water and 1/3 superplasticizer followed by 90 s mixing; and third, the introduction of 2/3 superplasticizer followed by 90 s mixing. The slump-flow value (including t$_{50}$ time), used as the criterion for acceptance on the building site, was kept constant whatever the initial temperature (20°C or 50°C). In order to compensate for the water evaporation due to the increase in the mix temperature, it was decided to maintain the slump flow by additions of water. The incorporation of extra water is a breach of the current recommendations for hot weather concreting and the effect of such incorporation on some hardened properties is discussed below. Once the slump flow target had been verified, other workability tests were employed to assess the self-consolidating ability: L-box and sieve stability tests. All the tests were performed immediately after mixing, in the following order: Slump flow (t$_0$ + 1 min), L-box (t$_0$ + 5 min), Sieve stability (sample of concrete taken from the mixer at t$_0$ and tested at t$_0$ + 15 min). In parallel, the apparent specific gravity and the entrapped air volume were measured. In the case of mixing temperature at 50°C, the flow and L-box tests were repeated until 30 minutes after mixing in order to verify whether the self-compacting properties were affected or not.

c. Curing of specimens

SCC specimens (11 cm x 22 cm cylinders) were subjected to two curing regimens: a) conditions specified in the French standard (NF P 18-404) for manufacturing control (20°C, 100% RH) throughout the test session; b) 35°C for the first 5 hours after mixing, followed by a decrease in temperature until 24 h, and storage at 20°C, 100% RH until the time of tests. The second curing condition, still against the current recommendations, simulated the time that elapsed between the fabrication of specimens and transport to the laboratory.

d. Synopsis of the tests performed at the different stages

Table 3 summarizes together the tests carried out in compliance with the related standards or procedures.

Table 3. Synopsis of the tests performed at the different stages

Fresh state	*References*	*Hardened state:*	*References*
Density	EN 12350-6	*Instantaneous behavior.*	
Slump test	EN 12350-8	Compressive strength at 1, 7, 28 days (MPa)	EN 12390-2/3
Air content measurement	EN 12350-7		
L-Box test	EN 12350-10	Elasticity modulus (MPa)	NF P18 459
Sieve segregation test	EN 12350-11		
Hardened state:		*Hardened state:*	
Physical properties.		*Delayed behavior.*	
Water porosity (%)	NF P18 459	Total and autogenous creep (µm/m/MPa)	RILEM–TC 107-CSP
Water absorption: Ab_{1h} (kg m^{-2}), Abs (kg m^{-2} h$^{-1/2}$)	AFPC AFREM, 1997		

EXPERIMENTAL RESULTS AND DISCUSSION

1. Fresh state

Table 4 presents the fresh state properties of all SCC mixtures, namely: density, air content, water content, slump flow (t_{50} and final average spread), L-box (time t_{45} to reach a distance of 45 cm in the horizontal part, H_2/H_1 ratio), and sieve segregation.

Table 4. Properties in the fresh state.

	SCC1-20	SCC2-20	SCC1-50	SCC2-50
Density (kg/m^3)	2350	2365	2345	2360
Air content (l/m^3)	17	9	19	19
Real water content (l/m^3)*	195.4	194.6	195.3	182.0
Slump flow test (t0**+1')/(t0**+15')				
Average diameter (cm)	71.5	72.5	71.0/72.5	73.5/75.0
t_{50} (s)	1.6	1.8	1.8/2.0	1.5/1.5
L-Box (3 rebars) (t0**+5')/(t0**+20')				
t_{45} (s)	1.7	1.4	1.0/1.4	1.0/2.0
H_2/H_1 ratio	0.85	0.91	0.80/0.80	0.93/0.81
Sieve segregation test (%)	10.0	19.0	16.7	13.8

* *(wt. % of water contained in a sample taken from the mixer immediately after mixing) x apparent specific gravity of concrete Average accuracy on the measurements = ±3 l/m^3.*

*** t0 end of mixing*

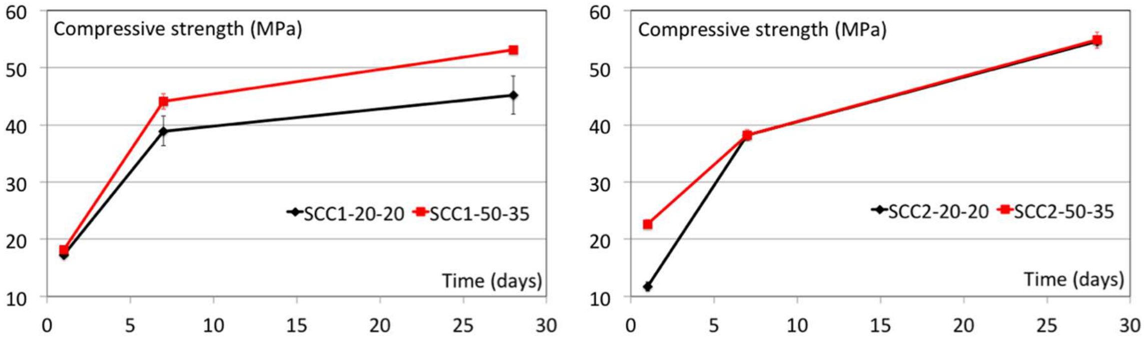
When the initial mix temperature was raised to 50°C, the addition of water enabled the self-compacting ability to be maintained for concrete incorporating cement CEM I (SCC1-50, Table 2). In this case, the stability of the mixture decreased slightly. In contrast, CEM III concrete (SCC2) required no additions of water and remained self-compacting; in addition, the stability of SCC2 mixed at 50°C increased (see Table 4). From the measurement of the real water content (Table 4), it is clear that the addition of water was compensated by the water evaporation during mixing in the case of SCC1 concretes. Regarding SCC2 mixes, the evaporation of water during mixing involved a decrease in the real water content of approximately 13 liters per cubic meter of concrete. Moreover, the self-compacting abilities of SCC-50 concretes were not significantly affected from immediately to 20 minutes after mixing.

2. Hardened state

a. Instantaneous mechanical properties

The compressive strength (1, 7 and 28 days) and the experimental scatter are presented by Figure 1. At an age of 28 days, the average bulk modulus of elasticity was measured from three loading-unloading cycles [7] (Table 5). Irrespective of the design (SCC1 or SCC2), it was observed that a rise in the initial mix temperature and the curing temperature did not adversely affect the compressive strength at 1, 7 or 28 days of age.

Fig.1. Compressive strength at 1, 7 and 28 days for all SCC tested.



In the case of SCC1, the addition of water in the warm mix followed by curing of specimens at elevated temperatures usually encountered in hot weather made it possible to obtain strengths equal to or higher than those of a concrete cast and cured at a temperature of 20°C. Contrary to observations made on vibrated concrete in the same experimental context [5], the addition of water, advised against in the recommendations, was not detrimental to the strength development of SCC. This may be explained by the presence of HRWA limiting the addition of water necessary to a) maintain the self-compacting ability and b) to compensate for the inevitable evaporation due to high temperature (Table 4). Regarding CEM III SCC design (SCC2), although some water evaporated, a complementary addition of water was not required at 50°C, certainly because of the low reactivity of CEMIII (60% of clinker by weight) in comparison with CEM I (98.5% of clinker) and the use of HRWA. In that case, it is worth noting that the rise in both the initial mixing and the curing temperature increased the 1-day strength. In practice, formwork can be removed earlier when CEM III-based SCC is cast under elevated temperatures.

In comparison with the control specimens (SCC-20-20), the modulus of elasticity (Table 5) slightly decreased (resp. increased) with elevated temperatures for SCC1 (resp. SCC2). In all cases, based on the compressive strength results, the variations in the E-modulus cannot be considered significant.

b. Physical properties

Table 5 presents the average values of the water porosity (calculated from measurements on three samples at 35 days of age,) and the corresponding experimental scatter. As expected from the compressive strength results and irrespective of the composition, the increase in the mixing and the curing temperatures did not significantly change the porosity.

Table 5. E-modulus and transfer property measurements.

	SCC1-20-20	SCC1-50-35	SCC2-20-20	SCC2-50-35
Elasticity modulus (MPa)	30925±716	29844±33	32016±40	32627±54
Water porosity (%)	15.22±0.37	14.72±0.70	14.58±0.27	14.39±0.86
Water absorption				
Ab$_{1h}$ (kg/m^2)	1.17±0.04	1.19±0.05	0.77±0.02	0.75±0.01
Abs (kg/m^2/h$^{1/2}$)	1.27±0.05	1.44±0.04	0.76±0.02	0.81±0.01

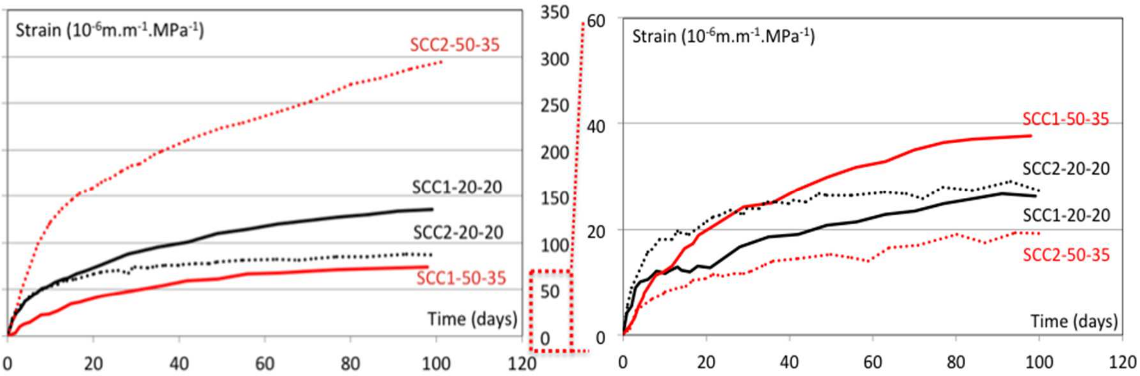
The mean values and the experimental scatter of the water absorption indicators by capillary suction are given in Table 5. The initial absorption, Ab$_{1h}$, is characterized by the mass of water absorbed after 1h in contact with water and the absorptivity (Abs) is the mass absorbed between 1h and 24h. For a given design, the increase in temperatures did not affect Ab$_{1h}$ values, which represent the filling up of the largest capillaries. In contrast, the rise in both mixing and curing temperatures increased the absorptivity related to the finest capillaries, with no adverse effect on the compressive strength (see section 2a).

c. Delayed behavior

The total delayed strains were measured from 7 to 100 days of age (loading rate equal to 40% of the 7-day compressive strength). Although the different components of the total delayed strains are inter-dependent, creep can be dissociated from the elastic and shrinkage strains. Creep results are presented in the specific creep format: creep strain value divided by loading value. The total and autogenous specific creep vs time curves are plotted in Fig.2.

It is noteworthy that the concrete incorporating the ternary binder (clinker+slag+limestone filler) was remarkably prone to total creep when mixed and cured under elevated temperatures, in comparison with any concrete tested in this study. At the same time the autogenous creep remained in the same order of magnitude, whatever the design and the temperature conditions. The marked total creep of SCC2-50-35 was also confirmed when loading was applied at 28 days of age.
An explanation of the level of the total creep for SCC2-50-35 can be found by plotting the drying shrinkage versus the mass loss (Fig. 3).

Fig.2. Total (a) and autogenous (b) specific creep as a function of time after loading.



(a) (b)

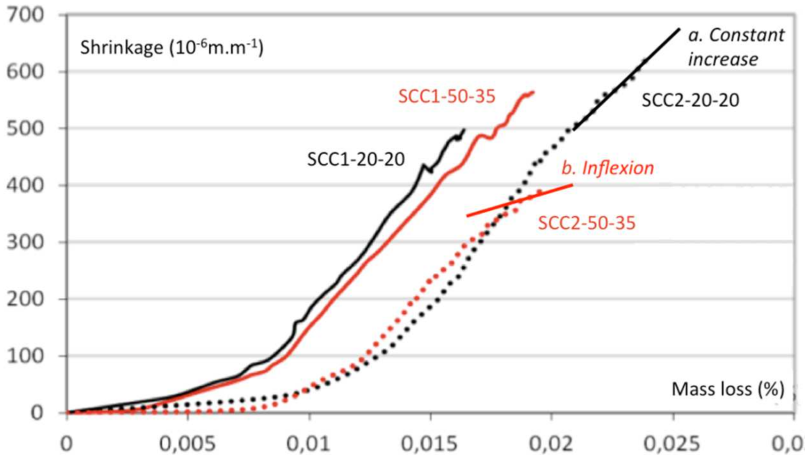


Fig.3. Drying shrinkage as a function of mass loss.

Two groups of curves can be observed which are related to the design nature (SCC1 and SCC2) and are independent of the temperature conditions. However, a noteworthy peculiarity is the inflexion at the end of the curve pertaining to SCC2-50-35 (b in Fig.3), indicating that the mass loss continued whereas the drying shrinkage slowed down. This evolution can be interpreted by loss of water through microcracking and this caused a higher total creep. Other explanation should be considered based on nature and amount of hydrated phases produced from ternary binder under elevated temperature. This result constitutes an important warning in the context of hot weather concreting because the mixtures tested in this study are not solely confined to buildings but may also be used in civil engineering structures.

CONCLUSIONS

Some mechanical properties and durability indicators were quantified for two SCC-mixtures and cured in conditions simulating hot weather in the context of manufacturing control specimens. The difference in the design was essentially in the binder nature (OPC/limestone filler or slag cement/limestone filler).

The most noteworthy results are:

- Unlike OPC/limestone filler binder, the slag cement/limestone filler binder required no addition of water to maintain its self-compacting ability when the mix temperature increased from 20°C to 50°C.

- Provided that the evaporation of water due to 50°C mixing temperature was compensated for a water addition or it decreased the actual water content of concrete, as expected, compressive strength and elastic modulus were similar to or higher than those pertaining to the reference mix.

- Unchanged or improved durability indicators (porous volume, distribution of capillary pores) were observed with the rise of mixture and curing temperatures, whatever the mixture.

- A significant increase in the total creep was observed for concrete incorporating slag cement, mixed and cured in hot weather conditions, probably caused by microcracking.

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