

Low Heat Development in Self-Compacting Concretes for Massive Structures

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Synopsis: Self-compacting concretes (SCC) are special cement mixes which can be placed without any vibration at all. The fresh mixes are characterized by very high fluidity and cohesion. These properties can be more easily obtained by decreasing the maximum size of the coarse aggregate and increasing the cement content. This characteristics is just the opposite of that required for concrete mixes for massive structures. These mixtures need coarse aggregate with high maximum size and low cement content in order to reduce the risk of thermal cracking related to the high heat development due to cement hydration.

Special SCC have been studied. They contain a gravel with a maximum size of 18 mm, a very low cement content ($\sim 150 \text{ kg/m}^3$) a large amount of limestone filler ($250\text{-}380 \text{ kg/m}^3$) and fly ash in the range of $50\text{-}150 \text{ kg/m}^3$ so that the amount of fine materials is approximately 500 kg/m^3 .

Due to the combined use of an acrylic superplasticizer and a viscosity agent based on a colloidal byopolimeric emulsion, unsegregable SCC with a slump flow of about 700 mm were manufactured. The compressive strength was about 20 MPa at 3 days and 30-40 MPa at 28 days.

Keywords: Bleeding, Fly Ash, Heat of Hydration, Self-Compacting Concrete, Superplasticizer.

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INTRODUCTION

Mass concrete structures are particularly vulnerable to the risk of cracking due to the development of thermal gradient (δT_t) between the nucleus of the structure and its periphery. This is related to the total heat of cement developed during hydration in the concrete (H_t) at the time t , and the difference in dissipating this heat from the nucleus and the outer part (Fig. 1).

From a practical point of view (by taking account the thermal expansion, the elastic strain as well as the creep of concrete) a thermal gradient not higher than 20°C is needed to avoid the risk of thermal cracking [2]:

$$\delta T_3 \cong \delta T_{\max} \leq 20^\circ\text{C} \quad (1)$$

where δT_{\max} is the maximum difference in temperature between the nucleus and the periphery of the structure (Fig. 1), which, in general occurs at a time of 3 days (δT_3). It is very difficult to calculate δT_{\max} since it depends on many parameters such as the thermo-insulating properties of the forms, the size and the shape of the structure, the environmental temperature and wind

conditions after placing, etc. However, we can easily calculate the maximum gradient δT_{\max} in extreme conditions such as:

- no thermal dissipation (adiabatic heating = ΔT) for the nucleus;
- complete thermal dissipation of the periphery ($\Delta T = 0$).

In these extreme and conservative conditions

$$\delta T_{\max} = \delta T_3 = \Delta T_3 \quad (2)$$

where ΔT_3 is the adiabatic heating of the nucleus after 3 days from the placing.

In the case of adiabatic heating for the nucleus, the maximum increase in the temperature of the structure at 3 days can be calculated as:

$$\Delta T_3 = H_3/(m \cdot s_h) = c \cdot h_3/(m \cdot s_h) \quad (3)$$

where h_3 is the heat of hydration of 1 kg of cement (unitary heat) at 3 days, c is the cement content in 1m^3 of concrete, m is the specific weight of 1m^3 of concrete (generally 2400 kg/m^3), and s_h is the specific heat of concrete (generally $1.1 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{C}^{-1}$). Therefore, ΔT_3 can be also written as:

$$\Delta T_3 \cong c \cdot h_3/(2400 \cdot 1.1) \cong c \cdot h_3/2600 \quad (4)$$

Therefore, if there is a limit of 20°C in the adiabatic heating of the nucleus at 3 days ($\Delta T_3 \leq 20^\circ\text{C}$) in real (not-extreme) conditions, the maximum thermal gradient between nucleus and periphery (δT_3) is even lower than 20°C :

$$\delta T_3 \ll \Delta T_3 \leq 20^\circ\text{C} \quad (5)$$

Then, in order to avoid any risk of thermal cracking, by taking into account the equations (4) and (5), a cement content (c) and a cement type, with a given unitary heat of hydration (h_3), must be adopted so that:

$$\frac{c \cdot h_3}{2600} \leq 20^\circ\text{C} \quad (6)$$

$$c \cdot h_3 \leq 52\text{MJ/m}^3 \quad (7)$$

In order to reduce the thermal cracking risk, a cement content as low as $200\text{-}250 \text{ kg/m}^3$ is usually adopted for very massive concrete structures such as dams. This means that aggregates with maximum size as large as $100\text{-}150 \text{ mm}$ are usually used to reduce the amount of mixing water (w) and consequently the cement content at a given w/c . For the same reason, concretes at a stiff consistency are usually adopted to reduce w and then c at a given w/c .

For both the large size of aggregates and the stiff consistency of the fresh mixture, this concrete is manufactured in special mixers and placed under very effective compaction methods.

PURPOSE OF THE WORK

The purpose of the present work was to study self-compacting concrete (SCC), with a relatively small maximum size of coarse aggregate (18 mm), which should be thermally crack-free in mass concrete structures such as slab foundations with very congested metallic reinforcement (Fig. 2).

The production of a low-heat and self-compacting concrete seems to be a conflicting task. Low heat and self-compaction of concrete mixes are apparently conflicting properties for the need of low and high cement content, respectively. However, due to the availability of very effective superplasticizers, and new anti-bleeding agents, this objective could be achieved.

EXPERIMENTAL

In the following sections the materials used and the methods adopted will be presented.

Materials

The following materials were used. A Portland cement according to EN 197/1 (*CEM I 52.5 R*) was used. Table 1 shows the unitary heat of hydration at different times of this cement and Table 2 shows its chemical composition.

Two different fine mineral additions were used to replace part of the cement and reduce the heat of cement hydration. Table 2 shows some typical characteristics of these mineral additions: ground limestone and fly-ash.

Natural aggregates in the form of 0-4 mm sand with a fineness modulus of 2.80 and 4-18 mm natural gravel were used. A superplasticizer based on acrylic polymer (*AP*) specially studied for low-slump loss ready-mixed concrete (Dynamon SR1 by Mapei, Milan, Italy) was used as well as a Viscosity Modifying Agent (VMA) based on a colloidal byopolimeric emulsion (Viscofluid SCC by Mapei, Milan, Italy).

Table 3 shows the composition of four concrete mixtures all containing about 150 kg/m³ of Portland cement and about 300-380 kg/m³ of a mixture of ground limestone and fly ash. The total binder content (including Portland cement, fly ash and ground limestone) was about 500 kg/m³. The dosages of VMA and superplasticizer were adjusted to obtain a slump flow of about 700 mm with a negligible bleeding by using only about 150 kg/m³ of mixing water. The superplasticizer dosage had to be increased if the fly ash – ground limestone ratio is increased (Table 3) due to the higher specific surface area of fly ash with respect to ground limestone (Table 2).

METHODS

The fresh mixtures were characterized by the measurements of their slump flow. Moreover, the bleeding capacity was determined by collecting the total amount of bleeding water (every 20 minutes) on the top of concrete into a container (5.2 l) up to the setting time.

Concrete mixtures after mixing were placed without vibration in an insulating polystyrene container of 500mmx500mmx500mm and, by the use of a thermocouple in the nucleus of the concrete, the change in the temperature (ΔT) was recorded for about 1 week in quasi-adiabatic condition. These tests were carried out to confirm whether or not these SCCs are suitable for mass concrete structures according to equation (7) where, for these concretes, $c = 150 \text{ kg/m}^3$ and $h_3 = 345 \text{ kJ/kg}$:

$$c \cdot h_3 = 150 \cdot 345 = 51\,750 < 52\,000 \text{ kJ/m}^3$$

The concrete mixtures were placed without any compaction in cubic molds (150 mm) for determining the compressive strength from 1 day up to 90 days. The curing was done at 20°C and 95% RH. Shrinkage tests were carried out on prismatic specimens (100mm·100mm·500mm) placed without vibration and exposed to dry air (RH = 50%) at 20±3°C after their demolding at 1 day.

RESULTS

Materials

Table 4 shows the slump flow and the bleeding capacity when increasing the content of fly ash (from Mix A to Mix D). There is a significant reduction in the bleeding capacity at equal slump flow and an increase in the cohesiveness of the mixture when the amount of fly ash increases.

Thermal Change

The thermal change in the nucleus of the mixtures A and D as a function of time is shown in Figure 2, where it is seen that the temperature increase (ΔT_3) at 3 days is lower than 20°C. In mixture D the temperature rising rate is lower than in mixture A for the higher amount of acrylic superplasticizer which retards early cement hydration. However, for both mixtures similar results were obtained when using 300 kg/m³ of ground granulated blast furnace slag cement [3]. These results are in agreement with equation (7) and confirm that these special SCCs are also suitable for mass concrete structures.

Compressive Strength

Figure 3 shows the results of compressive strength. Concretes containing fly ash (*FA*) give better results than those containing ground limestone (*GL*) at longer ages (> 28 days). This behavior is due to the pozzolanic activity of the fly ash. On the other hand, due to the higher dosage of the acrylic superplasticizer adopted in the case of the *SCCs* when increasing amounts of fly ash are used, there is a retarding effect in the hydration of Portland cement and this results in a lower strength rate at early ages in the fly ash mixtures. These results agree very well with the thermal change results shown in Fig. 2.

Shrinkage Test

Figure 4 shows the length change of the specimens kept in a dry environment (RH = 50%). These results indicate that the drying shrinkage of these *SCCs* is of the same order of magnitude as ordinary concretes [1] and does not depend substantially on the fly ash-limestone ratio.

CONCLUSIONS

The combined use about 150 kg/m³ Portland cement, of 1-2% *AP*-based superplasticizer, and about 350 kg/m³ powder mineral addition, 0.04% viscosity modifying agent, and aggregate with a maximum size of 18 mm allow to manufacture of **self-compacting concretes** characterized by a **low heat** development particularly suitable for **mass concrete structures**.

The use of the *AP*-based superplasticizer is useful for self-compacting concretes with negligible workability loss. The presence of the viscosity modifying agent is needed to reduce bleeding water and segregation, and improves the cohesiveness of the fresh mixtures.

The performance of *SCCs* in terms of compressive strength appear to be better when a mixture of ground limestone and fly ash instead of ground limestone alone is used as powder mineral addition with the materials that were studied.

The drying shrinkage of all the *SCCs* examined is of the same order of magnitude as for ordinary concretes.

REFERENCES

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Table 1 – Unitary heat of cement hydration at different times for CEM I 52.5 R

HEAT, kJ/kg	Time (days)
280	1
345	3
400	7
440	28

Table 2 – Chemical composition and physical properties of mineral additions

CHARACTERISTICS	GROUND LIMESTONE	FLY-ASH	PORTLAND CEMENT
CaCO ₃ (%)	98.1	-	4
SiO ₂ (%)	1.1	59.9	20.68
Al ₂ O ₃ (%)	-	22.9	3.95
Fe ₂ O ₃ (%)	-	4.7	2.52
Na ₂ O (%)	-	0.6	0.11
K ₂ O (%)	-	2.2	0.58
SO ₃ (%)	-	0.4	2.23
Specific Surface Area (m ² /kg)	310	350	500

Table 3 – Composition of concrete mixtures.

Mix	C*	FA*	GL*	Total* Binder (kg/m ³)	Aggregate (Max Size 18 mm) (kg/m ³)	Water (kg/m ³)	Admixture (% by total binder)		W/C	$\frac{W}{C + FA}$	$\frac{W}{C + FA + GL}$
							VMA	Super-plasticizer			
A	152	--	381	533	1788	153	0.038	1.14	1.01	1.01	0.29
B	153	51	319	523	1792	154	0.039	1.30	1.01	0.76	0.30
C	151	101	254	506	1777	152	0.040	1.66	1.01	0.61	0.30
D	151	151	192	494	1778	152	0.041	2.04	1.01	0.51	0.31

* C = Portland Cement ; FA = Fly Ash; GL = Ground Limestone;

$$\text{TOTAL BINDER} = C+FA+GL$$

Table 4 – Properties of the SCC in the fresh state.

Mix*	Specific Weight (kg/m ³)	Slump Flow (mm/sec)	Bleeding Capacity (% by vol.)	Cohesiveness by visual rating
A	2475	700/30	0.12	Fair
B	2470	680/25	0.09	Good
C	2440	680/30	0.06	Very Good
D	2430	680/35	0.01	Excellent

*In Table 3 the composition of the mixes are shown.

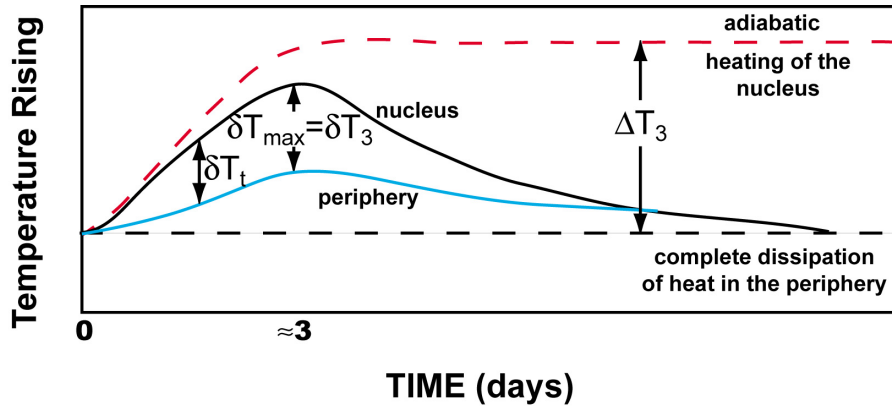


Fig. 1 – Schematic trend of the temperature of the nucleus and the periphery of a mass concrete structure in real or adiabatic conditions and complete dissipation of heat changes in temperature in real and extreme conditions.

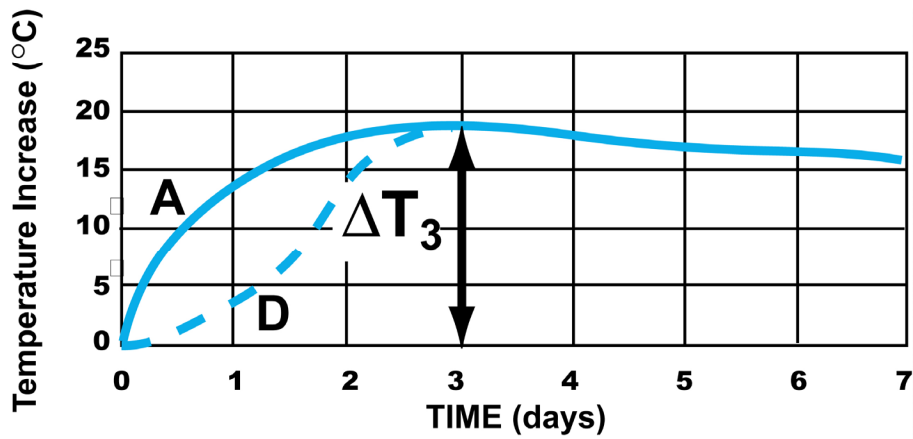


Fig. 2 – Temperature increase in the nucleus of SCC with mixes A and D (Table 3) in a quasi-adiabatic condition.

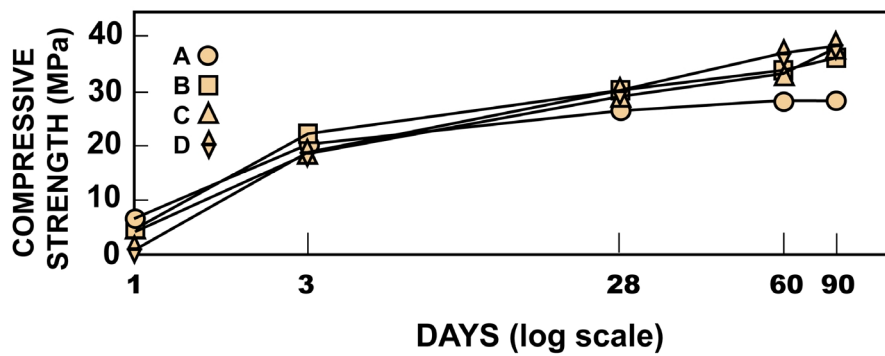


Fig. 3 – Compressive strength as a function of time of SCC with different mineral additions (Table 3).

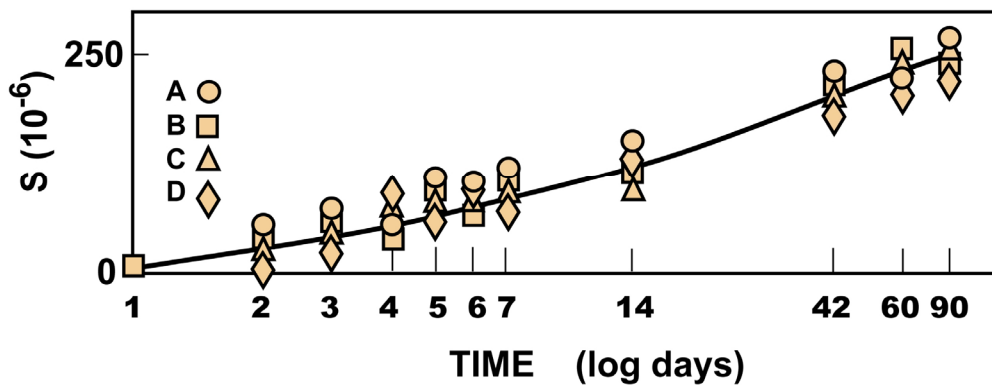


Fig. 4 – Drying shrinkage of concrete mixture as a function of time for SCC with different mineral additions (see Table 3 for the composition of mixes A, B, C and D).