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Effect of curing temperature and type of cement on early-age shrinkage of high-performance concrete

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Abstract

This paper presents the results of an experimental study on the influence of curing temperature and type of cement [Portland cement and blast-furnace slag (BFS) cement] on the autogenous deformations and self-induced stresses in early-age concrete. It was found that higher temperatures do not lead to higher deformations in the observed period, but generally cause a faster shrinkage and a faster development of self-induced stresses. Another experimental finding is that, at the temperatures tested, concrete made with BFS cement shows higher shrinkage in the first days than concrete made with Portland cement. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Temperature; Shrinkage; Granulated blast-furnace slag; Portland cement

1. Introduction

In high-performance concrete (HPC) mixtures, a low water/binder (w/b) ratio and addition of silica fume cause a significant drop of the relative humidity during hydration. As a consequence of self-desiccation, the cement paste undergoes shrinkage. Since the Young's modulus of the aggregates is higher than that of the hardening paste, autogenous shrinkage will result in tensile stresses within the cement paste and in bulk deformation of the concrete itself. Both these phenomena should be avoided as much as possible since they could induce micro- or macrocracking and impair the concrete quality.

In particular, internal restraint, due to the presence of the aggregates in the mixture, may cause microcracking. Many authors have predicted the occurrence of these cracks with analytical [1] or numerical methods [2]. The actual detection of the shrinkage microcracks using microscope observations is more difficult, due to problems with the sample preparation [3].

On the other hand, at the scale of the concrete structure, autogenous shrinkage, added to temperature-induced deformations, may lead to surface cracks and also to through-cracks. Even in the case of isothermal sealed curing, where autogenous shrinkage is the only cause of deformation, self-induced tensile stresses caused by external restraint may induce cracking of the concrete [4–6], potentially compromising the durability.

Measurements of autogenous deformation are normally performed at room temperature. Up to now, only a few authors have investigated the effect of different curing temperatures on autogenous shrinkage. Most of these tests focus on cement pastes [7–9]. From these studies, a rather unsystematic temperature dependency of the autogenous deformation emerges. According to Ref. [6], autogenous deformation at different curing temperatures cannot be predicted only with a maturity function. Results in Ref. [10], on the other hand, show a more systematic behavior, and the authors conclude that autogenous deformation can be simulated with the maturity concept, provided that also a further temperature-correcting factor is applied.

Most of the experimental research on autogenous shrinkage has been concentrated on Portland cement mixtures. In some European countries, blast-furnace slag (BFS) cement has been used for more than a century. In particular, in the Netherlands, BFS cements (with slag contents of up to 70%)

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have been widely and successfully applied, particularly in marine structures [11]. Advantages of this kind of cement include environmental friendliness (due to the reuse of a waste material), low hydration heat and a finer pore structure, which improves water tightness [12] and durability. Since both self-desiccation and autogenous deformation depend on the chemical composition of the cement [13] and on the pore size distribution of the cement paste [14], it is expected that BFS cement mixtures will show different shrinkage behavior than Portland cement mixtures. In fact, higher shrinkage values for BFS mixtures have been reported by different authors [15–17].

2. Materials and methods

In the present research, the effects of different curing temperatures and cement types on autogenous deformation of HPC mixtures were investigated. Four different curing temperatures (10, 20, 30 and 40 °C) were imposed. Also the type of cement (Portland cement, BFS cement and a blend of the two) was varied, in order to assess its influence on the early-age deformations. For every concrete mixture and curing temperature, the self-induced stresses in the case of total restraint were measured and the occurrence of cracking was registered.

Mixtures with w/b ratio of 0.35 and 5% silica fume were considered (see Table 1). Portland cement (CEM I 52.5 R) was used in Mixture A, BFS cement (CEM III/B 42.5 LH HS) in Mixture B and a blend of the two in Mixture C. Details about the chemical composition of the cements are reported in Table 2. It is noticed that the slag content of the BFS cement amounts to about 70%, and the Blaine fineness of the two cements is 490 m^2/kg for the BFS cement and 530 m^2/kg for the Portland cement. Data about the performance of Mixture C cured at 20°C were obtained in a previous research study [5]. For this particular mix and curing conditions, the Young's modulus was not measured.

Measurements of the free deformations were performed with an Autogenous Deformation Testing Machine (ADTM) [5,14]. The concrete was cast in a prismatic mould, $1000 \times 150 \times 150$ mm^3, made with thin steel plates provided with an external insulating material. The mould could be cooled or heated by a system of tubes located between the plates and the insulating material. Temperature differences inside the concrete could be kept as low as 1.5 K. Length changes of the hardening concrete were measured with two external quartz rods provided with linear variable differential transducers (LVDTs) at both ends. The quartz rods were connected to steel bars cast in the concrete and measured displacements over a length of 750 mm. The rods could be fixed to the cast-in bars when the concrete had reached sufficient strength to support them (see Fig. 1a). After casting, the top surface of the concrete was covered with a tight cover in order to avoid moisture loss to the environment. The autogenous deformation up to 6 days after casting was recorded.

Table 1
Mixture compositions of concrete with w/b ratio of 0.35

Mixture composition (kg/m^3)	A	B	C
CEM I 52.5 R (Portland cement)	475.0	–	238.0
CEM III/B 42.5 LH HS (BFS cement)	–	475.0	237.0
Water (including water in admixtures)	175.8	175.8	175.8
Crushed aggregate (4–16 mm)	944.2	944.2	944.2
Sand 0–4 mm	772.5	772.5	772.5
Lignosulphonate	0.9	0.9	0.9
Naphtalene sulphonate	8.1	7.1	7.6
Silica fume slurry (50% powder, 50% water)	50.0	50.0	50.0

Table 2
Chemical composition of the cements used

	CEM I 52.5 R (Portland) Blaine ~530 m^2/kg	CEM III/B 42.5 LH HS (BFS cement) Blaine ~490 m^2/kg
CaO	64%	46%
SiO_2	21%	30%
Al_2O_3	5%	10%
Fe_2O_3	3%	1.5%
MgO	2%	8%
SO_3^{2+}	3.3%	3%
Cl^-	~0.05%	~0.03%
Slag content	–	~70%
Loss on ignition	~1%	–
Insoluble residue	~1%	~1%
Na_2O-equiv.	0.6%	0.5%

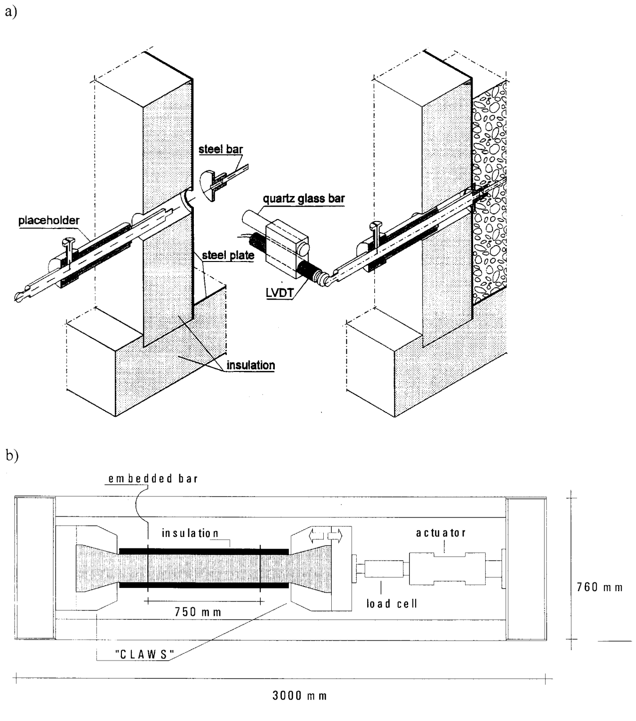

Fig. 1. (a) Detail of experimental setup for the measurement of the free deformations of hardening concrete (ADTM) and (b) top view of experimental setup for the determination of stress development in hardening concrete (TSTM).

The self-induced stresses were measured with a Thermal Stress Testing Machine (TSTM) [5]. This device consisted of a steel frame (for details and dimensions, see Fig. 1b) supporting a mould in which the concrete was cast. The specimens had a prismatic shape with dovetailed heads at the ends. Two rigid steel claws held the specimen and were able to exert a tensile or a compressive force. The imposed strain on the concrete in the TSTM was deduced from the free deformations measured in the ADTM; the control of the device was fully automatic. In this research, only stresses obtained under total restraint were measured.

For the same mixtures, the compressive strength and the Young's modulus at different ages were also tested, on sealed specimens cured at the four different temperatures. The compressive strength was measured on concrete cubes, 150 × 150 × 150 mm^3; the Young's modulus in compression was tested on prisms, 100 × 100 × 400 mm^3. Cubes and prisms were cast in temperature-controlled steel moulds. The specimens tested at later ages were removed from the moulds after 6 days, sealed with plastic and aluminum foils and stored at constant temperature until the moment of testing.

3. Results

Results of compressive strength and E-modulus are reported in Tables 3 and 4. The results represent the average value of three specimens. Mixture A, made with Portland cement, shows, as expected, both the fastest strength gain and the highest value at 28 days, followed by Mixture C. The strength of Mixture B develops slowly, especially at the lower temperatures. Similar trends are found for the Young's modulus.

Table 3
Cube compressive strength of concrete with w/b ratio of 0.35, sealed curing at different isothermal temperatures

		Mean cube compressive strength (MPa)						
Mixture	Temperature (°C)	1 day	2 days	3 days	7 days	14 days	28 days	56 days
A	10	–	57.2	65.8	81.7	91.7	97.7	–
	20	53.2	65.1	–	85.9	94.0	99.5	–
	30	55.4	68.5	78.6	92.3	100.1	–	–
	40	66.5	74.2	86.6	92.5[a]	97.0	–	–
B	10	–	5.2[b]	13.1[c]	34.5	51.8	58.9	–
	20	4.9	20.4	32.7	53.8	–	65.9	–
	30	23.6	44.6	50.6	59.6	64.8	–	–
	40	31.8	47.7	53.6	59.4[a]	–	–	69.7
C	10	–	31.1[b]	38.1[c]	57.4	72.2	82.8	–
	20	42	52	58	70	–	82	–
	30	40.7	54.5	63.9	–	84.8	–	–
	40	44.9	65.1	71.4	78.8[a]	79.2	–	–

[a] Tested 8 days after casting.
[b] Tested 1.5 days after casting.
[c] Tested 2.5 days after casting.

Table 4
Young's modulus of concrete with w/b ratio of 0.35, sealed curing at different temperatures

		Young's modulus (GPa)						
Mixture	Temperature (°C)	1 day	2 days	3 days	7 days	14 days	28 days	56 days
A	10	–	30.1	32.2	–	34.5	35.5	–
	20	30.6	33.7	–	–	35.7	38.2	–
	30	31.4	33.0	33.9	–	37.4	–	–
	40	32.0	35.2	35.7	–	39.7	–	–
B	10	–	6.7[a]	18.4[b]	–	29.3	33.5	–
	20	11.7	24.2	27.3	–	–	36.7	–
	30	27.4	32.3	32.6	–	35.5	–	–
	40	28.3	33.5	33.7	–	–	–	38.7
C	10	–	24.9[a]	26.5[b]	32.7	–	37.3	–
	30	27.8	32.2	32.2	–	39.5	–	–
	40	30.7	34.5	34.2	–	38.0	–	–

[a] Tested 1.5 days after casting.
[b] Tested 2.5 days after casting.

In Figs. 2–4, the autogenous deformations and self-induced stresses of Mixtures A, B and C are plotted. The autogenous deformations were zeroed at the time when stresses were first recorded in the TSTM. Thus, only the stress-inducing deformations are shown. For Mixtures A and C, this means only shrinkage, since only tensile stresses

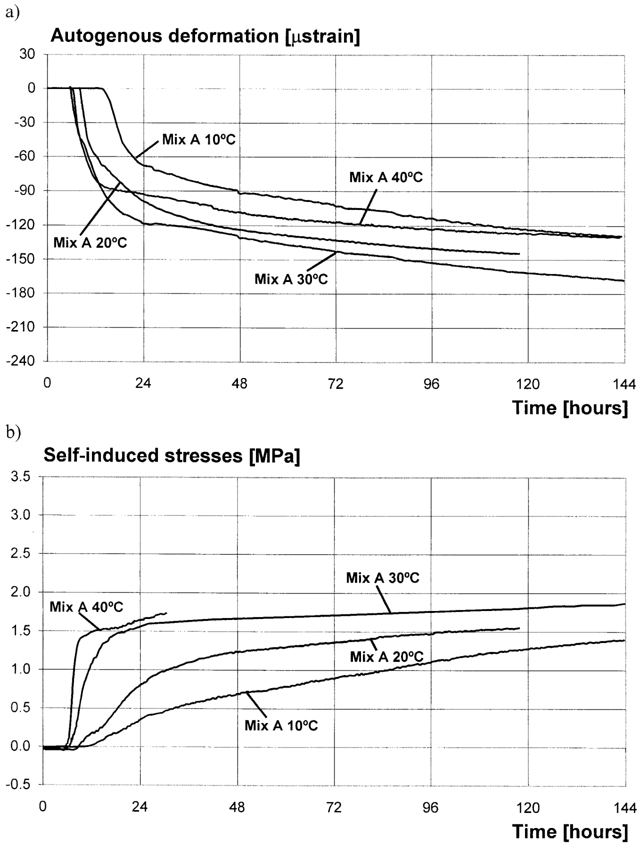

Fig. 2. (a) Autogenous deformation and (b) self-induced stresses of Mixture A (see Table 1). Isothermal sealed curing at different temperatures (10, 20, 30 and 40°C). Shrinkage is plotted as negative.

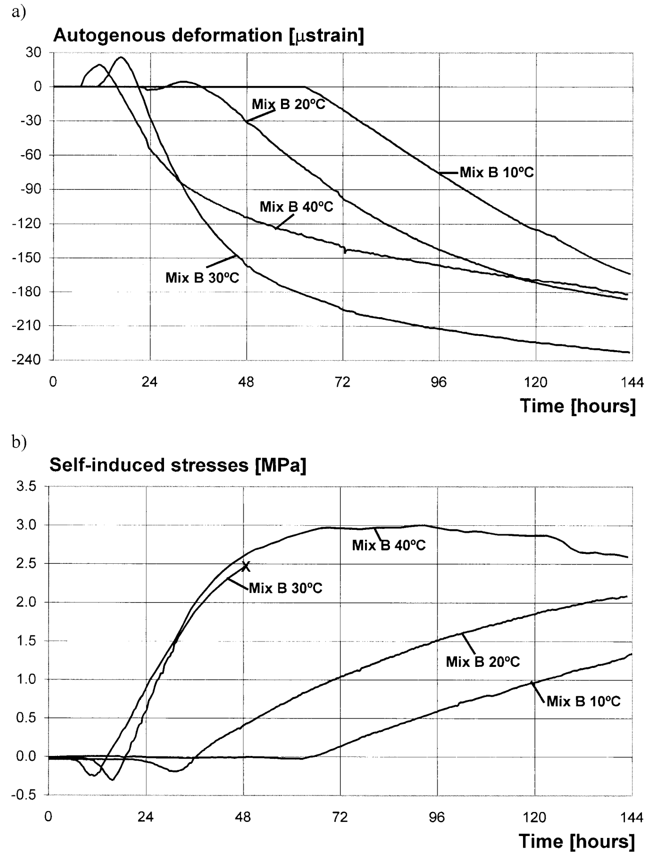

Fig. 3. (a) Autogenous deformation and (b) self-induced stresses of Mixture B (see Table 1). Isothermal sealed curing at different temperatures (10, 20, 30 and 40°C). Shrinkage is plotted as negative. A cross indicates failure of the specimen.

were measured in the stress-rig. For Mixture B, at some curing temperatures, shrinkage was preceded by swelling, inducing a low (<0.3 MPa) compressive stress in the TSTM. The stress-inducing deformations were preceded by a phase, lasting for some hours, where the concrete deformed plastically without generating any stress in the TSTM. In this plastic phase, all the concrete mixtures expanded shortly after the beginning of the measurements, with swelling up to 50 microstrain. For example, Fig. 5 shows the complete record of the deformations in the first 2 days in the case of 40°C curing.

The results of Mixture A, regarding stress-inducing deformations and stress development, are shown in Fig. 2. The stress-inducing shrinkage developed rather unsystematically with temperature. For example, the specimen cured at 40°C showed a faster shrinkage in the first hours, but then it slowed down. After 1 day, the total value was less than for 20°C curing. Shrinkage values after 6 days varied between 130 and 170 microstrain for the four curing temperatures. The self-induced stresses in case of totally restrained deformations increased with temperature increase. The recording of the stresses at 40°C curing was stopped at about 30 h after casting, due to technical problems. The other specimens showed maximum stresses between 1.5 and 2 MPa after 6 days. No specimen cracked in the testing period. In order to compare the data obtained at different temperatures, the degree of hydration of the mixes was calculated with the program HYMOSTRUC [18]. The degree of hydration at 5 days from casting was 0.58 for 10°C curing, 0.63 for 20°C curing, 0.65 for 30°C curing and 0.69 for 40°C curing.

In Fig. 3, the results of Mixture B, made with BFS cement, are shown. Also in this case, the influence of the curing temperature on the autogenous deformation is uncertain. The initial swelling of the specimens cured at 20, 30 and 40°C was stress-inducing, with compressive stresses lower than 0.3 MPa. The following shrinkage occurred earlier for the specimen cured at 40°C, but 30 h after casting the shrinkage of the specimen cured at 30°C became higher. Shrinkage of the specimen cured at 10°C developed slowly, but at the end of the test it was about the same as in the case of 40°C curing. Shrinkage values after 6 days were about 170–180 microstrain for curing at 10, 20 or 40°C, and about 230 microstrain for curing at 30°C. These values are noticeably higher than those found for Portland cement mixtures (see Fig. 2). Also in this case, the self-induced

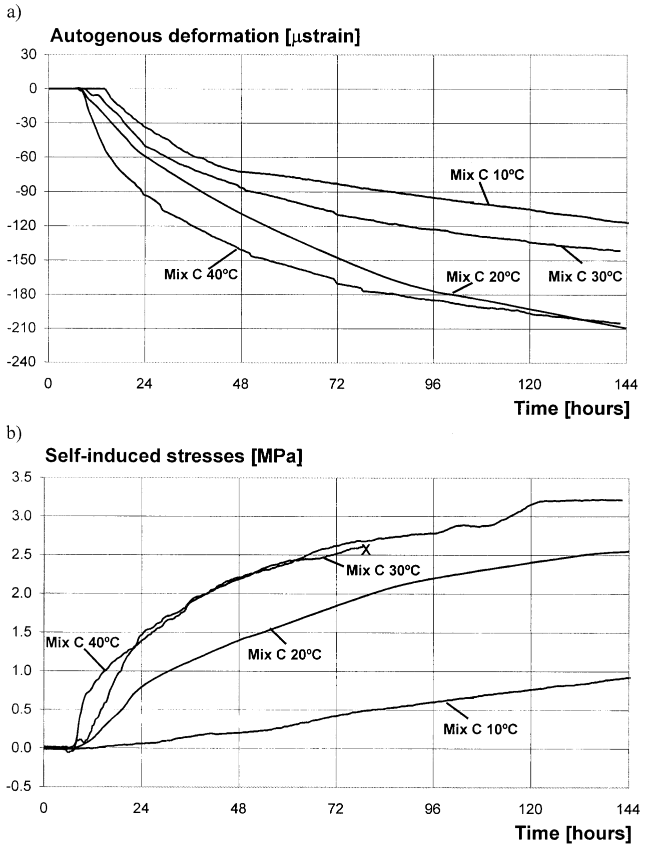

Fig. 4. (a) Autogenous deformation and (b) self-induced stresses of Mixture C (see Table 1). Isothermal sealed curing at different temperatures (10, 20, 30 and 40°C). Shrinkage is plotted as negative. A cross indicates failure of the specimen.

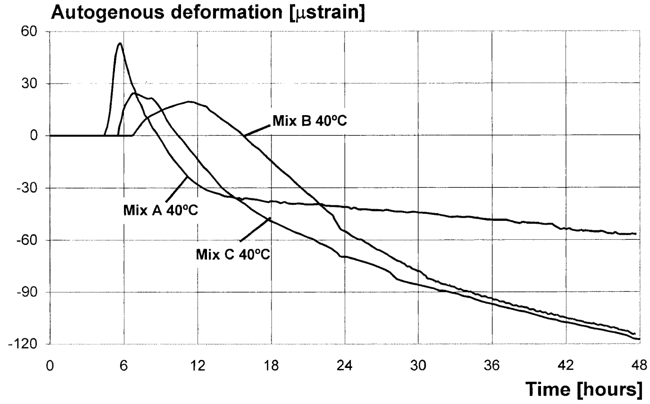

Fig. 5. Autogenous deformations of Mixtures A, B and C in the first 48 h after casting, cured at 40°C. All the measured deformations are shown.

stresses gave a clearer picture, with higher stresses at higher curing temperatures. It should be noticed that the specimen cured at 30°C cracked 2 days after casting, when the measured stress was about 2.5 MPa. The specimen cured at 40°C probably experienced microcracking around that age, a fact that is shown by the decreasing slope of the stress curve, while the deformations were still increasing. In this case, the calculated degree of hydration after 5 days ranged from 0.4 for 10°C curing to 0.58 for 40°C curing.

Results of tests on Mixture C, made with blended cement, are shown in Fig. 4. Shrinkage was lowest for 10°C and highest for 40°C curing. The specimen cured at 20°C showed faster shrinkage development than the one cured at 30°C. It should be pointed out, however, that the data at 20°C curing had been obtained in a previous research [5]; the materials used might have been slightly different (different cement batches, for example). Shrinkage values after 6 days were 120 microstrain for 10°C curing, 140 microstrain for 30°C and 210 microstrain for 20 or 40°C. These values lie between the ones found for Mixtures A and B. Self-induced stresses were higher for curing at 40 and 30°C. The specimen cured at 30°C cracked 3 days after casting, with tensile stresses of about 2.5 MPa. The specimen cured at 40°C did not crack in the testing period, reaching stresses higher than 3 MPa. The stresses of the specimen cured at 10°C were extremely low, below 1 MPa after 6 days. For this concrete, the calculated degree of hydration after 5 days ranged from 0.53 for 10°C curing to 0.68 for 40°C curing.

4. Discussion and conclusions

From the analysis of the experimental results on three concrete mixtures and four different curing temperatures, the following conclusions can be drawn.

Comparison of the results for the same mixture at different curing conditions shows that, although higher temperatures improve the initial strength development, the value at a later stage, 14 or 28 days, seems to be penalized, as already observed by other authors [19]. For example, comparing specimens of Mix A and C cured at 30 and 40°C, it can be noticed that specimens cured at the higher temperatures show a lower strength at 14 days.

The Young's modulus development shows trends similar to the compressive strength for the three mixes but, as already observed [20], the stiffness increases faster than the strength.

The phenomenon of the very early-age swelling is well known in literature, and seems to occur with concretes of different w/b ratios and to be independent from the measuring device [4,6,8,15,21], even if the absolute values may differ quite substantially. A possible reason of this swelling could be reabsorption of bleeding water. It has been observed [6] that removing the bleeding water reduces the swelling, but does not eliminate it totally. The residual swelling could be due to internal bleeding in the mixture. In the present research, no external bleeding has been observed, but the occurrence of internal bleeding cannot be excluded. Another possible explanation of this phenomenon could be found at the scale of the hydration products. Even if the reaction products have a lower volume (about 7% less) than the reagents, due to their shape they form a spatial network. Growth of further reaction products inside the network generates an internal pressure that may cause moderate swelling of the system [22]. Other authors attribute the swelling to ettringite formation [23].

The effect of a temperature increase on the development of the autogenous deformations is unsystematic and varies for different sorts of cement. It seems that higher temperatures do not necessarily lead to higher deformations. This fact confirms previous findings by other authors [6,8]. Differences in the shrinkage values after 6 days could also be due to experimental scatter in the results (a maximum of two tests was run for each temperature, with a difference of about 8%).

Nevertheless, it can be stated that higher temperatures generally cause faster development of shrinkage and self-induced stresses, which might increase the cracking risk. In fact, none of the specimens cured at 10 or 20°C cracked in the testing period, while some of the specimens cured at higher temperature did. While it is not excluded that the specimens cured at lower temperatures would crack at later ages, it could be supposed that higher curing temperatures increase the cracking risk, since the deformations develop at a higher rate. It has been observed [24] that the rate of the autogenous deformation is at least as important as its absolute value, in determining the cracking risk.

Another experimental finding is that, at all temperatures, BFS cement concretes show higher shrinkage after 6 days than Portland concretes. This fact has already been reported [15–17]. The phenomenon could be related to the supposed denser structure of the BFS cement paste, which shows smaller pores [15]. These smaller pores could induce higher capillary forces during the self-desiccation process, increasing the autogenous shrinkage. The consequences of this fact on the self-induced stresses and the cracking risk of BFS mixtures still have to be evaluated. The higher autogenous deformation, in fact, seems not to result in higher stresses than for Portland cement mixtures, since the BFS concretes show a later setting time and a slower stiffness development.

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