Reaching Beyond Internal Curing: The Effects of Superabsorbent Polymers on the Durability of Reinforced Concrete Structures

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Abstract. With the current demands for more sustainable and durable structures, the search for smarter and innovative building materials plays a crucial role in the further development of the construction industry. The discovery of the synergetic effect between superabsorbent polymers (SAPs) and cementitious materials gave space to uncountable new possibilities. SAPs have since then been proven to effectively mitigate autogenous shrinkage, increase resistance to freeze-thaw damage, promote immediate sealing of cracks, enhance self-healing, etc. In this paper, the use of SAPs as internal curing agents in large-scale reinforced concrete walls is described with focus on the effects of internal curing on the crack formation and consequent corrosion initiation. Two reinforced concrete walls (with and without SAPs) were produced and monitored after casting. Multireference electrodes were used for monitoring the corrosion potential while the shrinkage strain was monitored by means of optical fiber sensors. Cracks were observed in the reference wall already five days after casting, while the SAP-wall remained crack-free after 24 months. The reference wall showed an indication of possible corrosion initiation near two of the crack locations six months after casting. In contrast, no corrosion potential was identified in the crack-free wall with SAPs.

Keywords: SAPs · MuRe · SOFO sensors · Corrosion

1 Introduction

Superabsorbent polymers consist of a natural and/or synthetic water-insoluble 3D network of polymeric chains crosslinked by chemical or physical bonding. They possess the ability to take up a significant amount of liquids from the environment (in amounts up to 1500 times their own weight) [1] and form an insoluble gel [2]. This amount of absorbed water can be released due to drying or osmotic pressure, consequently causing the SAPs to shrink in size [3, 4].

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The use of SAPs has expanded the frontiers of cementitious materials in the previous 20 years, paving the way for smart, innovative, more durable and sustainable structures [5, 6]. The combined use of the polymers with cementitious matrices has allowed for a synergetic performance that diminished an intrinsic disadvantage of the latter: shrinkage-cracking.

Besides counteracting the effects of (autogenous) shrinkage, mainly by means of internal curing of the cement matrix at very early ages [7, 8], the use of SAPs has been proven to be beneficial to the better performance of cementitious materials in many other aspects. To name a few: 1) promoting sealing of cracks [9, 10]; 2) enhancing the autogenous healing potential of the cement matrix [11–13]; 3) controlling the rheology [6]; 4) increasing the resistance against salt-scaling under freeze-thawing [14, 15].

In this paper, the use of SAPs for internal curing in real size structures is illustrated. The effects of the internal curing on the cracking behavior are demonstrated by the reduction in shrinkage strain, avoidance of shrinkage cracks, and delay in the initiation of corrosion in reinforced concrete walls built with and without SAPs.

2 Experimental Program

2.1 General Description

The experimental program was based on the construction and monitoring of two reinforced concrete walls under realistic conditions. A reference wall (W_REF) with no SAPs and a second wall (W_SAP) containing a combination of two different types of SAP were built. The choice of the combined use of two different SAPs aimed at achieving an optimal combination of both internal curing and self-sealing of cracks. The walls had dimensions 14 m × 2.75 m × 0.80 m. They were cast in the last week of August 2020 (W_REF) and first week of September 2020 (W_SAP) with average minimum and maximum temperatures between 10.9 and 19.2 °C (for the period for the construction and monitoring of both walls), and demolded 48 h after casting. A detailed description of the testing campaign of the walls, covering aspects beyond this paper, can be found in [16].

The walls were equipped with two types of embedded sensors for real time monitoring. The first type of sensors (SOFO sensors) comprised optical fiber sensors used for the monitoring of shrinkage, while the second was based on multi-reference electrodes for the monitoring of corrosion potential. Further description of the mix design and reinforcement of the walls, as well as the sensor installation will be provided in the next sections. For a further description on the use of the SOFO sensors for monitoring of shrinkage strain please refer to [17].

2.2 Mix Design and Construction Details of the Walls

The reference wall was produced with a total water-to-cement ratio of 0.44. The SAP-containing wall was produced with a total water-to-cement ratio of 0.62. This amount of 0.62 corresponds to the total water-to-cement ratio including the mixing water factor of 0.44 as in W_REF plus the entrained water in the SAPs (the amount of entrained water was determined based on the absorption capacity of the SAP). The concrete used for W_REF was considered to have a strength class C35/45. The crack width was designed and limited to 0.3 mm with reinforcement of diameter 16 mm every 9.6 cm. W_SAP was built with a concrete having a strength class C30/37. The crack width was limited to 0.3 mm with reinforcement of diameter 16 mm every 10.7 cm (Fig. 1). Both walls were built on top of reinforced concrete slabs made with the same concrete as W_REF. The slabs were constructed at least three months in advance to the walls.

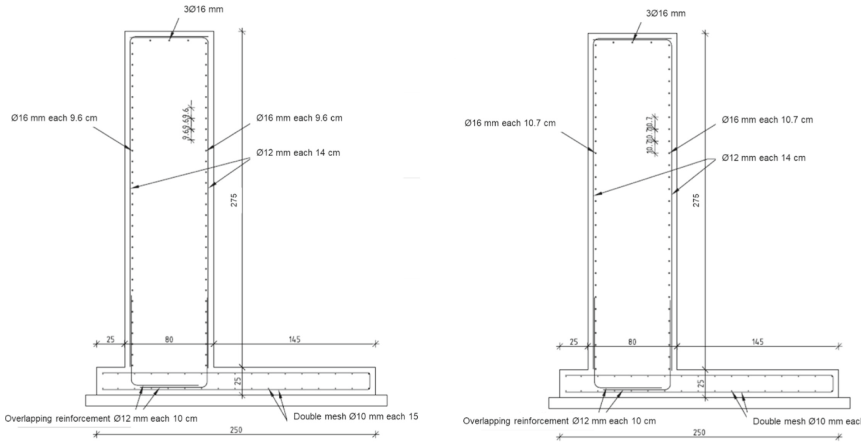

Fig. 1. Reinforcement details of the walls W_REF (on the left) and W_SAP (on the right).

Both walls were produced with concrete having a consistency class S4. All concrete mixtures were produced with cement type CEM III-B 42.5N – LH/SR (CBR, Belgium); a polycarboxylate superplasticizer (Tixo, 25% conc., BASF, Belgium); a modified polycarboxylate superplasticizer (Sika-Viscoflow 26, SIKA, Belgium); sea sand 0/4 (absorption of 0.4% in mass); and limestone 2/20 (absorption of 0.5% in mass). The mixture design of the concrete produced for each wall is given in. For each wall, 32 m^3 of concrete was produced. This amount was split into two trucks of 11 m^3 and one truck of 10 m^3 (Table 1).

Table 1. Mix design of the concrete mixtures used in the walls.

Wall	Cement	Sand	Limestone	Adm1	Adm2	SAP1	SAP2
W_REF	360	736	1116	2.42	1.56	0	0
W_SAP	360	702	1078	2.42	1.56	1.37	3.6

Adm1 refers to the superplasticizer Tixo (25% conc., BASF, Belgium).
Adm2 refers to the superplasticizer Sika-Viscoflow 26 (SIKA, Belgium).

2.3 The SAPs

SAP1, made by SNF Floerger (France), is a crosslinked acrylate copolymer produced through bulk polymerization. It was used with a d_{50} of 360 μm and absorption capacity in fresh concrete of 21 g/g. Due to commercial confidentiality, extra details about the production of the SAP are not available. SAP2, produced by ChemStream bv (Belgium) is solely composed of monomer NaAMPS (2-acrylamido-2-methyl-1-propanesulfonic acid sodium salt) and it possesses a second (alkali unstable) crosslinker. This SAP has a much lower initial swelling degree, but once the compound has been in the alkaline environment of the cementitious materials for a few hours/days, the crosslinks that are constituted by the second crosslinker are hydrolyzed and the swelling potential of the SAP becomes much greater again in situ. The idea behind this concept is to enable the use of higher dosages of SAPs without the need of higher amounts of additional water to compensate for the loss in workability, which normally leads to a significant increase in the air content in the hardened state of the concrete (due to the formation of macropores) and a resulting decrease in compressive strength. Once the alkali-unstable crosslinker is hydrolyzed, the SAP particles can swell more, which can be a benefit for the promotion of self-sealing of future cracks. This SAP was used with a d_{50} of 100 μm and absorption capacity in concrete of 13 g/g. A more detailed study on this innovative SAP is given in [9].

2.4 Monitoring System

For the monitoring of corrosion potential, nickel based multi-reference electrodes (MuRe) developed by Cescor (Italy) were used. The electrodes were embedded in the concrete, attached to the reinforcement (Fig. 2) every 20 cm, placed 70 cm from the bottom of the wall. The electrodes were connected to a measuring unit that enabled the monitoring of up to eight electrodes at a time. This unit was placed in an access box inside the wall, with an opening to the outside from where the active electrodes could be changed if needed. The measuring unit was connected to the Smartmote.NET system (Smartmote, Germany) which allowed wireless and real time monitoring, with all data stored online. The electrodes were numbered sequentially based on their location to facilitate the choice of electrodes to be monitored depending on the location of cracks.

For the monitoring of the shrinkage, SOFO sensors (produced by SMARTEC, Switzerland) were used, as previously described in [17]. SOFO sensors are transducers that transform a distance variation into a change in the path unbalance between two optical fibers that can be measured with a reading unit connected to a computer. 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. The sensors used in this study have an active length of 5 m and a passive length of 20 m. They were attached to the reinforcement of the walls before casting, at a height of 50 cm from the bottom of the wall (Fig. 3).

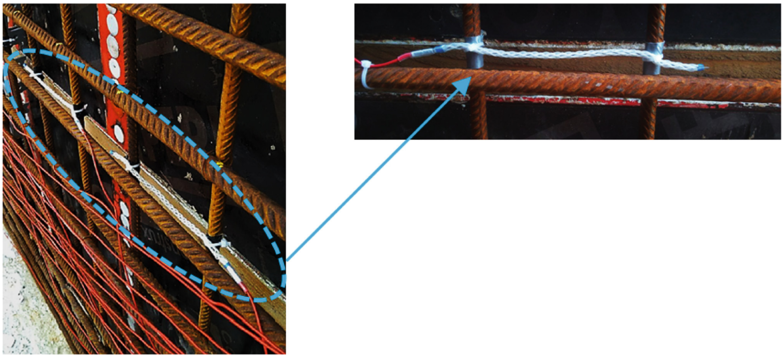

Fig. 2. Nickel electrodes attached to the reinforcement steel of the wall.

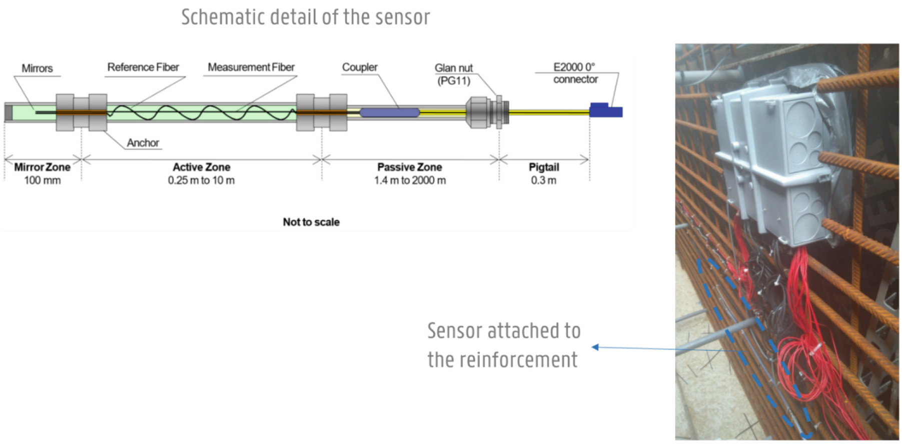

Fig. 3. Schematic detail of the sensor attached to the reinforcement. The drawing of the sensor is a courtesy of SMARTEC.

3 Results and Discussion

The cracking pattern observed on the reference wall after the first 28 days since the casting in shown in Fig. 4. For the SAP-containing wall no cracks were noticed even after 24 months.

The shrinkage levels of the walls (Fig. 5) showcase the effects of the internal curing promoted by the SAPs. A reduction of 55% in the strain levels at 7 days of the SAP mixture was found in comparison to the reference mixture. This reduction was only 18% at 28 days, which was enough to prevent the appearance of shrinkage cracks in the young concrete. The shrinkage measurements were zeroed at the knee-point of the shrinkage strain curve for each mixture.

For the monitoring of corrosion potential, initially, eight electrodes nearby the access box were connected just to make sure the system was working properly. The potential was then measured for approximately one month. Two months after the casting of the walls,

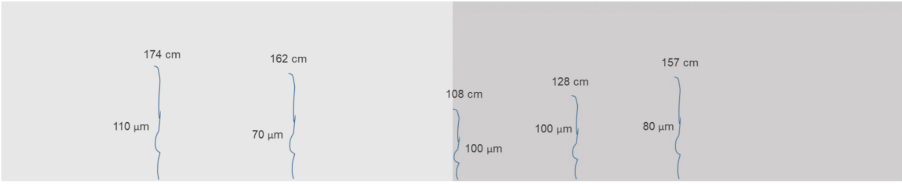

Fig. 4. Cracking pattern of the refence wall 28 days after casting. Showing the total height of the crack measured from the bottom [cm] and the average width [µm].

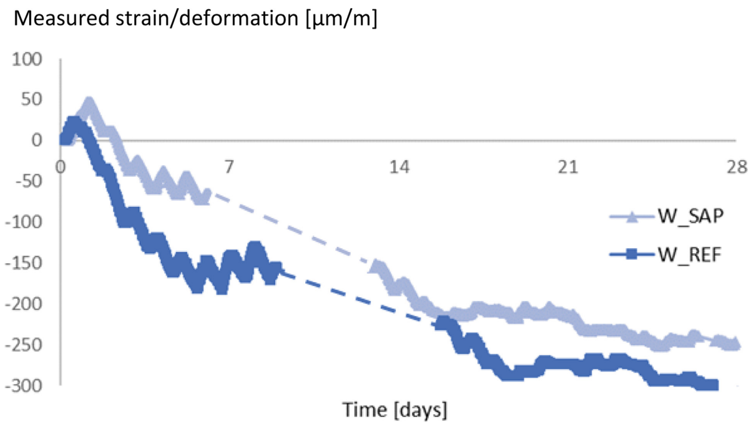

Fig. 5. Measured strain/deformation in the walls W_REF and W_SAP measured with the optical fiber sensors. The dashed line in both curves represents a momentous cut in the power supply of the measuring unit on site.

different electrodes were connected to the measuring unit, following the appearance of cracks. The location of such electrodes is indicated in Fig. 6.

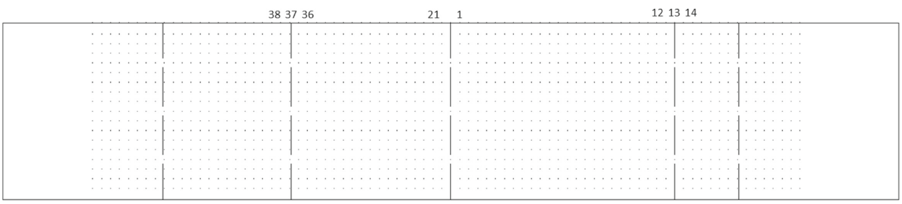

Fig. 6. Mapping of the location of the electrodes. The numbers at the top correspond to the location of the electrodes represented in the results section. The vertical dashed lines represent the cracks.

The measurements of potential are shown in Fig. 7. In the graph, a dashed line marks the characteristic corrosion potential for nickel (−257 mV), indicating the most likely passive and active region for the corrosion process. For approximately 4 months, the potential values were quite stable in all the locations. At around 6 months after the casting of the walls, a sudden decrease in the value of the potential was noticed for the sensors located at the points 37 and 38 (indicated in Fig. 6), near one of the cracks. The values observed for those electrodes are positioned in the active region, indicating that some localized corrosion process might have started. For wall W_SAP, since no cracks developed, the electrodes that were initially active after the casting of the wall remained connected to the measuring unit. Due to a malfunctioning regarding the communication between the reading unit in this wall and wireless station on site, only a limited dataset is available. Despite of that, all electrodes recorded potential values in the passive region, indicating that no corrosion started (Fig. 8).

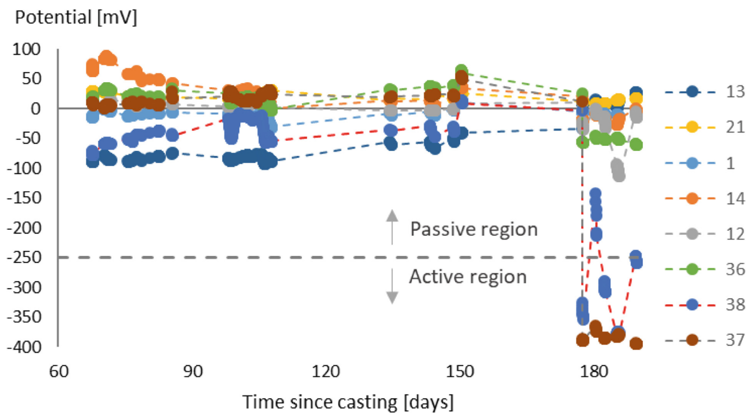

Fig. 7. Potential measured near some cracked locations of wall W_REF. The dashed lines represent the moment where the measuring unit was not recording.

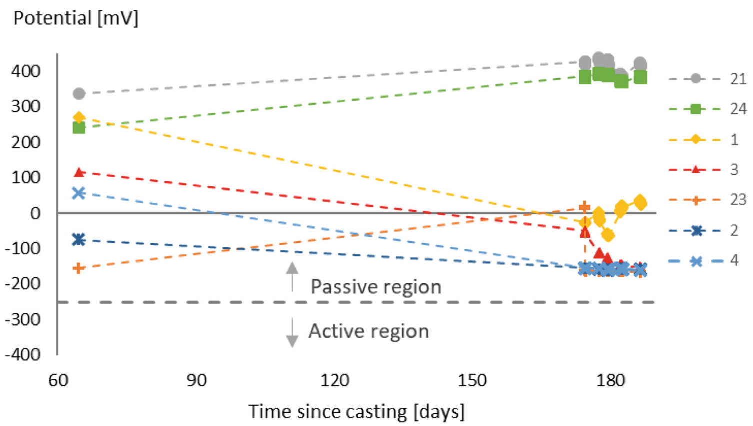

Fig. 8. Potential measured at different locations of wall W_SAP. The dashed lines represent the moment where the measuring unit was not recording.

4 Conclusions

In this study, superabsorbent polymers have been used in the largest testing campaign to date in Europe. One commercially available SAP and an "in-house" developed SAP constituted with different alkali-(un)stable crosslinkers were studied.

The use of the commercial SAP was intended to promote internal curing in the concrete structure, thus reducing the cracking potential due to early-age shrinkage. The "in-house" developed SAP was initially designed for the promotion of instant sealing of cracks with later enhancement of the self-healing potential of the concrete. The combination of both SAPs was foreseen as the way to build the ideal concrete wall, which would not only possess an internal curing agent for mitigation of shrinkage but also an internal system to enhance the self-sealing/healing of possible occurring cracks.

The inclusion of SAPs promoted a reduction of up to 55% in the shrinkage strain at 7 days in comparison with a reference mixture without SAPs. That reflected in a SAP wall that presented no cracks after 24 months of monitoring, while the reference walls without SAPs presented going-through cracks in the first seven days after casting. Even though the potential for self-sealing/healing could not be verified in the SAP walls, this could be considered as the most positive result in our campaign, since the addition of the SAPs eliminated the occurrence of the expected cracks.

A very positive effect of the internal curing was also observed in terms of corrosion initiation. No indication of a corrosion potential was observed in several locations of the SAP wall, while it was the case for the reference wall in regions nearby some cracks only 6 months after the casting. Although there is no reported direct effect of the SAPs in the corrosion itself, the prevention of cracks due to internal curing promoted by the SAPs can be described as the main factor behind the difference in both walls in terms of corrosion potential, thus highlighting the positive aspects of using SAPs also in the prevention of corrosion.

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