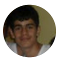
Assessment of the potential of superabsorbent polymers as internal curing agents in concrete by means of optical fiber sensors

Article *in* Construction and Building Materials · March 2020

DOI: 10.1016/j.conbuildmat.2019.117751



José Roberto Tenório Filho
Ghent University
18 PUBLICATIONS **13** CITATIONS
SEE PROFILE

Els Mannekens
Chemstream
11 PUBLICATIONS **102** CITATIONS
SEE PROFILE

Kim Van Tittelboom
Ghent University
32 PUBLICATIONS **80** CITATIONS
SEE PROFILE

Didier Snoeck
Ghent University
133 PUBLICATIONS **2,595** CITATIONS
SEE PROFILE

Assessment of the potential of superabsorbent polymers as internal curing agents in concrete by means of optical fiber sensors

José Roberto Tenório Filho[1,2]; Els Mannekens[3]; Kim Van Tittelboom[1]; Didier Snoeck[1]; Nele De Belie[1*]

[1]Magnel Laboratory for Concrete Research, Department of Structural Engineering, Faculty of Engineering and Architecture, Ghent University, Tech Lane Ghent Science Park, Campus Ardoyen, Technologiepark Zwijnaarde 60, B-9052 Ghent, Belgium.

[2]SIM vzw, Technologiepark Zwijnaarde 48, B-9052 Ghent, Belgium.

[3]Chemstream bvba, Drie Eikenstraat 661, B-2650 Edegem, Belgium.

*Corresponding author: nele.debelie@ugent.be

ABSTRACT

Superabsorbent polymers (SAPs) have been widely explored in concrete technology due to their promising application as internal curing agent. SAPs act by reducing the shrinkage deformation, thus reducing the risk of early-age cracking. In this paper, the efficiency of SAPs is assessed by means of long-gauge optical fiber sensors embedded inside the matrix and mechanical strain gauges. Two commercial and two in-house developed SAPs are used. The two commercial SAPs and one of the in-house developed SAPs were found to completely mitigate the autogenous shrinkage of concrete and all four showed a reduction of 30% in the total shrinkage. The optical fiber sensors showed a superior performance in comparison to the mechanical strain gauges.

Keywords: autogenous shrinkage; superabsorbent polymers; hydrogels; optical fiber sensors; concrete monitoring.

1. INTRODUCTION

Shrinkage in concrete structures has been the focus of many studies, and lately, a lot of attention has been given to autogenous shrinkage. Based on the type of concrete, autogenous shrinkage occurs at different levels. In ordinary concrete structures (with water-to-cement ratio above 0.42) it is not a very prominent phenomenon, but it may increase the risk of cracking, especially when supplementary cementitious materials are used [1, 2]. On the other hand, it can be the main cause of early-age cracking in systems with water-to-binder ratio lower than 0.42 (high or ultra-high performance concrete, for example) [3, 4].

Recently, a lot of research has been performed on the use of superabsorbent polymers (SAPs) to reduce or mitigate shrinkage in cementitious materials, mostly at mortar or paste level [5-13] and some focusing on high performance concrete compositions (HPC) [1, 2, 14, 15].

Superabsorbent polymers (or hydrogels) consist of a natural or synthetic water-insoluble 3D network of polymeric chains cross-linked by chemical or physical bonding. They possess the ability to take up a significant amount of liquids from the environment (in amounts up to 500 times their own weight) [16].

Once in contact with the mixing water of the fresh cementitious material, the SAPs absorb and retain a certain amount of the water (depending on their absorption capacity), later on acting as water reservoirs for the system, keeping its level of internal relative humidity high for a considerable time frame.

Most of the studies cited have made use of synthetic and commercially available SAPs, all showing that a dosage of SAPs in the range of 0.2-0.6% with respect to the cement mass should be enough to considerably reduce or completely mitigate the deformation due to autogenous shrinkage. It should be noted that this amount depends on the SAP composition (i.e. chemical structure), swelling kinetics and characteristics of the SAP and the concrete composition.

Commercially available SAPs are usually powders that consist of a specific chemistry, particle size distribution (PSD) and show a specific swelling capacity in water. Most of them are built from the acrylic acid (AA) monomer, partially neutralized to its salt form ($-COO^-M^+$), and acrylamide (AAm) [17]. They are only slightly cross-linked in order to have absorption capacities up to 300-400 g of demineralized water per g of SAP.

Not only commercially available SAPs but also "in-house" developed SAPs are studied. In this paper, the chemistry used in this case is not based on carboxylate chemistry ($-COO^-M^+$) as mentioned before, but on sulfonate chemistry ($-SO3^-M^+$), as can be seen in Figure 1.

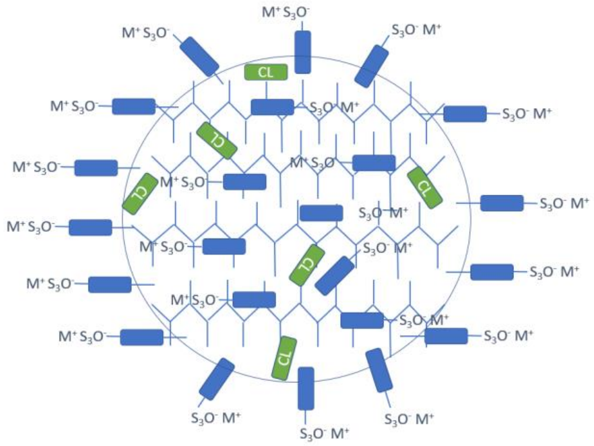


Figure 1 - Schematic representation of a SAP particle containing a dense network of sulfonate groups and some crosslinks (CL).

Sulfonic acids are stronger in comparison to carboxylic acids and they lead to much higher osmotic forces to attract the water into the formed hydrogel network. Additionally, they are less influenced by changes in the pH of their environment. Furthermore, their salts are very safe to work with since they do not entail any risk and safety issues during the production of the SAP, which is very beneficial in contrast to the very corrosive and harmful acrylic acid (AA) that is commonly used in commercial SAPs during manufacturing, especially when upscaling is required. Nevertheless, after manufacturing, also the AA based SAP types are safe to be used in concrete and other applications.

Up to now, most of the studies described in the literature investigating the deformation due to autogenous shrinkage of concrete have relied on test methods based either on volumetric or linear measurements. The latter have been performed with the use of length transducers placed on the top surface of prismatic specimens, with the measurements starting at different times (6 h, 9 h or 24 h), following the prescription of the ASTM C157/C157M-17 (24 h) [18] or the setting of the mixtures [14, 15, 19, 20]. This means that different shrinkage values are reported and part of the shrinkage is neglected when the measurements are started too late, i.e. after setting.

Concerning the time to initiate the measurements or consider them for shrinkage calculations (commonly called the "time-zero"), several studies have been dedicated to the investigation of its influence on the strain values, especially when using internal curing agents [21-25]. Being able to choose an appropriate time-zero value is of utmost importance since it might have a major impact on the interpretation of the shrinkage values which could lead to misinterpretations of results such as an underestimation of strain or overestimation of the effect of internal curing/shrinkage reducing agents.

The techniques applied to monitor shrinkage of concrete structures might lead to different responses at different locations due to crack formation or due to the presence of internal voids and discontinuities. For that reason, the use of long-gauge deformation sensors will allow a more global and precise understanding of the material/structure under investigation compared to the traditional methods.

Studies using optical fiber sensors to monitor real concrete structures have been reported since the 90's, especially with regard to displacement monitoring in bridges, decks, dams and railway infrastructure [26-34]. These sensors allowed the monitoring of the strain development in concrete structures under different environmental conditions since the moment of casting, which can be of great interest to study the effect of shrinkage in concrete at very early age.

In this paper, long-gauge deformation sensors based on low-coherence interferometry in optical fiber sensors are used to investigate the influence of SAPs on the autogenous and total shrinkage of concrete mixtures. The material response due to shrinkage deformation is also evaluated by a more traditional approach, using a demountable mechanical strain gauge (DEMEC), and the suitability of both techniques is discussed.

2. MATERIALS AND METHODS

The experimental program was based on the shrinkage measurement of concrete specimens with or without superabsorbent polymers with two different techniques: manual measurements with a demountable mechanical strain gauge (DEMEC) and automatic measurements with optical fiber sensors. For the manual measurements two conditions were investigated, the first one with the specimens covered with aluminum tape to reduce the moisture exchange and drying effects, and a second one where the specimens where exposed to the air. All tests were performed in a room with a controlled atmosphere of 20 ± 2 °C and 60 ± 5% RH.

2.1. Superabsorbent polymers

SAP1, made by SNF Floerger (France) is a cross-linked acrylate copolymer produced through bulk polymerization and has a mean particle size (D_{50}) of 360 µm. SAP2, provided by BASF (Germany), is a copolymer of acrylamide and sodium acrylate also produced through bulk polymerization having a mean particle size (D_{50}) of 40 µm. Both have been previously studied as internal curing agent and self-sealing/healing promoter for mortar mixtures [6, 10].

SAP3 and SAP4 are both in-house developed SAPs, produced by ChemStream bvba (Belgium). SAP3 mainly consists of the co-monomers NaAMPS (2-acrylamido-2-methyl-1-propanesulfonic acid sodium salt) and SVS (sodium vinyl sulfonate), diluted with a non-charged or neutral monomer ACMO (acryloyl morpholino acrylate) (50% mol). It has a mean particle size (D_{50}) of 100 µm and it is based on ChemStream's prior art EP2835385, initially developed to meet the requirements of an internal curing promoter.SAP4 is solely composed of the monomer NaAMPS, with two different cross-linkers and a mean particle size (D_{50}) of 100 µm. Given its lower absorption capacity in demineralized water and still relatively high absorption capacity in cement filtrate in comparison with SAP3 (see section 3.1), this SAP was originally produced to be applied as self-sealing/healing promoter, but previous results with cement pastes showed this SAP is also promising to obtain internal curing [35].

2.2. Absorption capacity of the SAPs

Prior to the concrete mixing and testing, the superabsorbent polymers were tested to assess their absorption capacity. The filtration method was performed in compliance with [36]. The SAPs were tested in demineralized water and in a cement filtrate solution prepared with the same cement used to produce the concrete mixtures. The cement filtrate was produced following the proportion of 1 kg of cement and 5 L of demineralized water.

Apart from that, the absorption capacity was also studied by means of flow table tests with cement pastes and slump tests with concrete mixtures. A reference cement paste mixture was produced, followed by a series of other mixtures containing SAPs. Then, the amount of additional water to be inserted in the SAP mixtures was determined in order to obtain the same workability of the reference mixture. The measurements were performed exactly 10 min after the first contact of the SAPs with the mixing water. Slump measurements on the concrete mixtures containing SAPs also showed the same workability as the reference.

2.3. Mixture compositions

All tests were performed on concrete mixtures produced with cement type CEM III-B 42.5N – LH/SR (CBR, Belgium); a polycarboxylate superplasticizer (Tixo, 25% conc., BASF, Belgium, at a constant dosage of 1.8 m% in relation to the cement mass); sea sand 0/4 (absorption of 0.4% in mass); sea sand 0/3 (absorption of 0.3% in mass); limestone 2/20 (absorption of 0.5% in mass) and four superabsorbent polymers earlier identified as SAP1, SAP2, SAP3 and SAP4 that are added on top of the reference mixture. More details about the compositions of the concrete mixtures is given in Table 1.

Table 1 - Composition of the studied concrete mixtures, values in kg/m^3.

Mixture	Cement	Sand 0/3 - Sand 0/4	Limestone 2/20	Superplas-ticizer	SAP	Additional water	w/c$_{(total)}$ [-]	Compressive strength at 28 days [MPa] (n=3)
REF0.46	356	421 - 343	1086	6.35	0	0	0.46	54.88 ± 1.97
REF0.57	340	406 - 331	1046	6.12	0	0	0.57	45.75 ± 1.79
C_SAP1	340	406 - 331	1046	6.12	1.70	37.42	0.57	47.59 ± 1.72
C_SAP2	339	405 – 330	1043	6.10	1.70	40.68	0.58	42.67 ± 2.39
C_SAP3	324	386 - 315	996	5.83	1.62	84.15	0.72	31.96 ± 0.72
C_SAP4	340	406 - 331	1046	6.12	3.40	37.42	0.57	45.76 ± 1.79

The reference concrete composition (REF0.46) was provided by CBR-Belgium. It is generally used for the construction of tunnel walls. The concrete mixture has a slump of 160 mm. The amount of additional water was determined in a way that all the SAP-containing mixtures had the same workability as the reference, reflecting the absorption of the SAPs in the concrete mixture [37-39]. The workability is assessed here as the slump measured 10 min after the first contact of the cement with the water. The slump of the SAPs-containing mixtures were 140 mm for C_SAP1 and C_SAP3, 165 mm for C_SAP2 and 150 mm for C_SAP4.

Following the indications found in literature, a SAP dosage of 0.5 m% in relation to the cement mass was added to the concrete mixtures C_SAP1, C_SAP2 and C_SAP3. For the concrete mixture C_SAP4, given the lower absorption capacity of SAP4, a dosage of 1 m% was chosen aiming to achieve the same total water-to-cement ratio as C_SAP1 and C_SAP2 which showed a better performance in comparison to C_SAP3 (as shown later). A second reference mixture (REF0.57) was produced with a water-to-cement ratio similar to C_SAP1, C_SAP2 and C_SAP4 to illustrate the effect of adding SAPs and additional water versus the effect of only the additional water to the system.

All concrete mixtures were produced in a mixer with a capacity of 12 L, in batches of 10 L. In the mixing procedure the dry materials were first mixed for 1 min (including SAPs, when present), then the mixing water and superplasticizer are added and mixed for an additional 2 min. When SAPs were present, the additional entrained water was added during the third minute and the mixing proceeded for an additional 2 min. The total mixing time was 3 min for the reference mixture and 5 min for the SAP-containing mixtures.

2.4. Shrinkage measurements with DEMEC

For each mixture, four prismatic specimens (100 mm x 100 mm x 400 mm) were cast and cured for 23 h in a room with controlled atmosphere of 20 ± 2 °C and RH > 95%. Right after casting, the free surface of the specimens was covered with a layer of plastic foil, attached to the mold with a thin layer of vaseline to improve the adhesion and prevent drying.

After the curing period, the specimens were demolded and half of them were wrapped with aluminum tape to avoid moisture exchange with the environment, thus reducing the effects of drying shrinkage. All specimens (covered and non-covered) were left in a room with a controlled atmosphere of 20 ± 2 °C and 60 ± 5% RH. Two measuring points were glued to the surfaces of the specimens (except for the troweled surface due to the fact of shape irregularities that could hinder the measurements), placed 200 mm apart on the central line of the specimens' surface. In total, each specimen had three measuring surfaces. The measurements were performed once per day for 28 days and started 24 h after the first contact of cement with the mixing water.

2.5. Shrinkage measurements with optical fiber sensors

The optical fiber sensors were used to assess the shrinkage of the concrete mixtures REF0.46, C_SAP2 and C_SAP3. One specimen was prepared for each of the concrete mixtures studied. The sensors used were produced by SMARTEC (Switzerland). They are composed of an active part, responsible for measuring the deformation, and a passive part, responsible for transmitting the data to a reading unit (Figure 2). They have an active length of 250 mm and a passive length of 10 m.

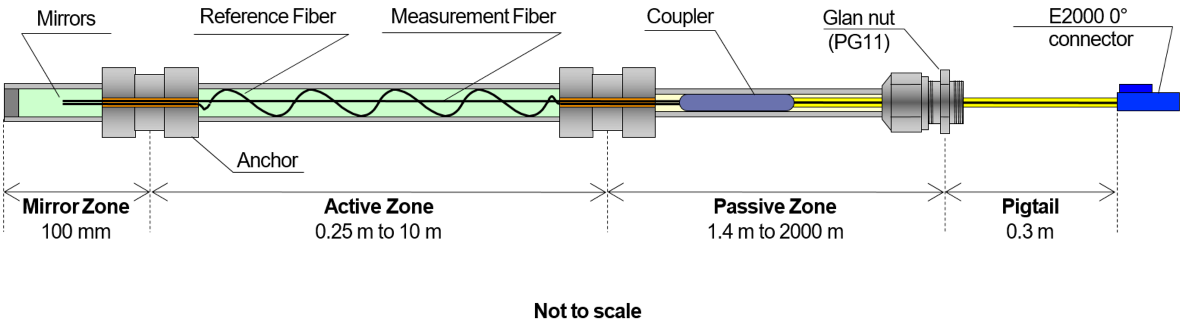


Figure 2 - Overview of the sensor. Courtesy of SMARTEC.

The specimens used for the measurements with the sensors had the same dimensions as those mentioned in section 2.4 (100 mm x 100 mm x 400 mm). At the middle height of the mold, a steel bar with a diameter of Ø 6 mm and length of 440 mm was placed to ensure a correct position of the sensors. After casting, the specimens were covered with plastic foil, attached to the molds with a thin layer of vaseline to prevent drying. The sensors were attached to the rebar with plastic rings and remained embedded in the concrete during the test. The specimens were cured for 23 h in a room with controlled atmosphere of 20 ± 2 °C and RH > 95%. After curing, they were transferred to a room with a controlled atmosphere of 20 ± 2 °C and 60 ± 5% RH, where the measurements were performed.

The measurements were performed automatically, every 10 min for 28 days, starting 30 min after concrete mixing. The values of strain were zeroed at the fluid-solid transition point. The transition point was determined considering the moment where the rate of autogenous strain became zero [25], corresponding to the knee point in measuring autogenous shrinkage. This approach can be of interest specially because it allows not only time saving but also material saving, since no additional testing to determine time-zero is required. It has been reported as a suitable technique to determine the time-zero for autogenous shrinkage measurements [21, 22, 25].

3. RESULTS AND DISCUSSION

In this section, the results of the absorption capacity measurements of the different SAPs are presented and discussed (3.1). Afterwards, the shrinkage measurements performed with the DEMEC and the optical fiber sensors are presented (3.2 and 3.3), and a comparison is made (3.4).

3.2. Absorption capacity of the SAPs

The values of water uptake of the SAPs in different environments are shown in Table 2. Except for SAP3, the absorption capacity decreased from demineralized water to cement filtrate solution and to paste, which was already expected as the cement paste has a higher concentration of monovalent ions in comparison with the cement filtrate [40, 41] and physical forces are exerted on the SAPs in the fresh mixture. The same can be extended to the absorption capacity of the SAPs in concrete mixtures.

Table 2 - Water uptake [g/g SAP] of the SAPs in demineralized water, cement filtrate solution, cement paste and concrete.

SAP	Water uptake [g/g]			
	Demineralized water (24 h, n=3)	Cement filtrate solution (24 h, n=3)	Cement paste (10 min)	Concrete (10 min)
SAP1	292 ± 9	29 ± 4	22	21
SAP2	201 ± 11	37 ± 5	27	24
SAP3	253 ± 7	44 ± 2	50	49
SAP4	53 ± 4	33 ± 3	13	12

For SAP3, the absorption capacity in cement paste was higher than the one in cement filtrate solution. This fact might be related to the higher amount of soluble materials present in SAP3 (26%) while SAP1 and SAP2 are almost pure (SAP2 has less than 0.5% of solubles) and SAP 4 has only 8% of solubles. Once this portion of the SAPs solubilizes in contact with the fluid during the filtration test, the initial mass of dry SAPs that actually absorbs the fluid is overestimated, leading to a calculated absorption capacity that will be lower than the real one. For SAP3, the calculated absorption capacity for a purified SAP (0% of solubles) is around 60 g/g (35% higher than the value presented in Table 2).

When comparing the absorption capacity determined based on the workability of the concrete and the paste, the results are comparable, showing that the use of the flow table test with cement paste is a good parameter for an indirect estimation of the absorption capacity of the SAPs at small scale. It can then be done prior to the assessment of concrete, reducing the waste of material and saving time.

The water absorption of the SAPs also shows an important influence on the mechanical properties of the concrete mixtures. The values of the compressive strength at 28 days (Table 1) show a reduction in all SAP-containing mixtures when compared to the REF0.46. When comparing the values obtained for the mixtures C_SAP1, C_SAP2, C_SAP4 and REF0.57, all with the similar total water-to-cement ratio of 0.57, it is noticed that adding SAPs with additional water has the same effects on the compressive strength than if only additional water was added to the concrete mixture. In this case, where the effective water-to-cement ratio is 0.46 and the amount of SAPs is higher than 0.5 m%, a comparison between the compressive strength of the SAP-containing concretes C_SAP1, C_SAP2 and C_SAP4 and the REF0.46 indicates a loss of strength in the SAP-containing mixtures. Even though further hydration would be expected in a system with internal curing, the amount of SAPs and additional water used tends to unbalance the relation between the gain in strength due to further hydration and the loss in strength due to the increased void volume. Similar trends have been reported in literature [42, 43].

3.3. Shrinkage measurements with DEMEC

Given the covering with aluminum tape applied to half of the specimens before starting the DEMEC measurements, it is possible to state that no/very limited moisture exchange occurred between the concrete and the environment, thus, for that series, the shrinkage strain measured can be associated with the self-desiccation and then be referred to as autogenous shrinkage.

When studying the reference concrete (R0.46 and R0.57), clear autogenous shrinkage is seen and the strain values are comparable to those found in literature for concrete mixtures with similar composition and the same type of cement [44]. This autogenous shrinkage needs to be compensated, else shrinkage cracking might occur.

When studying the SAP-containing mixtures, SAP1, SAP2 and SAP3 were able to completely mitigate the autogenous shrinkage (Figure 3).

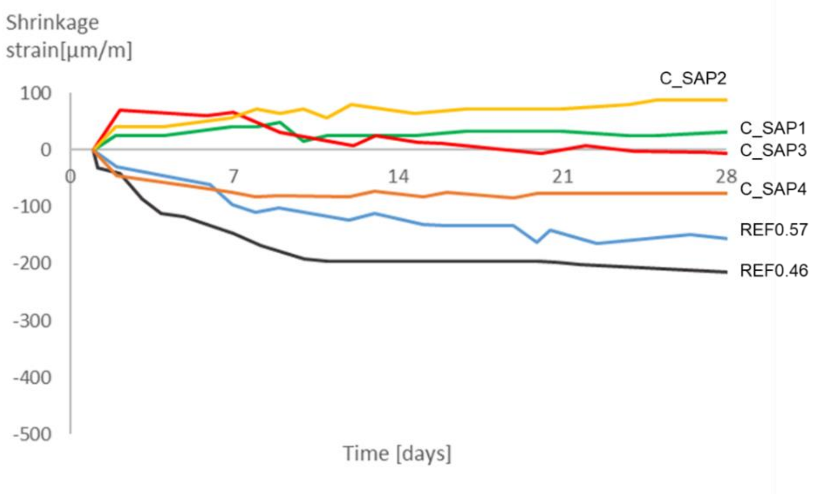


Figure 3 – Autogenous strain of covered concrete specimens measured with DEMEC. Measurements started 24 h after mixing. The lines represent the average values for two specimens with three measurements per specimen. The maximum standard deviation found was ± 50 µm.

After 7 days, the autogenous strain in both reference mixtures keeps showing only shrinkage (at a lower level for REF0.57). For the SAP containing mixtures, both C_SAP1 and C_SAP2 can keep a minor constant expansion trend of strain while SAP3 starts to show a slight increase in the shrinkage strain with the curve presenting a reduction in the positive values, approaching zero. This can be related to the kinetics of water release by the SAPs. Both SAP1 and SAP2 seem to have a more gradually controlled water release (which can be verified by the constant trend in the strain levels).

A continued hydration caused by the gradual release of water promotes expansion keeping the strain levels constant during the whole time. As for SAP3, the sudden decrease in the positive values after 7 days can be an indication that this SAP is releasing all the stored water quicker in comparison to SAP1 and SAP2 and has released most of its stored water at 7 days, not contributing to the volume expansion due to further hydration after this period. Up to 7 days, C_SAP4 shows a behavior very similar to

REF0.57 but then reaches a constant level of strain, which is lower than REF0.57. This indicates that SAP4 is releasing its water later in time (in comparison to the others), which allows to reduce the shrinkage strain only partially.

SAPs should be able to release their stored water for internal curing over a certain time span, initiating it around fluid-solid transition. A too early release leads to a cementitious matrix with a higher total water-to-cement ratio and a too late release to inefficient mitigation of autogenous shrinkage and self-desiccation.

In comparison to REF0.57, all SAP-containing mixtures show a lower level of shrinkage strain. When comparing REF0.57 with C_SAP1, C_SAP2 and C_SAP4 (all with a similar water-to-cement ratio) the addition of SAPs and additional water is more efficient than just adding the same amount of water on top of the reference mixture, in terms of shrinkage mitigation.

Figure 4 shows the shrinkage strain for the exposed specimens from the reference mixtures (REF0.46 and REF0.57) and for the SAP containing mixtures C_SAP1, C_SAP2 and C_SAP4.

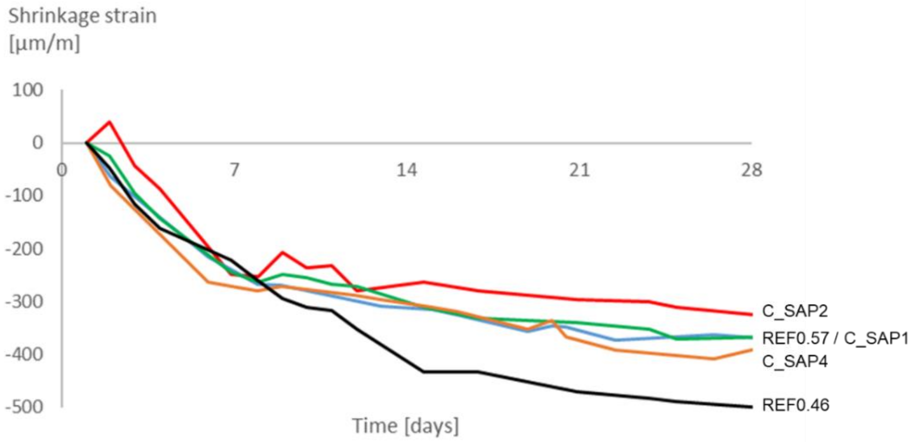


Figure 4 - Shrinkage strain of exposed concrete specimens measured with DEMEC. Measurements started 24 h after mixing.

Different from what was observed for the covered concrete specimens (Figure 3), none of the SAPs was able to completely mitigate the shrinkage strain. With the specimens exposed to the air, the strain values take into account both autogenous and drying shrinkage. Even though a reduction of around

30% was observed in comparison to REF0.46 at 28 days, the shrinkage strain in all SAP containing mixtures is still higher than both references when compared to the covered specimens. Other authors [45] using 0.4 m% of a SAP based on acrylamide/acrylic acid copolymers reported a reduction of only 9% in comparison to a reference mixture at the same age.

The strain levels of all SAP containing mixtures were very similar to the REF0.57 mixture, which can indicate that once the specimens are totally exposed to the air, the effect of drying tends to force a fast water release by the SAPs. This effect then brings the SAP containing mixtures to the same state as the reference mixture with the same total water-to-cement ratio in terms of moisture content, and thus, the SAPs are not efficient to mitigate drying shrinkage.

3.4. Shrinkage measurements with optical fiber sensors

The strain values measured with the optical fiber sensors are presented in Figure 5.

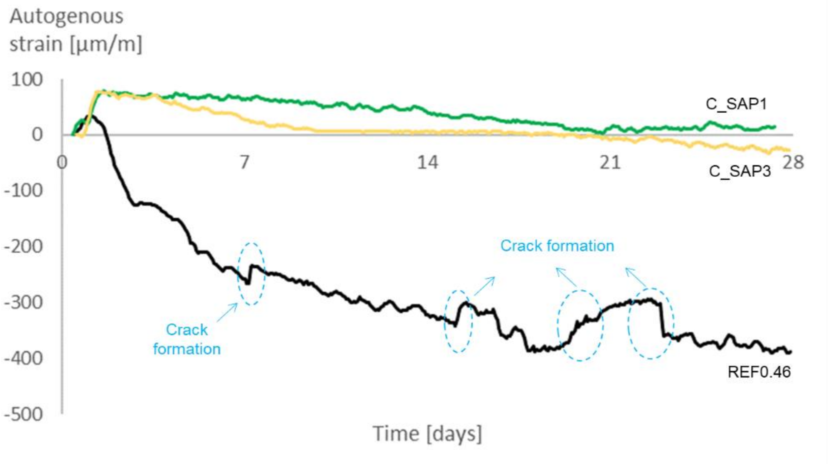


Figure 5 - Autogenous strain of concrete specimens measured with optical fiber sensors. Measurements zeroed at the fluid-solid transition point for each mixture. Crack formation is also indicated.

In this scenario, SAP1 can keep the values of strain above zero during the whole period of testing. SAP3 experiences again a decrease in its efficiency with a steep decrease at around 7 days, followed by a period of constant strain around zero until day 21 when the concrete starts to experience more shrinkage.

An interesting feature of the optical fiber sensors is the additional possibility to identify the formation of cracks inside the material. As highlighted in Figure 5, some sudden “jumps” in strain values are noticed in the reference mixture (REF0.46) at around 7, 16 and 20 days. As the sensor covers a length of 250 mm (corresponding to 62.5% of the total length of the specimens), it is expected that a crack appearing within the sensor reading area will be identified in the measurements.

These ”jumps”, however, are not found in the SAP containing mixtures. Even though both SAP containing specimens show a reduction in the expansion over time and C_SAP3 starts to show shrinking after 21 days, the values of strain developed in these mixtures will not initiate crack formation.

After the measurements were finished, the specimens were demolded and cut to expose the region nearby the sensors and no debonding was noticed. Furthermore, for the reference mixture (REF0.46), micro-cracks up to 50 µm were found within 1 cm from the location of the sensor and along the complete active length (Figure 6 and Figure 7).

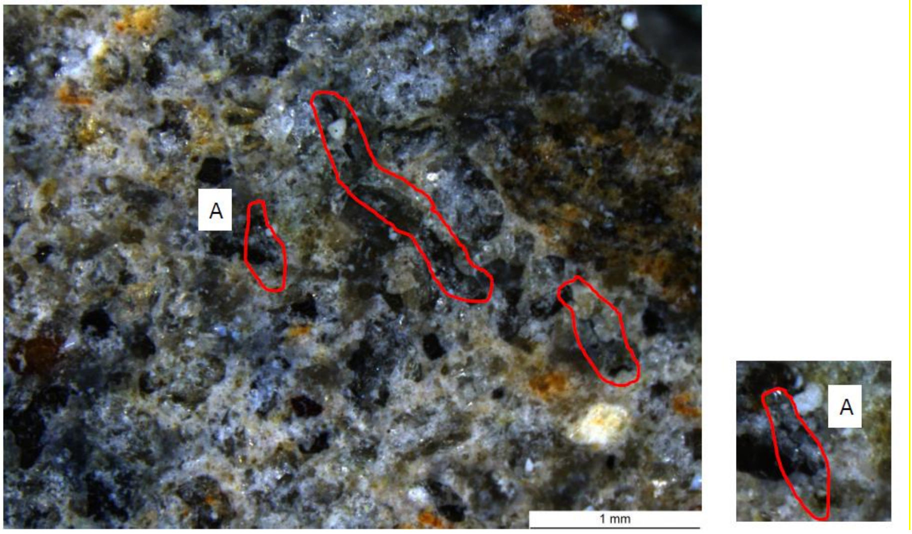


Figure 6 - Micro-cracks identified in the cement matrix in the surroundings of the sensor.

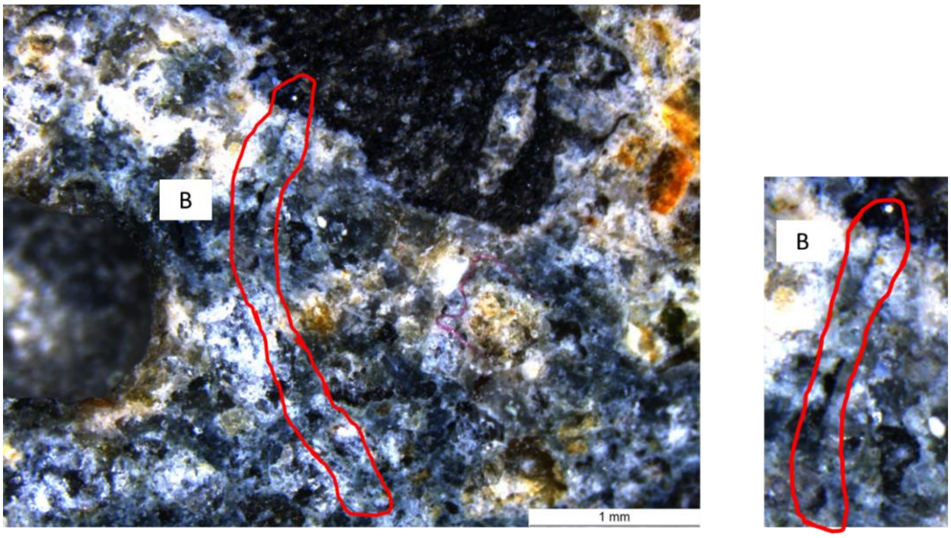


Figure 7 – Another micro-crack identified in the cement matrix in the surroundings of the sensor.

3.5. A comparison of the methods

A certain caution is advised when using the manual measurements with the DEMEC to judge the efficiency of internal curing agents. Considering the 24 h starting point as the time-zero for the autogenous shrinkage measurements can generally lead to an underestimation of strain values for the reference mixtures without internal curing agents and hence to an underestimation of the efficiency of the internal curing agents [21-23, 25].

When the measurements only start after 24 h, a time period of around 12-14 h since the fluid-solid transition of the material is not being recorded, which can lead to shrinkage strain values that not correspond to the total strain developed due to autogenous shrinkage. Therefore, another measuring technique would be of interest, i.e. the use of electronic sensors.

The results of the measurements with the optical fibers are again shown in Figure 8, but this time with the strain values zeroed at 24 h in order to compare them with the results obtained with the DEMEC (covered specimens).

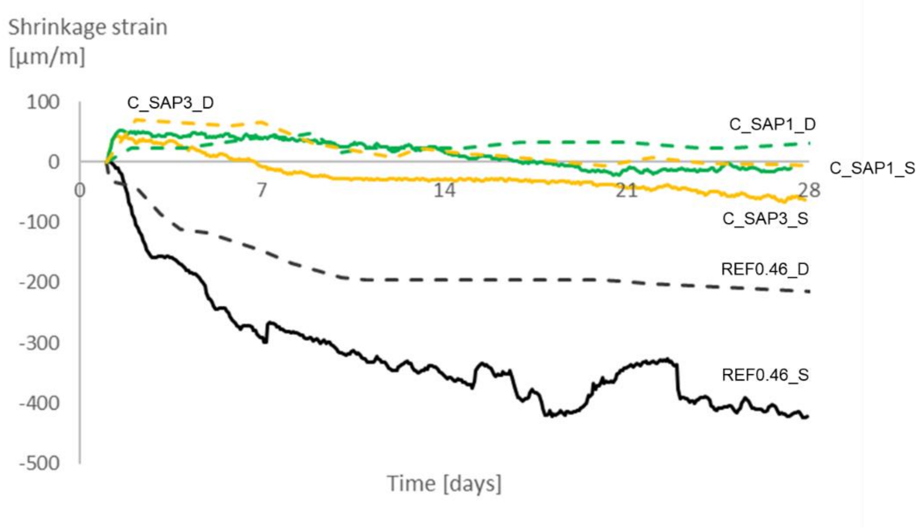


Figure 8 – Comparison of the autogenous strain of concrete specimens measured with both optical fiber sensors and DEMEC. Measurements zeroed 24 h after mixing. _S stands for sensor and _D stands for DEMEC.

It is noticed that the strain values measured with the sensors are more negative compared to the values measured with the DEMEC. This can be related to the protection of the specimens, which was different in both tests. Even though the specimens with embedded sensors remained inside the formwork, the casting surface was only covered by a thin layer of plastic foil, which might not have been as efficient as the aluminum tape used for the specimens on which DEMEC measurements were performed in terms of preventing/reducing the effects of drying shrinkage. According to the fiber sensor measurements, after 16 days and 7 days, respectively, SAP1 and SAP3 show no more mitigation of the shrinkage strain, but both are still able to keep the strain around zero (especially SAP1). Apart from that, the same overall trend is noticed.

4. CONCLUSIONS

In this paper, four different superabsorbent polymers were used as internal curing agent to reduce/prevent the crack formation due to autogenous shrinkage in concrete mixtures. Two different methods are used for assessing the autogenous strain: a more traditional approach consisting of a demountable mechanical strain gauge and a more innovative approach consisting of long-gauge deformation sensors based on optical fiber sensors. In the traditional approach, two different exposure conditions were used for the specimens.

The following conclusions can be drawn:

- All SAP mixtures were able to show a significant reduction in the shrinkage strain in comparison to the reference mixtures with and without additional water, fully mitigating the autogenous shrinkage;
- The chemical composition and the moment of water release by the SAPs played an important role in the efficiency of shrinkage mitigation. SAP 1, SAP2 and SAP3 showed a complete mitigation of shrinkage strain, but SAP3 demanded a higher amount of additional water. SAP4 promoted a significant reduction in the autogenous strain but it was not able to reach a full mitigation.
- Both the DEMEC and the sensors were able to capture the effect of the SAPs in comparison to the reference mixture, but the absolute values of strain are different. This was the case especially for the reference mixture, as a consequence of the different coverages used to avoid drying.
- While practical and relatively cheaper, the use of traditional approaches might lead to misinterpretation of results by not considering a significant portion of strain in the time between the transition state point of the mixture and the moment that the measurements are started;
- The optical fiber sensors were able to provide an indication for the moment of crack formation without the need of additional tests or indirect measurements;
- While still costly, in comparison with other techniques, the use of the embedded sensors brings more advantages, higher level of precision and reduced person-hours in the monitoring of shrinkage deformation in the concrete, which can be even more valuable when considering the monitoring of larger scale specimens and structures.

ACKNOWLEDGMENTS

The work has been financed by SIM program SHE (Engineered Self-Healing Materials) within the ICON project iSAP (Innovative SuperAbsorbent Polymers for crack mitigation and increased service life of concrete structures).

As a Postdoctoral Research Fellow of the Research Foundation-Flanders (FWO-Vlaanderen), D. Snoeck would like to thank the foundation for the financial support (12J3620N).

REFERENCES

1. Jiang, C.H., et al., *Autogenous shrinkage of high performance concrete containing mineral admixtures under different curing temperatures.* Construction and Building Materials, 2014. **61**: p. 260-269.
2. Wu, L.M., et al., *Autogenous shrinkage of high performance concrete: A review.* Construction and Building Materials, 2017. **149**: p. 62-75.
3. Jensen, O.M. and P.F. Hansen, *Autogenous deformation and RH-change in perspective.* Cement and Concrete Research, 2001. **31**(12): p. 1859-1865.
4. Jensen, O.M. and P.F. Hansen, *Water-entrained cement-based materials I. Principles and theoretical background.* Cement and Concrete Research, 2001. **31**(4): p. 647-654.
5. Jensen, O.M., *Use of Superabsorbent Polymers in Construction Materials.* Microstructure Related Durability of Cementitious Composites, Vols 1 and 2, 2008. **61**: p. 757-764.
6. Snoeck, D., *Self-Healing and Microstructure of Cementitious Materials with Microfibres and Superabsorbent Polymers*, in *Faculty of Architecture and Engineering*. 2015, Ghent University: Ghent, Belgium.
7. Snoeck, D., O.M. Jensen, and N. De Belie, *The influence of superabsorbent polymers on the autogenous shrinkage properties of cement pastes with supplementary cementitious materials.* Cement and Concrete Research, 2015. **74**: p. 59-67.
8. Snoeck, D. and N.D. Belie, *Effect of superabsorbent polymers, superplasticizer and additional water on the setting of cementitious materials.* International Jouornal of 3R's, 2015. **5**(3): p. 721-729.
9. Snoeck, D., L. Pel, and N. De Belie, *The water kinetics of superabsorbent polymers during cement hydration and internal curing visualized and studied by NMR.* Scientific Reports, 2017. **7**.
10. Tenório Filho, J.R., D. Snoeck, and N. De Belie. *The effect of superabsorbent polymers on the cracking behavior due to autogenous shrinkage of cement-based materials*. in *60th Brazilian Concrete Conference*. 2018. Foz do Iguacu, Brazil: Brazilian Concrete Institute.
11. De Meyst, L., et al., *Parameter Study of Superabsorbent Polymers (SAPs) for Use in Durable Concrete Structures.* Materials, 2019. **12**(9).
12. Snoeck, D., L. Pel, and N. De Belie, *Superabsorbent polymers to mitigate plastic drying shrinkage in a cement paste as studied by NMR.* Cement & Concrete Composites, 2018. **93**: p. 54-62.
13. Geiker, M.R., D.P. Bentz, and O.M. Jensen, *Mitigating autogenous shrinkage by internal curing.* High-Performance Structural Lightweight Concrete, 2004. **218**: p. 143-154.

14. Craeye, B., M. Geirnaert, and G. De Schutter, *Super absorbing polymers as an internal curing agent for mitigation of early-age cracking of high-performance concrete bridge decks.* Construction and Building Materials, 2011. **25**(1): p. 1-13.
15. J. Piérard, V. Pollet, and N. Cauberg. *Mitigating autogenous shrinkage in HPC by internal curing using superabsorbent polymers*. in *International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation*. 2006. Lyngby, Denmark: RILEM Publications SARL.
16. Mechtcherine, V. and H.W. Reinhardt, *Application of Super Absorbent Polymers (SAP) in Concrete Construction*, in *State-of-the-Art Report Prepared by Technical Committee 225-SAP*. 2012, RILEM. p. 165.
17. Zohuriaan-Mehr, M.J. and K. Kabiri, *Superabsorbent polymer materials: A review.* Iranian Polymer Journal, 2008. **17**(6): p. 451-477.
18. International, A., *ASTM C157 / C157M-17, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. 2017: West Conshohocken.
19. Sven Mönnig and H.-W. Reinhardt. *Results of a comparative study of the shrinkage behaviour of concrete and mortar mixtures with different internal water sources*. in *International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation*. 2006. Lyngby, Denmark: RILEM Publications SARL.
20. Barcelo, L., M. Moranville, and B. Clavaud, *Autogenous shrinkage of concrete: a balance between autogenous swelling and self-desiccation.* Cement and Concrete Research, 2005. **35**(1): p. 177-183.
21. Sant, G., P. Lura, and J. Weiss. *A discussion of analysis approaches for determining 'time-zero'from chemical shrinkage and autogenous strain measurements in cement paste*. in *International RILEM conference on Volume Changes of Hardening Concrete: Testing and Mitigation*. 2006.
22. Sant, G., et al. *Examining time-zero and early age expansion in pastes containing shrinkage reducing admixtures (SRA's)*. in *2nd International RILEM Symposium on Advances in Concrete through Science and Engineering* 2006. RILEM Publications SARL.
23. Chang-Wen, M., et al., *Water consumption of the early-age paste and the determination of "time-zero" of self-desiccation shrinkage.* Cement and Concrete Research, 2007. **37**(11): p. 1496-1501.
24. Darquennes, A., S. Staquet, and B. Espion, *Determination of time-zero and its effect on autogenous deformation evolution.* European Journal of Environmental and Civil Engineering, 2011. **15**(7): p. 1017-1029.
25. Tenório Filho, J.R., et al., *Discussing different approaches for the time-zero as start for autogenous shrinkage in cement pastes containing superabsorbent polymers.* 2019.
26. Vulliet, L., et al., *Development and laboratory tests of deformation fiber optic sensors for civil engineering applications.* Optical Inspection and Micromeasurements, 1996. **2782**: p. 97-108.
27. Kawano, Y., T. Mikami, and K. Ikushima, *A Suggestion of Health Monitoring for the Road Bridge Floor with Fiber Optic Sensor.* Structural Health Monitoring 2015: System Reliability for Verification and Implementation, Vols. 1 and 2, 2015: p. 240-246.
28. Kawano, Y., T. Mikami, and F. Katsuki, *Health Monitoring of a Railway Bridge by Fiber Optic Sensor (SOFO).* Structural Health Monitoring 2010, 2010: p. 1319-1324.
29. Zonta, D., et al., *Design and laboratory validation of a structural element instrumented with multiplexed interferometric fiber optic sensors.* Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2008, Pts 1 and 2, 2008. **6932**.
30. Inaudi, D., A. Elamari, and S. Vurpillot, *Low Coherence Interferometry for the Monitoring of Civil Engineering Structures.* Second European Conference on Smart Structures and Materials, 1994. **2361**: p. 216-219.
31. Inaudi, D., S. Vurpillot, and N. Casanova, *Bridge monitoring by interferometric deformation sensors.* Fiber Optic Sensors V, 1996. **2895**: p. 34-45.

32. Inaudi, D., et al., *Development and field test of deformation sensors for concrete embedding.* Industrial and Commercial Applications of Smart Structures Technologies - Smart Structures and Materials 1996, 1996. **2721**: p. 138-148.
33. Inaudi, D., S. Vurpillot, and E. Udd, *Long-gage structural monitoring for civil structures.* Fourth Pacific Northwest Fiber Optic Sensor Workshop, 1998. **3489**: p. 93-100.
34. Kronenberg, P., et al., *Dam monitoring with fiber optics deformation sensors.* Smart Systems for Bridges, Structures, and Highways - Smart Structures and Materials 1997, 1997. **3043**: p. 2-11.
35. Tenório Filho, J.R., et al. *Investigating the efficiency of "in-house" produced hydrogels as internal curing agents in cement pastes*. in *2nd International Conference of Sustainable Building Materials*2019. Eindhoven, The Netherlands.
36. Snoeck, D., C. Schrofl, and V. Mechtcherine, *Recommendation of RILEM TC 260-RSC: testing sorption by superabsorbent polymers (SAP) prior to implementation in cement-based materials.* Materials and Structures, 2018. **51**(5).
37. Mechtcherine, V., L. Dudziak, and S. Hempel. *Mitigating early age shrinkage of Ultra-High-Performance Concrete by using Super Absorbent Polymers (SAP)*. in *Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures*. 2009. Ise-Shima, Japan: Taylor & Francis.
38. Monnig, S. and P. Lura, *Superabsorbent polymers - An additive to increase the freeze-thaw resistance of high strength concrete.* Advances in Construction Materials 2007, 2007: p. 351-358.
39. Schrofl, C., V. Mechtcherine, and M. Gorges, *Relation between the molecular structure and the efficiency of superabsorbent polymers (SAP) as concrete admixture to mitigate autogenous shrinkage.* Cement and Concrete Research, 2012. **42**(6): p. 865-873.
40. Kang, S.H., S.G. Hong, and J. Moon, *Importance of monovalent ions on water retention capacity of superabsorbent polymer in cement-based solutions.* Cement & Concrete Composites, 2018. **88**: p. 64-72.
41. Kang, S.H., S.G. Hong, and J. Moon, *Absorption kinetics of superabsorbent polymers (SAP) in various cement-based solutions.* Cement and Concrete Research, 2017. **97**: p. 73-83.
42. M.T. Hasholt, M.H.S. Jespersen, and O.M. Jensen. *Mechanical properties of concrete with SAP part I: Development of compressive strength*. in *International RILEM Conference on Use of Superabsorbent Polymers and Other New Additives in Concrete*. 2010. Lyngby, Denmark: RILEM Publications SARL.
43. Snoeck, D., et al., *Effect of high amounts of superabsorbent polymers and additional water on the workability, microstructure and strength of mortars with a water-to-cement ratio of 0.50.* Construction and Building Materials, 2014. **72**: p. 148-157.
44. Lura, P., K. van Breugel, and I. Maruyama, *Effect of curing temperature and type of cement on early-age shrinkage of high-performance concrete.* Cement and Concrete Research, 2001. **31**(12): p. 1867-1872.
45. Mechtcherine, V., et al. *Internal curing by super absorbent polymers (SAP) - effects on material properties of self-compacting fibre-reinforced high performance concrete*. in *International RILEM Conference on volume changes of hardening concrete: testing and mitigation*. 2006. Technical University of Denmark, Lyngby, Denmark: RILEM