Impact of Super Absorbent Polymers on Early Age Behavior of High Performance Concrete Walls

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Abstract. The prediction of the early age behavior of cementitious materials is a difficult task, because many of the material properties are very sensitive to curing conditions as it is the case for High Performance Concrete (HPC), which usually has a very low water to cement ratio ($0.2 < w/c \leq 0.3$). Early age cracking, a common problem for HPC, is caused by Autogenous Shrinkage (AS) and self-desiccation during the cement hydration reactions when the deformation is restrained. However, to avoid the crack development initiated by AS, several solutions can be adopted; one example is the addition of a promising material considered as an internal curing agent, the Super Absorbent Polymers (SAP) which limits the capillary depressions that enhance the formation of the crack. In this study the main goal is to mitigate the shrinkage using SAPs in infrastructure under severe conditions. Therefore, a demonstrator wall was built simulating a typical case with high risk of cracking. With the help of fiber optic SOFO sensors embedded in the wall, real-time deformations are recorded and compared with the demountable mechanical strain gauges (DEMEC) measurements to further investigate the behavior of SAPs in real scale infrastructure. The amount of extra water (in SAP) needed to mitigate shrinkage was determined by performing chemical shrinkage tests on different cement paste combinations. Tests of autogenous shrinkage were performed on mortars using corrugated tubes and showed that SAPs reduce to some extent the AS. Under restrained conditions via ring tests, SAP specimens did not crack. Therefore, SAPs were found promising towards mitigating the shrinkage and enhancing the early age behavior of concrete for a better durability.

Keywords: Super Absorbent Polymers (SAP), Autogenous Shrinkage, Early-Age Cracking, High-Performance Concrete (HPC).

1 Introduction

Early-age behavior prediction of cementitious materials is not an easy task, because many properties of the material are sensitive to curing conditions, as it is the case for High Performance Concrete (HPC), which has a low water to cement ratio ($0.2 < w/c \leq 0.35$), small aggregate size and supplementary cementitious materials (silica fume, fly ash...) with admixtures [1,2]. Due to their exceptional mechanical properties and durability, HPCs are highly demanded these days especially for structures placed under severe conditions. Early-age cracking is their challenge, since high performance concrete goes through a lot of autogenous shrinkage which develops fast within the first days of age due to cement hydration reactions. Because of the low water to cement ratio, there's an insufficient amount of water for maximum hydration with low water to cement ratios but these ratios are kept low to enhance the durability by reducing porosity [3]. The lack of enough water for a full hydration and the reduced porosity in the concrete matrix result in a drastic decrease of the relative humidity (RH) in the pore structure, and an increase of the pressure within the pore structure which in turn causes the appearance of autogenous shrinkage [4,5]. The tensile stresses inside pores arising from high autogenous shrinkage at early age cause macroscopic cracks due to the low tensile strength of the matrix at that age, especially in restrained conditions [6,7]. The formation of cracks in these structures threatens their service life span and their functionality since numerous chemical agents can penetrate through these cracks, along with water and gases that induce carbonation, steel corrosion, chloride intrusion, frost and chemical attacks. Thus, it is very important to follow the evolution of AS deformations in order to effectively limit the early-age cracking risk. In order to enhance the life span of the reinforced infrastructures, early age properties must be studied. In order to reduce or mitigate the shrinkage an internal curing agent must be added. The idea behind this method is the release of water in the concrete matrix during hydration when the RH decreases and initiates self-desiccation. Considered as an effective method, internal curing mitigates self-desiccation of HPCs by maintaining high RH [8-10]. Super Absorbent Polymers (SAPs) are the agents commonly used for providing internal curing [11]. SAPs are introduced as dry materials in the mix, when mixed with water, these polymers take up water from the mix and swell. In this way, an internal reservoir is created by the curing agent inside the concrete mix, that will further release its absorbed water gradually during matrix hardening to maintain high RH and continue the hydration process [11,12]. Thus, to decide on the design for a reference HPC wall without SAP an early age crack assessment was done which would show early age cracking. This wall would then be compared to a SAP wall in order to see the effect of SAPs towards mitigate shrinkage cracks, thus different shrinkage tests were performed on concrete. In addition, to measure the real time deformation behavior of walls, fiber optic (SOFO) sensors were embedded inside the walls to record AS over a period of 4 months to monitor full shrinkage of the walls. Results obtained were then compared with demountable mechanical strain gauges DEMEC using points that were glued on the wall after demolding at the same position of SOFOs and recorded manually. Restrained shrinkage tests were also performed on the mix using the ring method, to further study the behavior of SAPs towards mitigating shrinkage under restrained condition since the walls are restrained at the bottom (attached to a slab). Chemical shrinkage tests were used in order to calculate the amount of SAPs and extra water needed to be added to the mix.

2 Materials and Methods

2.1 Super Absorbent Polymers

Commercial SAPs based on poly (acrylamide-co-acrylic acid) were used in the restrained and autogenous shrinkage tests for the wall. These SAPs have an average dry particle size of 100 μm and an absorption capacity in cement slurry equal to 27g per g of SAP.

2.2 Parameter determination for simulation of the HPC wall

A set of parameters is needed in order to simulate the strains in an HPC wall (cast on a non-deforming slab). These parameters result from specific experiments performed on the examined concrete mix which can be found in Table 1. The parameters are the following according to the developed procedure by Klausen [13]: hydration heat development (measured), autogenous shrinkage (measured), compressive and uniaxial tensile strength development (measured), coefficient of thermal expansion – CTE (measured), creep (measured) and activation energy (assumed based on experience).

In addition, one test was performed in the Temperature-Stress Testing Machine (TSTM at NTNU, Trondheim, Norway) (Fig. 1), simulating the heat of hydration in a 50 mm thick wall (under realistic condition for temperature). It is built to measure the stress generation of a sealed concrete specimen during the phase of hardening under a chosen degree of restraint (R = 30%).

It was decided to build a wall of 2 m x 1.5 m x 0.05 m on a mature slab based on the simulation results (Fig. 2). A fast temperature rise was predicted followed by a fast temperature drop after peak temperature, and an even faster drop after removal of the formwork at 18 h of age. After about 20 h a stress/strength ratio >1 would be reached.

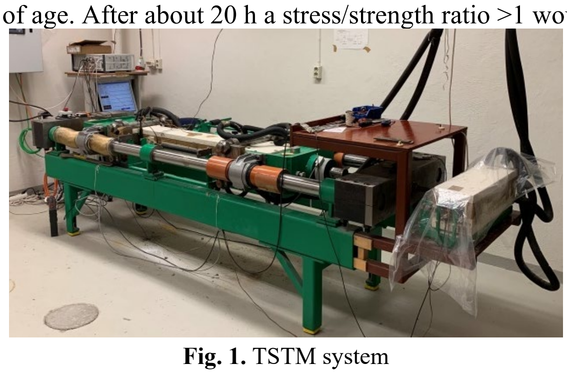


Fig. 1. TSTM system

Table 1. Mix design of HPC concrete walls

Materials	REF (kg/m³)	SAP (kg/m³)
Cement CEM III/A 52.5 R - Dyckerhoff Variodur 40	778	778

Silica fume - Elkem Microsilica D940	154	154
Free water	186	186
Filler - Betofill VK50	185	185
Sand - Årdal taksteinsand (0-4mm)	402	402
Aggregates - Steinskogen Basalt (4-8mm)	649	649
Superplasticizer - SIKA UHPC 2	8.6*	9.33**
SAP	-	2.33***
Extra water for SAP	-	63

* 1.1m% by weight of CEM III/A 52.5 R for REF
** 1.1m% by weight of CEM III/A 52.5 R + 0.1m% extra for BASF
*** 0.3m% SAPs by weight of CEM III/A 52.5 R

Fig. 2. Reference wall (left), SAP wall (right)

2.3 Chemical Shrinkage

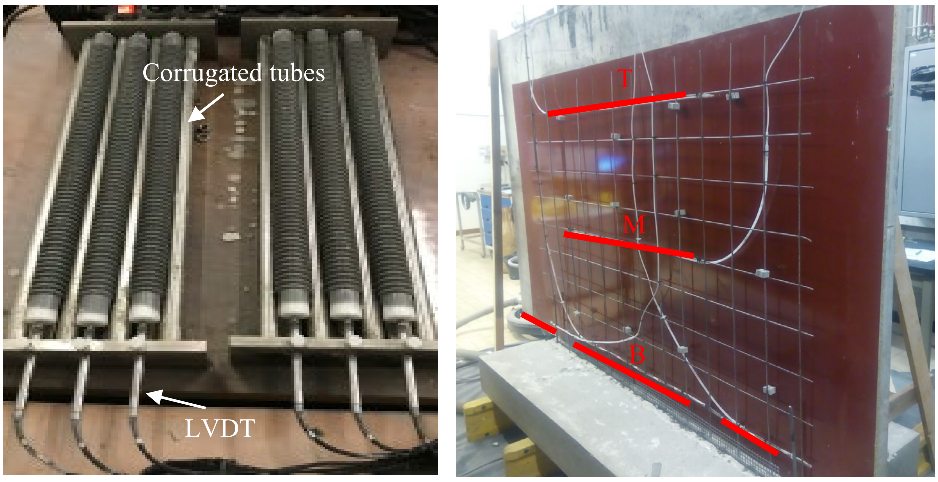
According to ASTM C1608, chemical shrinkage tests were performed on pastes to choose the amount and the extra water needed for SAPs to mitigate shrinkage. After setting, chemical shrinkage is measured while water is being sucked into the sample refilling the emptied pores. Tests are followed for 28 days to ensure that pastes have undergone enough hydration. Measurements are undertaken on saturated specimens with limited sample size (thickness less than 3 mm) to avoid the emptying of water filled pores inaccessible by the top water added gently on top of the paste.

2.4 Autogenous shrinkage

HPC concrete specimens were performed according to the standard ASTM C1698. Concrete is poured in sealed corrugated tubes that are placed over supports provided with spring-loaded LVDTs (linear variable differential transformers) at each end for measuring length changes, under isothermal conditions (see Fig. 3-a). These LVDTs have a measuring range of 5 mm and an accuracy of 2.5 µm. Measurements (the change in length) were recorded every ten minutes for 20 days. The setup was placed in a climate controlled room where the temperature is 20ºC ± 2ºC and relative humidity is 60% ± 5%. Mass of the tubes were recorded at the beginning and end of the test to make sure there was no evaporation or absorption during the test.

To monitor the real time deformations in the concrete structures, AS measurements were recorded through fiber optic SOFO sensors embedded inside the HPC walls for a period of 120 days. Five SOFOs were installed in the cast wall: 3 long sensors of a 1 m length for the top (T) at 130 cm above the connection with the plate, the middle (M) at 70.5 cm and the bottom (B) at 13 cm and 2 short ones with a length of 25 cm for the bottom edges as seen in Fig. 3-b).

Deformations on the outside of the wall were manually measured by demountable strain gauges. DEMEC points were glued on the walls at the same positions of the SOFO sensors and recorded daily for 20 days. Measurements were recorded to 120 days at irregular intervals.



(a) (b)

Fig. 3. (a) Representation of ASTM C 1698 setup and (b) Position of fiber optic SOFO sensors embedded inside the HPC walls

2.5 Restrained Shrinkage

The standard method ASTM C1581-04 known as the ring test was performed on concrete specimens. Fresh mixed concrete is poured around a steel ring equipped with strain gauges that measure its deformation. For the reference and the SAP mixes one ring was cast and kept in a climate controlled where temperature is 20ºC ± 2ºC and relative humidity is 60% ± 5%. After 24h, the shrinkage in outer steel ring was removed and the specimen was covered with plastic foil to avoid drying shrinkage in order to only observe the effect of SAPs against autogenous restrained condition.

3 Results and Discussion

The amount of extra curing water (divided by the total mass of binder) that should be used in the mix for the SAPs to mitigate shrinkage was determined based on the chemical shrinkage tests performed on different binder paste compositions and is equal to w/b_sap = 0.078. In order to determine the amount of SAPs needed, an amount of 0.3% over the cement mass was considered based on the water absorption of SAP in cement slurry and RILEM recommendation [14].

3.1 Autogenous shrinkage

A representation for the autogenous shrinkage results measured using corrugated tubes can be found in Fig. 4. The starting point for theses curves i.e. t_0 is equal to the final setting time recorded from penetrometer tests performed on concrete. For reference mixture t_0=5.5h of age and for SAP t_0=9h. Three tubes were measured for each mixture, the reference curves (curves lying in the negative range) show a shrinkage in the range of 500 to 600 µm/m, which means that the reference mixture undergoes a lot of autogenous shrinkage. Whereas curves of the SAP mixture lie in the positive range indicating a slight expansion counteracting the shrinkage behavior. These results show

The effectiveness of SAPs towards reducing autogenous shrinkage.

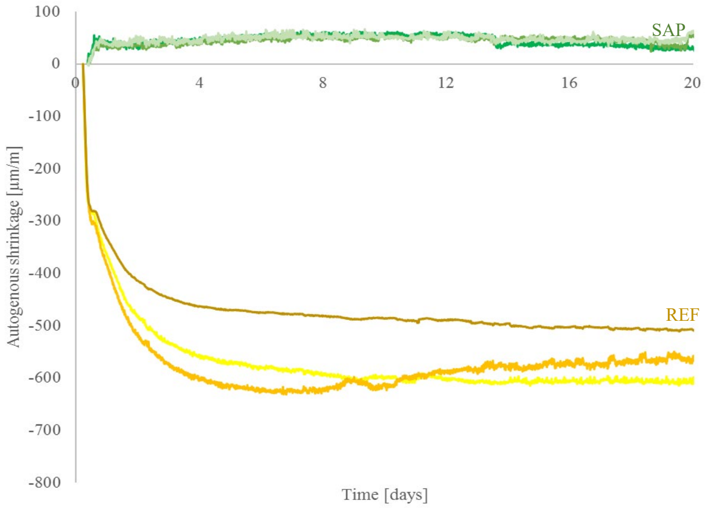


Fig. 4. Representation of autogenous shrinkage results for reference concrete mixture (negative curves) and SAP mixture (positive curves)

3.2 Restrained shrinkage

For the restrained shrinkage in the ring test, a sudden peak in the results is an indication of a crack. The reference concrete cracked at the age of 2 days, while no cracks were recorded for the SAP specimens that were followed for 20 days in the ring tests as seen in Fig. 5. The curves represent the results taken from the sensors recording the steel ring deformations. There were three sensors for each ring and one ring for each mix. For the reference curves, only two were shown because one sensor was not working properly. The values obtained shows the effectiveness of SAP towards reducing shrinkage under restrained conditions as it is the case of the walls that are restrained at the bottom since they are connected to a slab.

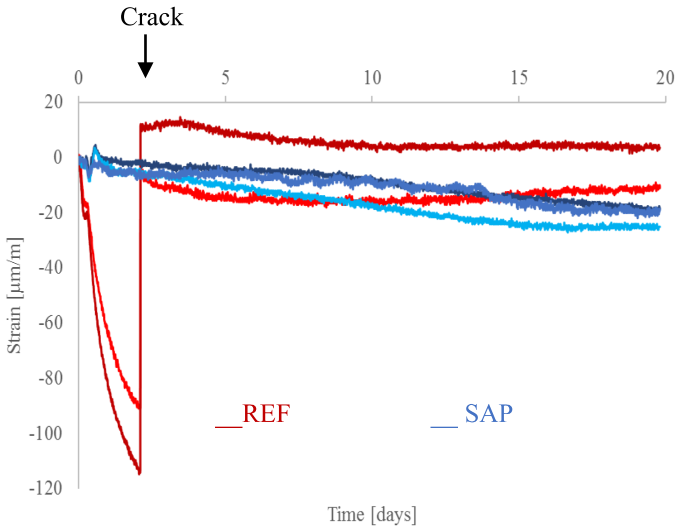


Fig. 5. Result of restrained shrinkage using ring test method for the reference (REF) and SAP concrete mixtures for 20 days

3.3 Deformations in a restrained HPC wall

Real time deformation results recorded from fiber optic sensors embedded inside the walls are represented in Fig. 6. Measurements were plotted from the final setting time of the mixtures recorded by penetrometer tests and equal to 5.5 h of age for the reference concrete and 9 hours for SAP mix. Over the period of 120 days, shrinkage strain increases in time, for the reference wall shrinkage is way higher than SAP wall shrinkage. The order of the shrinkage, even though it is not so relevant for the SAP wall, is the same for both walls in such a way that he top shrinks more than the middle that shrinks more than the bottom part. An expected result since the walls are restrained at the bottom and therefore cannot freely shrink unlike the top part.

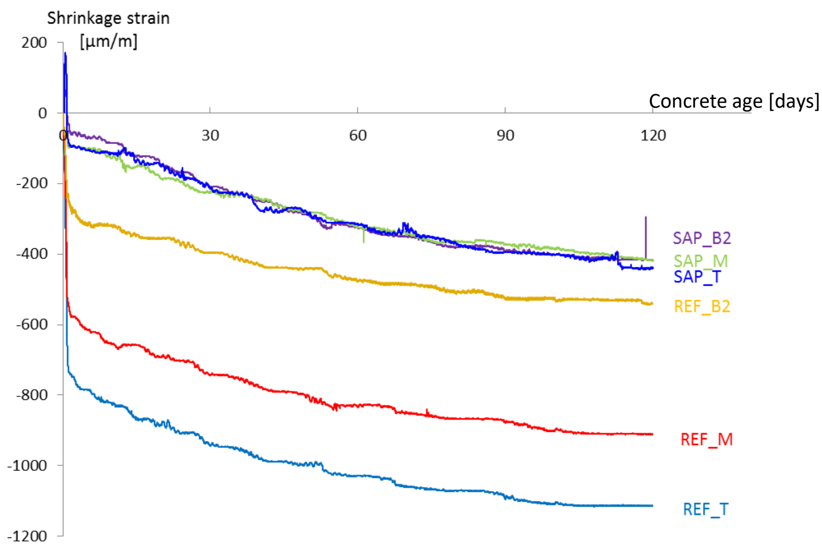


Fig. 6. Representation of autogenous results recorded from fiber optic SOFO sensors embedded inside the walls with t_0=5.5h of age for reference mixture (REF) and t_0=9h for SAP mixture (SAP) at different positions: top (T), middle (M) and bottom (B2).

Shrinkage curves obtained from DEMEC measurements were also in accordance with the results found from SOFO sensors. The curves overlap for the first 30 days and then continue with the same behavior for the whole measurement period at each position: bottom (a), middle (b) and top (c) for the reference wall. Same behavior was also seen for the SAP wall. DEMEC measurements for the SAP wall show lower values that coincide with the SOFO ones and therefore prove that SAPs reduce the autogenous shrinkage.

4 Conclusion

The behaviour of SAPs towards mitigating shrinkage in large scale wall specimens was investigated in this study, and the conclusions can be summarized as follows.

Autogenous shrinkage results for the SAP mix showed how the addition of these polymers in concrete reduces the AS over the testing period of 4 months. This type of shrinkage was investigated using corrugated tubes.

Two HPC walls were cast: a REF and one with SAP, cracks were shown on the reference wall at early age after 20 hours. The biggest crack runs up to half of the height of the wall and is 180 µm wide at the bottom. On the other hand, no cracks occurred for the SAP wall. Real-time deformations were recorded using fibre optic SOFO sensors embedded in the walls which were also compared to measurements taken from mechanical strain gauges that were placed on the wall. The early release of water from the SAPs into the mix reduces the shrinkage over the whole service life of a structure. Restrained shrinkage was also performed on concrete using ring tests to further understand the behaviour of SAP toward restrained conditions. This measurement was essential for the walls, because they were restrained at the bottom, it reflects the behaviour of real structures constructed with HPC. The specimens for the reference mixtures cracked after only 2 days, whereas SAP specimens didn't crack.

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