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

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Abstract

Early age cracking, a common problem for Ultra-High Performance Concrete (UHPC), is caused by Autogenous Shrinkage (AS) and self-desiccation arising from the chemical shrinkage 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 can 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 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: Autogenous Shrinkage, Super Absorbent Polymers (SAP), Early-Age cracking, Ultra-High Performance Concrete (UHPC)

1. Introduction

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 UHPC, which usually have a very low water to cement ratio ($0.2 < w/c < 0.3$) [1][2]. Due to the excellent mechanical properties and exceptional durability UHPC is a highly demanded type of concrete nowadays. The challenge is the risk of early age cracking, since UHPC has a significant autogenous shrinkage which develops fast, typically within the first days of age. The functionality and durability of these structures is compromised by the formation of the cracks. It is very important to correctly estimate the evolution of AS deformations in order to limit the cracking risk [3]. Early age properties must be investigated in order to enhance the lifetime of these reinforced concrete infrastructures operating under severe conditions. Therefore, an early age crack assessment was done to decide on the design for a reference UHPC wall without SAP which would show early age cracking. This will then be compared to a wall containing SAP in order to mitigate shrinkage cracking.

2. Materials and Methods

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 40 μm and an absorption capacity in cement slurry equal to 27g/g of SAP.

2.1 Parameter determination for simulation of the UHPC wall

To simulate the strains in an UHPC wall, cast on a non-deforming slab, a set of parameters is needed, resulting from specific experiments on the investigated concrete, of which the mix design can be found in Table 1. According to a procedure developed by Klausen [4], the parameters are the following:

- Hydration heat development (measured)
- Activation energy (assumed based on experience)
- Compressive and uniaxial tensile strength development (measured)
- Coefficient of thermal expansion - CTE (measured)
- Creep (measured)
- Autogenous shrinkage - AS (measured)

In addition, one test was performed in the Temperature-Stress Testing Machine (TSTM) system, see Figure 1, and two tests were performed in the Free Deformation (FD) system. The test in the TSTM was performed under realistic temperature curing conditions i.e. simulating the heat of hydration in a 50 mm thick wall, whereas the tests in the FD system were performed under 20 °C isothermal curing conditions. Material models and corresponding model parameters describing the property development over time for the given concrete were deduced based on the above described tests.
The TSTM System used (NTNU, Trondheim, Norway) consists of a dilation rig and a TSTM. Both rigs are connected to a temperature-control system, which can provide an accurate control of the concrete temperature during testing. The dilation rig measures the free deformation, i.e. thermal dilation (TD) and autogenous deformation (AD), of a sealed concrete specimen. The TSTM is constructed to measure the stress generation of a sealed concrete specimen during the hardening phase under a chosen degree of restraint (R). For the current test, the degree of restraint was set to R = 30%.
During the test in the TSTM, a set of comprehensive stress-strain relations over time is obtained. These stress-strain relations provide an incremental E-modulus development (i.e. obtained from incremental loading) over time for the concrete in question. Results from the TSTM tests are also used to determine the start time for stress calculations, t_0 (here 8 h), and the coefficient of thermal expansion (CTE). The FD system measures autogenous shrinkage under 20 °C isothermal curing conditions on sealed prisms with dimensions 100x100x500mm.

Table 1: Mix design of concrete walls.

Materials	**REF** (kg/m³)	**SAP** (kg/m³)
Cement III/A 52.5 R	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

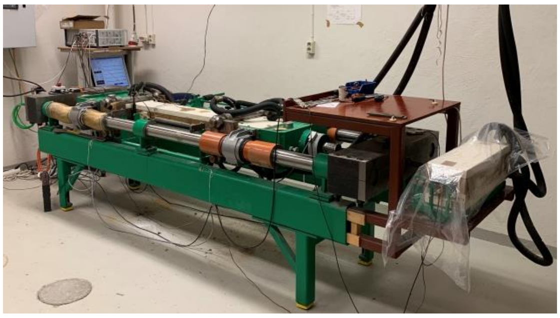

Figure 1: The TSTM system.

Based on the results and simulations, it was decided to build a wall of 2 m x 1.5 m x 0.05 m on a mature slab. A fast temperature rise was predicted from approximately 10 hours, followed by a fast temperature drop after the peak temperature and an even faster drop after removal of the formwork at 18 h of age. A stress/strength ratio > 1 would be reached after about 20 h.

2.2 Restrained Shrinkage

A restrained shrinkage test was performed using two methods: the standard ASTM C1581 method and the ring test developed at Ecole Centrale de Nantes (ECN) [5]. Concrete is cast around a steel ring equipped with strain gauges that measure the deformations of the concrete. In the ECN apparatus, a 20 mm notch is placed in the concrete to locate and accelerate cracking.

2.3 Chemical Shrinkage

In order to choose the best amount of extra water to entrain in the SAPs to mitigate shrinkage, a chemical shrinkage test was used according to ASTM C1608. After setting, chemical shrinkage can be measured while water is being sucked into the sample refilling the emptied pores. Therefore, measurement of chemical shrinkage is undertaken on a saturated sample with limited sample size to avoid the emptying of water filled pores inaccessible by the above water.

2.4 Autogenous Shrinkage

The following tests were performed for mortar and concrete UHPC specimens according to the standard ASTM C1698. Mortar specimens have the same composition as for the concrete ones. The linear autogenous deformations are measured as a function of time beginning at the time of final set determined by Vicat tests. The material is poured in a sealed corrugated tube that is placed over supports provided with spring-loaded linear variable differential transformers (LVDT) at each end for measuring length changes, see Figure 3. Isothermal conditions during the test should be maintained. Measurements for

both concrete and mortar specimens were performed for at least 2 weeks. It should be noted that mass should be recorded at the beginning and the end of test to make sure there was no evaporation or absorption during the test.
For the UHPC wall, AS measurements are recorded with the help of SOFO sensors that consist of an optical fiber system that can be embedded in the concrete structure and monitor the real time deformations. Five SOFOs were installed in the casted wall: 3 long sensors (1 m) for the top, the middle and the bottom and 2 short ones (25 cm) for the bottom edges as seen in Figure 2).

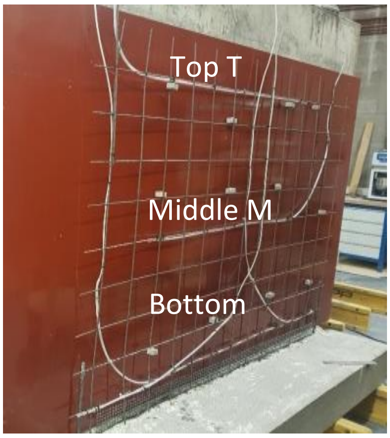

Figure 2: SOFO sensor positions in the concrete wall.

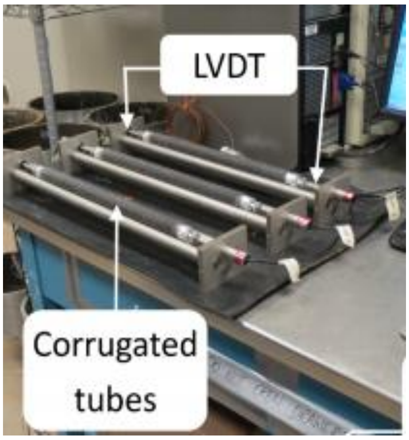

Figure 3: ASTM C1698 corrugated tube apparatus for AS measurements.

3. Results and discussions
Based on the chemical shrinkage tests performed on different binder compositions, the amount of internal curing water (divided by the total mass of binder) that should be used in the mix for the SAPs to mitigate shrinkage is w/b_{SAP}= 0.078; this value was taken from sample containing only the Variodur 40 cement as binder. RILEM [6] recommended an equation based on the chemical shrinkage measurements, in order to determine the amount of SAPs needed, thus an amount of 0.289% over the cement mass was considered for AS mortar measurements. Other mortar specimens with an amount of SAPs equal to 0.3% over the cement mass were also used, this value was chosen in order to have equal workability tests (slump/flow) with a reference specimen having a w/c = 0.3; in this case the w/b_{SAP} is equal to 0.067. Figure 4 represents the shrinkage behavior of mortar specimens containing SAP (0.3% over the cement mass) and the reference ones taken from the knee point. The deformations in the figure indicate that no shrinkage is developing in the early age for SAP specimens, thus the polymers played their role and proved that they mitigate autogenous shrinkage. The measurements on concrete specimens are still ongoing.
For the restrained shrinkage, the reference concrete cracked at 1 day when following the ASTM method and at around 4 days for the method developed at ECN as shown in Figure 5, while no cracks were recorded for the SAP specimens that were followed for 28 days in the ring tests (ASTM C1581).
In Figure 6, the real time deformations of the cast reference wall are shown. These values were zeroed at the final setting time determined by penetrometer tests. It can be seen that the top of the wall shrinks the most, followed by the middle and then the bottom which shrinks less due to the restrained condition imposed. Cracks were seen at around 1 day of age, directly after demolding, (corresponding to the expectations from modelling), whereas for the SAP wall no cracks were yet seen.

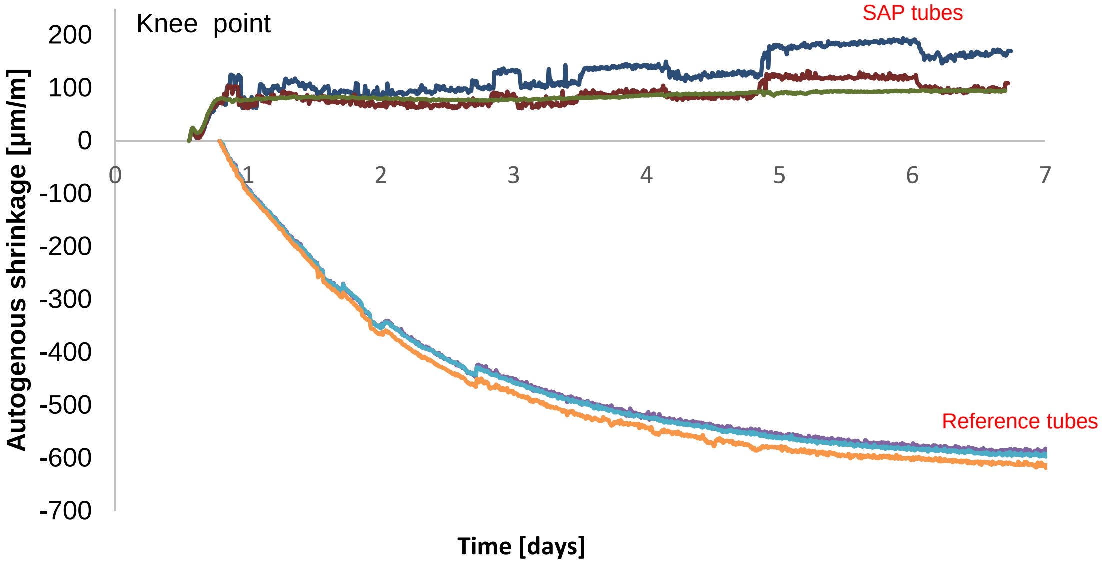

Figure 4: AS results for mortar specimens.

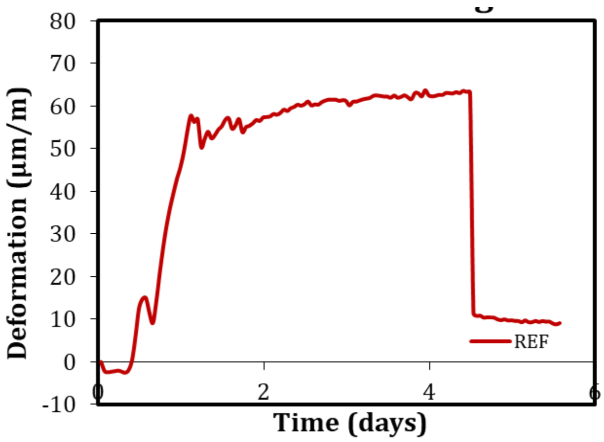

Figure 5: Restrained shrinkage for reference concrete using ring test developed at ECN.

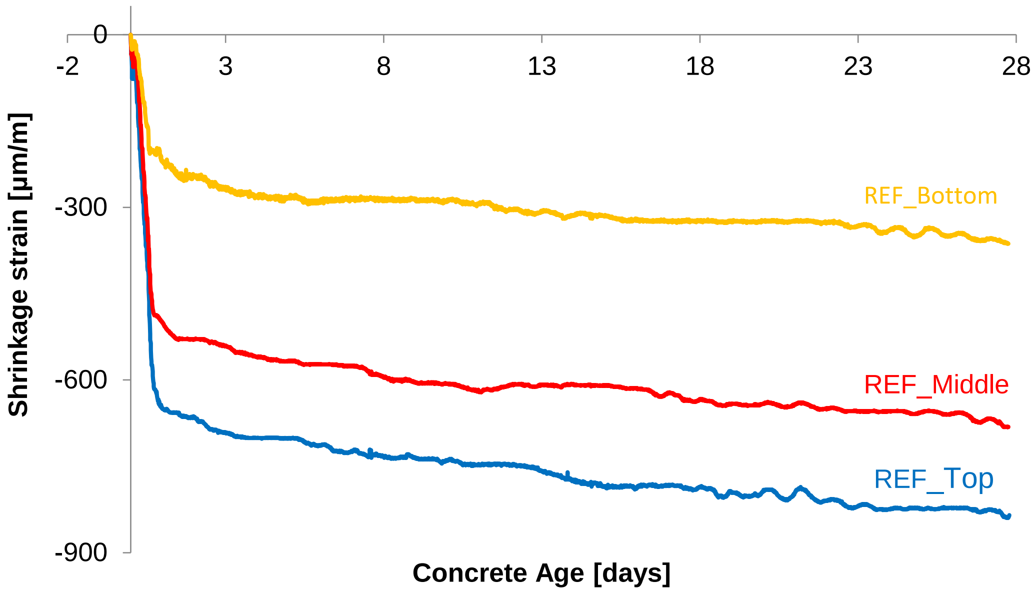

Figure 6: Autogenous shrinkage result from SOFO sensors in the wall.

4. Conclusion

As a conclusion, it was clearly seen that Super Absorbent Polymers are a promising material towards mitigating the shrinkage, hence enhancing the durability and service life of the UHPC infrastructure.

These statements were concluded from the measured results obtained from an early age crack assessment, shrinkage tests on mortar and concrete and on real time deformations in an UHPC wall with the help of SOFO sensors. More interesting results will follow on this subject with the update on the shrinkage of the SAP wall and the AS measurements on the concrete tubes.

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References

[1] D. P. Bentz, O. M. Jensen, K. K. Hansen, J. F. Olesen, H. Stang, and C. Haecker, "Influence of Cement Particle-Size Distribution on Early Age Autogenous Strains and Stresses in Cement-Based Materials," vol. 35, no. 188803, pp. 129–135, 2001.

[2] V. Baroghel Bouny and P. Mounanga, "Autogenous Deformations of Cement Pastes: Part II. W/C Effects, Micro–Macro Correlations, and Threshold Values," 2006.

[3] A. Darquennes, S. Staquet, and B. Espion, "Determination of time-zero and its effect on autogenous deformation evolution," no. December 2014, pp. 37–41, 2011.

[4] A. B. E. Klausen, "Early age crack assessment of concrete structures Experimental investigation of decisive.," 2016.

[5] R. JAAFRI, "Impact du liant sur le comportement structurel des matériaux cimentaires fluides : Mécanismes et modélisation," Ecole Centrale de Nantes, 2018.

[6] M. Wyrzykowski, V. Mechterine, P. Lura, and S.-I. Igarashi, "Recommendation of RILEM TC 260-RSC : using superabsorbent polymers (SAP) to mitigate autogenous shrinkage," in *Materials and Structures*, vol. 51, no. 5, Springer Netherlands, 2018, pp. 1–7.