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MITIGATING AUTOGENOUS SHRINKAGE IN HPC BY INTERNAL CURING USING SUPERABSORBENT POLYMERS

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Abstract

When the water-to-cement ratio of concrete is lower than a critical value, a marked self-desiccation may occur, leading to autogenous shrinkage. This volume reduction can induce stress when the shrinkage is restrained, and may cause microcracks, compromising the long-term durability of the concrete. For a more extensive use of high-performance concrete (HPC), it is essential to find appropriate ways to avoid such a risk of cracking at early ages.

Methods based on the concept of internal concrete curing have been suggested in the literature. These methods consist in the formation of water-filled inclusions in the fresh concrete, which prevent self-desiccation of the hardening concrete. The additional internal water can be supplied by using relatively small amounts of pre-saturated, lightweight, fine aggregates (LWA) or superabsorbent polymer (SAP) particles in the concrete.

This paper focuses on the reduction of autogenous shrinkage of HPC by means of the addition of SAP as an internal curing agent. Drying shrinkage and autogenous shrinkage tests were performed from the first hours after casting. The effects of different amounts of SAP on the properties of concrete are presented and discussed. Finally, the effectiveness of this internal curing method to mitigate autogenous shrinkage in HPC is compared to that of more conventional methods using other chemical admixtures, such as an expansive agent and a shrinkage reducing admixture.

1. INTRODUCTION

High Performance Concrete (HPC) is generally produced using high cement contents, supplementary cementitious materials such as silica fume, and low water-to-binder (w/b) ratio (less than 0.4). These concrete mixes are likely to develop significant autogenous shrinkage due to self-desiccation. Therefore, it is essential to find appropriate ways to reduce autogenous shrinkage to minimize the crack tendency of the young concrete.

A new method using superabsorbent polymer (SAP) particles as concrete admixture was proposed recently [1, 2]. During concrete mixing, the particles of SAP absorb huge amounts of water and form macro-inclusions containing free water. This free water is consumed during cement hydration providing internal curing to the surrounding paste matrix and preventing self-desiccation. This concept, called “water entrainment”, can also be achieved by using relatively small amounts of pre-saturated lightweight aggregates (LWA). It is described in detail in [3] and [4].

Anyway, it seems that few experimental results are actually available concerning the effectiveness of SAP in concrete. This paper focuses on the influence of SAP on the compressive strength and on both autogenous and drying shrinkages of a HPC mix. A comparison with other chemical admixtures is also given.

2. EXPERIMENTAL DETAILS

2.1 Measuring method of shrinkage

Measurements of both autogenous shrinkage and total shrinkage were conducted on the three mixes presented in table 2. Three identical specimens of 70×70×280 mm³ were used for each test. The testing samples were subjected to a slow rotation (4 revolutions per minute) after horizontally casting in order to reduce sedimentation and bleeding [5]. The specimens were demoulded at the end of the setting time.

Immediately after demoulding, the autogenous shrinkage specimens were sealed with two layers of adhesive aluminium tapes in order to prevent moisture loss from the specimens. It has been shown that this technique was at least as effective as the traditional resin coating [6]. Longitudinal length change was measured vertically with metal plugs embedded on the opposite sides of the specimens using a 1/1000-mm digital dial gauge (Fig. 1). Sampling of data was performed by data logger software automatically and continuously for 6 days. Afterwards, length changes of the specimens were measured at specified ages with the same device (manual measurements).

The total shrinkage was measured by the same device on specimens not sealed but exposed to ambient atmosphere maintained at 20±2°C and 65±5% RH. In this case, moisture evaporation takes place and drying shrinkage occurs.

Figure 1: Linear vertical device for measuring shrinkage of concrete (sealed specimens).

The end of the setting time was measured on samples of 150×150×600 mm³ to determine the time for demoulding the shrinkage specimens. The method used (known as Kelly-Bryant method [7]) consists in measuring the necessary strength to pull out one by one metal bars embedded in the concrete.

Temperature measurements were performed in parallel, in order to estimate the thermal deformations. However, as the maximum elevation of temperature in the specimens did not exceed 2°C, the effect of the heat of hydration has been neglected in the autogenous shrinkage curves which follow.

2.2 Internal relative humidity measurement

The decrease in internal relative humidity (RH) was measured at the centre of the concrete on three identical samples of 70×70×280 mm³, protected from moisture exchange and stored at constant temperature of 20±2°C (Fig. 2). The measurement was conducted continuously for 6 days using a RH-probe (capacitive sensor) of 5 mm diameter, previously calibrated with saturated salt solutions.

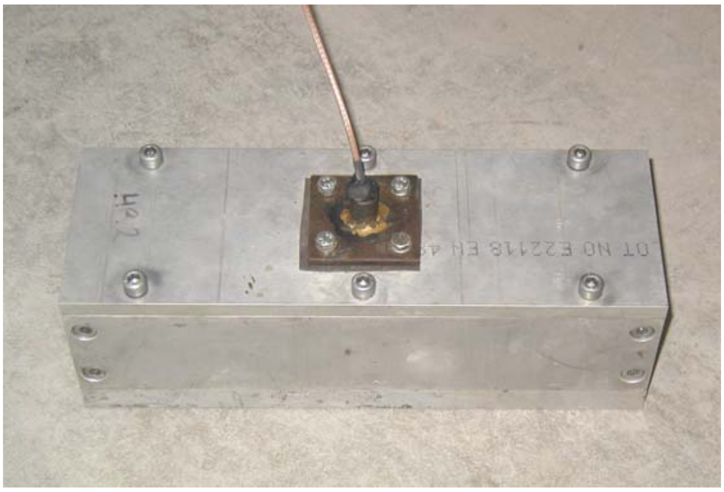

Figure 2: Device for measuring relative humidity in concrete (sealed specimens).

2.3 Materials

Superabsorbent polymers are commercially available as white solid particles (Fig. 3). They are mainly crosslinked copolymers obtained from acrylic acid and sodium acrylate. Folded up on itself at the dry state, the polymer network expands when in contact with water or an aqueous solution because each mesh of the net is highly hydrophilic. The powder then turns into a translucent gel within a few seconds, filling a volume several times bigger than the initial one (Fig. 4).

Figure 3: SAP particles.

Figure 4: SAP in dry state (on the left) and after addition of water (on the right).

The typical characteristics of the SAP tested in this study are summarized in table 1. Note that performances of SAP (especially absorption capacity) are linked to the type of fluid they are in contact with (influence of water hardness, salinity and pH).

Table 1: Main characteristics of tested SAP particles.

Appearance	White powder
Absorption (0.9% NaCl in demineralized water)	65 g/g
Retention (0.9% NaCl in demineralized water)	34 g/g
Absorption in demineralized water	500 g/g
Particle > 850 µm	< 3 %
Particle < 45 µm	< 0.5 %
Apparent density	0.75 g/cm³

2.4 Mix proportions

The w/b ratio of the reference concrete is 0.33. The superplasticizer is a polycarboxylic ether. Five percent of cement by weight was replaced with gray silica fume. Porphyry coarse aggregates, having a particle size mainly varying between 2 mm and 14 mm, were used.

SAP content was 0.3% and 0.6% of binder by weight. A dry mix of 30 seconds allows to ensure its repartition in the mix. Together with the mixing water, an amount of entrained water (w/b ratio) equal to 0.02 was added for each SAP addition of 0.3%. A delay between the introduction of water and superplasticizer allows minimising the absorption of the latter by the SAP. No attempt to achieve an equivalent consistency was made with these mixtures.

Mix proportions and properties of fresh concrete are shown in table 2. It can be seen that the addition of SAP reduces the workability and delays the setting time of concrete.

Table 2: Mix proportions and properties of fresh concrete.

Material [kg/m³]	**Ref.**	**SAP-0.3**	**SAP-0.6**	**SRA**	**EA**
Cement CEM I 52.5 R HSR LA	427.5	427.5	427.5	427.5	427.5
Gray Silica fume	22.5	22.5	22.5	22.5	22.5
River sand 0/2	151	151	151	151	151
River sand 0/5	604	604	604	604	604
Porphyry 2/4	302	302	302	302	302
Porphyry 4/7	245	245	245	245	245
Porphyry 7/10	264	264	264	264	264
Porphyry 10/14	321	321	321	321	321
Water	148.5	157.5	166.5	148.5	148.5
Superplasticizer (dry substance 35%)	4.05	3.38	3.38	3.60	4.50
Superabsorbent polymers	**0**	**1.35**	**2.70**	---	---
Shrinkage reducing admixture	---	---	---	**4.5**	---
Expansive agent	---	---	---	---	**20**
Water-to-cement (w/c) ratio *	0.35	0.37	0.39	0.35	0.35
Water-to-binder (w/b) ratio *	**0.33**	**0.35**	**0.37**	**0.33**	**0.33**
Slump [mm] acc. to [8]	200	80	155	210	220
Air content [%]	1.5	1.9	2.2	1.2	ND
Density [kg/m³]	2457	2444	2410	2471	2448
End of setting time [min] acc. to [7]	360	395	445	430	350

* w = total water content (including internal curing water for SAP-0.3 and SAP-0.6).

3. ANALYSIS OF TEST RESULTS

3.1 Internal relative humidity and compressive strength

The internal relative humidity (RH) was measured on three samples for each concrete. Non homogenous results were obtained considering the changeable dispersion of the SAP particles in the mix. However, certain probes, placed in the mixes with SAP, have indicated an internal RH as high as 99.5% after 6 days. In the reference mix (without internal curing water), the internal RH has dropped to 94% after the same period.

The compressive strength was measured after 2, 7 and 28 days on concrete cubes with side length 150 mm, cured at 20±2°C and min. 95% RH. The results are provided in table 3.

Table 3: Compressive strength and apparent density (average of three samples).

Mix	Ref.	SAP–0.3	SAP–0.6
2-day strength [N/mm²]	82	70	65
7-day strength [N/mm²]	97	84	76
28-day strength [N/mm²]	107	99	93
28-day apparent density [kg/m³]	2430	2400	2390

As can be seen from Figure 5, the early strength development (2-7 days) is somewhat slowed down with SAP, but the reduction in strength seems to decrease at later ages. After 28 days, the reductions in compressive strength are 7% and 13% for concrete with SAP content of 0.3% and 0.6% respectively. These losses may be attributed to the increased porosity of the concrete due to the hollow voids introduced by SAP particles. However, as mentioned in [9], it is possible that the long-term strength will be similar or even higher, as the hydration proceeds at a higher rate since a higher internal RH is maintained in the specimen. Further research should confirm this assumption.

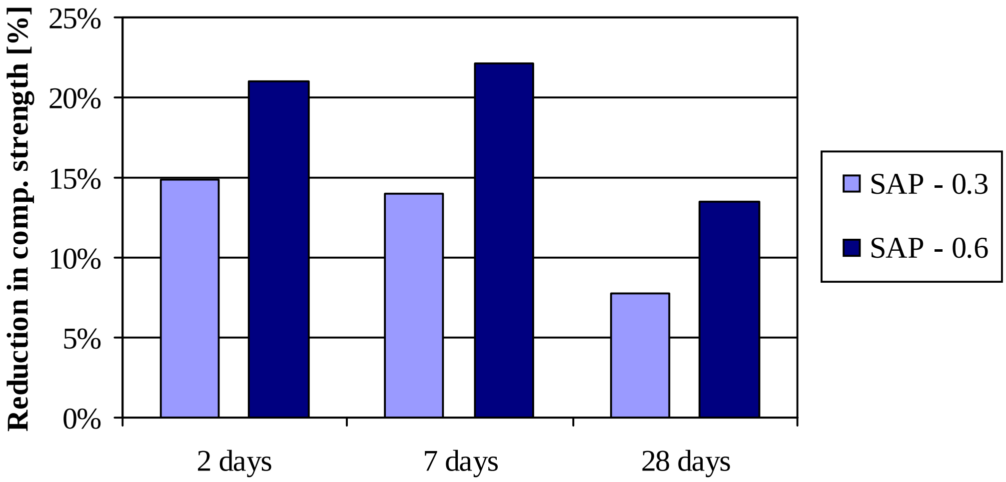

Figure 5: Influence of SAP on compressive strength.

3.2 Autogenous shrinkage (at early and later ages)

Figure 6 shows the results of the autogenous shrinkage measurements up to 144 hours (6 days) for the concrete with different amounts of SAP and without. Each deformation curve is the average of three individual measurements. It has been adjusted to zero at setting time (6-7 h after water addition).

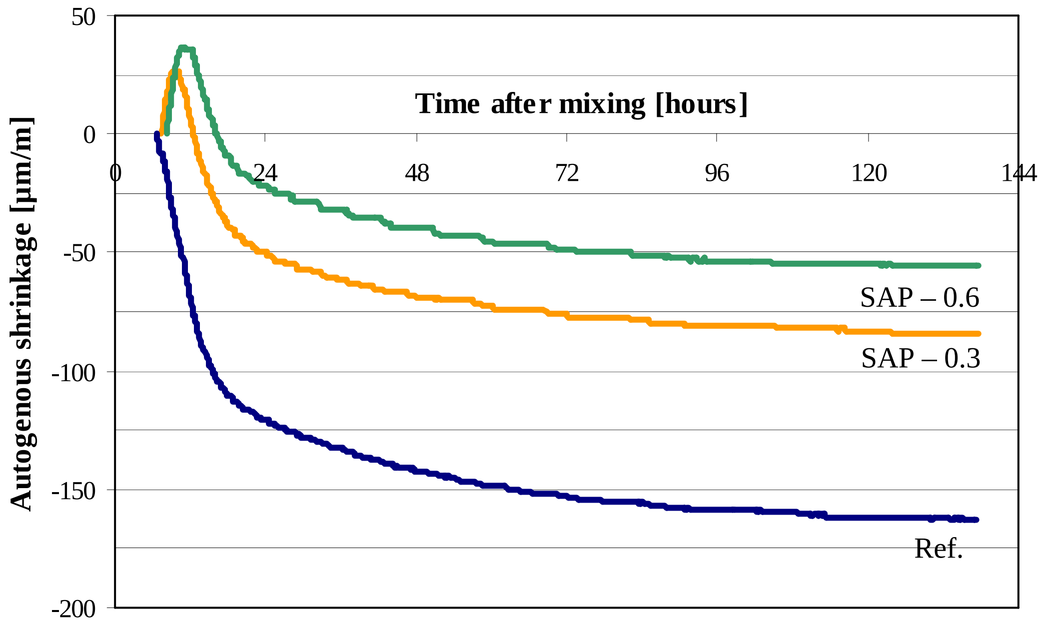

Figure 6: Influence of SAP on autogenous shrinkage at early age.

For the reference concrete, an average autogenous shrinkage value of about -160 µm/m is noticed after 144 hours of sealed hardening. Additions of 0.3% and 0.6% of SAP led to a reduction of this value of approximately 50% and 65% respectively, and even induced an expansion (25-35 µm/m) right after setting.

Table 4 presents the autogenous shrinkage values obtained after a period of 2 months. We record that the autogenous shrinkage of concrete with and without SAP develops approximately in the same proportions after 6 days. In each case, the autogenous shrinkage after 2 months is about the double of the value measured after 6 days.

Table 4: Autogenous shrinkage at early age and at later ages.

Mix	Autogenous shrinkage after 144 hours (µm/m)	Autogenous shrinkage after 2 months (µm/m)
Ref.	-160	-276
SAP-0.3	-85	-161
SAP-0.6	-56	-124

3.3 Total shrinkage in drying conditions

Three samples of each concrete were exposed to 65% RH at 20°C at setting time. As can be seen from Figure 7, all mixes exhibit a similar total shrinkage (including autogenous, thermal and drying shrinkages) of about 350-400 µm/m after 2 months. Thus, while the autogenous shrinkage of concrete with SAP – measured in sealed conditions – was at least 50% lower than for the reference mix, the drying shrinkage of internally water cured concrete seems to be increased. It is higher for increasing SAP content. This phenomenon was also observed for cement pastes [2]. This may be attributed to a higher loss of moisture, caused by the higher amount of water and the additional pore system introduced into the concrete.

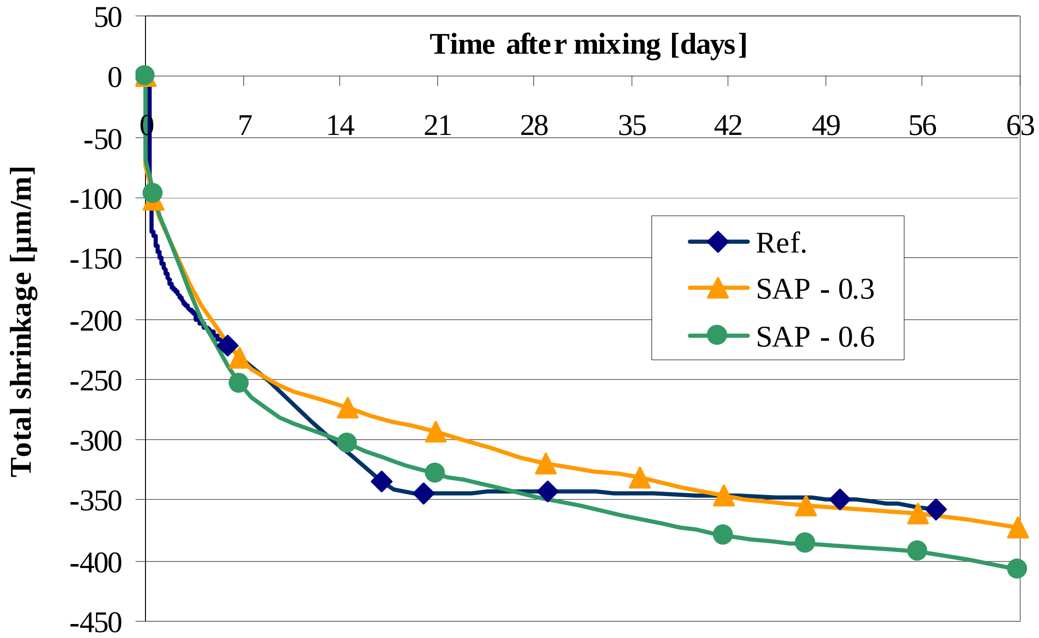

Figure 7: Influence of SAP on total shrinkage (drying conditions: 20°C and 65% RH).

3.4 Comparison with other methods of reducing shrinkage

The effectiveness of this internal curing method to prevent self-desiccation in HPC has been compared to that of other methods by addition of an Expansive Agent (EA) and a Shrinkage-Reducing Admixture (SRA), more commonly used to control drying shrinkage (table 5).

The most common method of producing an expansive cement is via the formation of ettringite. However, while self-desiccation generally develops very quickly and uniformly throughout a concrete, expansion due to ettringite crystal formation may be a highly localized phenomenon and maximal effect only takes place after a few days. For these reasons, a commercial expansive agent was used in form of calcium oxide (CaO) manufactured in a kiln at high temperature. Hydration of free CaO takes place here so that calcium hydroxide is formed and expansion occurs.

The SRA used in this study (98% active) has no expansion effect but acts chemically by altering the conditions for the shrinkage mechanisms, especially by reducing the surface tension of the pore solution.

Mix proportions of the reference mix are the same as mentioned above (see table 2). The w/b ratio of the three concrete mixes is kept constant but the superplasticizer content is adapted in order to obtain an equivalent consistency of 200-220 mm with Abrams cone.

Table 5: Characteristics of the chemical admixtures.

	SRA	EA
Form	Clear yellowish liquid	Beige powder
Used dosage	4.5 kg/m³	20 kg/m³
	1% of powder by weight	4.5% of powder by weight

The results of autogenous shrinkage measurements are plotted in Figure 8. In this case again, each deformation curve has been adjusted to zero at setting time (6-8h after water addition). From this figure, it is obvious that autogenous shrinkage of HPC can be at least partially offset by the use of these more conventional admixtures. The SRA allows a reduction of the autogenous shrinkage of the order of 40% after 6 days, whereas the CaO-based expansive agent allows to completely eliminate it. With this latter one, even a slight expansion (20 µm/m) is obtained after about 10 hours.

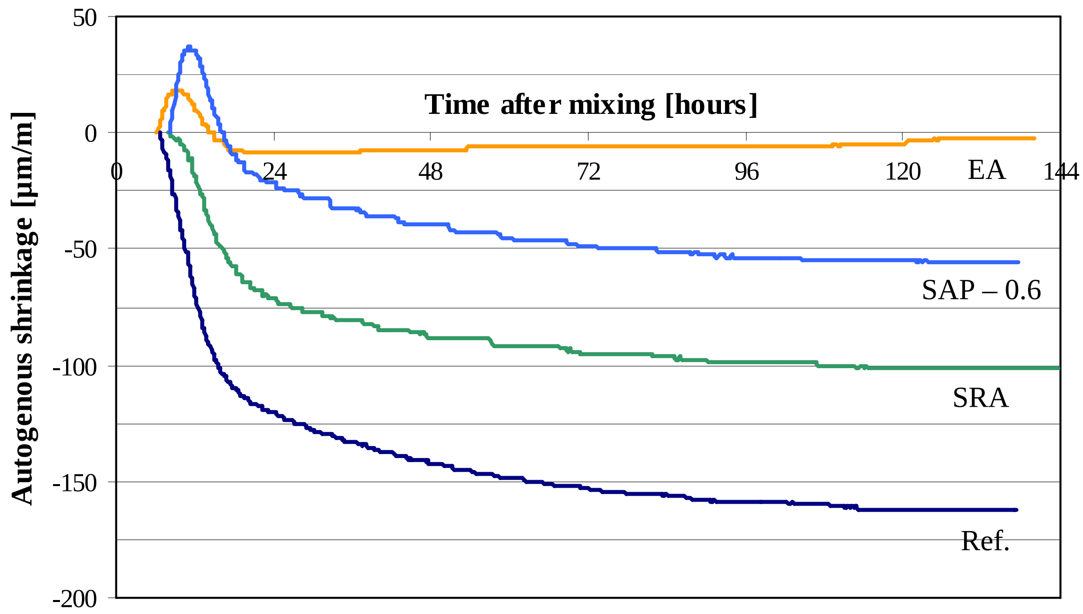

Figure 8: Influence of chemical admixtures on autogenous shrinkage.

To allow for an easier comparison, table 6 summarises the reduction in autogenous shrinkage obtained after 144 hours in comparison with the reference mix. In the same table, the reduction in compressive strength obtained at 28 days is also indicated.

Table 6: Autogenous shrinkage and compressive strength of HPC due to the use of a chemical admixture.

Mix	Autogenous shrinkage after 144 hours (µm/mm)	Shrinkage reduction compared to ref.	Compressive strength after 28 days (MPa)	Strength reduction (-) / gain (+) compared to ref.
SAP-0.3 *	-85	48%	99	-8%
SAP-0.6 *	-56	66%	93	-14%
SRA	-101	38%	97	-9%
EA	-2	99%	110	+3%

* w/b ratio and workability differ slightly from reference concrete.

4. CONCLUSIONS

Superabsorbent polymers (SAP) have been used in order to counteract self-desiccation in HPC. The effectiveness of this internal curing agent in reducing autogenous shrinkage has been compared to that of other chemical admixtures (added to the concrete mix).

Based on the experimental results reported in this paper, the following conclusions can be drawn:

– Internal curing by using SAP seems to have significant effect on mitigating autogenous shrinkage of HPC, as well at early age as at later ages (up to 2 months).

After 6 days, a reduction of 66% is achieved by using 0.6% of SAP of binder by weight.

- However, the use of SAP as internal curing agent can lead to some negative effects such as a poorer workability, a delayed setting time and a reduced compressive strength (especially at early age). To minimize these effects, as explained in [2], only the amount of water entrainment (and polymer particles) required to avoid cracking due to restrained autogenous shrinkage should be used.
- The drying shrinkage seems to be higher for increasing SAP content (with a total shrinkage similar to that of the reference concrete). Therefore, it seems important to combine this internal curing method with a traditional one, for instance with a curing compound or by covering the concrete surface during the first days after casting. Further research is needed to confirm the specifications of this combination.
- The admixture that seems to be the most efficient for reducing autogenous shrinkage is the CaO-based expansive agent. It allows to completely offset the autogenous shrinkage while conserving a high compressive strength at 28 days.
- For a same reduction in the compressive strength (less than 10%), the use of a SRA seems to be almost as efficient as the addition of 0.3% SAP in order to reduce the autogenous shrinkage of HPC (reduction of about 40-50% compared to ref.).
- Finally, seeing that SAP are introducing changes in the microstructure of the cement paste, their effects on longer term properties, such as durability of concrete, have yet to be clarified.

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