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The Effect of Superabsorbent Polymers on the Mitigation of Plastic Shrinkage Cracking of Conventional Concrete, Results of an Inter-laboratory Test by RILEM TC 260-RSC

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Abstract

This article presents the results of an inter-laboratory study performed by six international research groups in the framework of RILEM Technical Committee 260 RSC "Recommendations for use of superabsorbent polymers in concrete construction". Two commercially available superabsorbent polymer (SAP) samples with different chemical compositions were tested in terms of their ability to mitigate plastic shrinkage cracking of concrete. The SAP mixtures showed a clear reduction of plastic shrinkage cracking in conventional concrete. On the contrary, if only additional water is added and no SAP, the area of plastic shrinkage cracks increases. This suggest the ability of SAP to mitigate plastic shrinkage cracking. Upon addition of the predetermined amount of SAP and additional water, the compressive strength decreased on average by 3% for the mixtures with 0.15% SAP (by mass of cement) and by 10% for the mixtures with 0.30% SAP.

Keywords

Plastic shrinkage, inter-laboratory test, superabsorbent polymer, hydrogel

The study reported in this paper was performed within the framework of the RILEM TC 260 RSC "Recommendations for Use of Superabsorbent Polymers in Concrete Construction".The paper was reviewed and approved by all members of the RILEM TC 260-RSC.

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1. Introduction

Superabsorbent polymers (SAP) are relatively new concrete admixtures with many advantages (Mechtcherine and Reinhardt 2012; Mechtcherine 2016). The main reason why SAP were first investigated is their ability to reduce autogenous shrinkage of cement-based building materials (Jensen and Hansen 2001; Jensen and Hansen 2002; Mechtcherine et al. 2014). The reduction of autogenous shrinkage lowers the risk of cracking if the member is restrained (internally or externally). Hence, the application of SAP is especially beneficial in cementitious systems with low water-to-binder ratios (w/b), such as high to ultra-high strength concrete (Dudziak and Mechtcherine 2010; Justs et al. 2015). As the SAP cause the formation of macro pores, these pores are also beneficial in terms of freeze-thaw mitigation, as was studied in a previous inter-laboratory study of RILEM TC 260-RSC (Mechtcherine et al. 2017). Other applications include rheology modification (Mechtcherine et al. 2015), self-sealing (Lee et al. 2010) and self-healing (Snoeck 2018; Snoeck et al. 2014).

SAP have the ability to absorb aqueous solutions (in the particular case of concrete, pore solution) and then release these solutions when pores empty and the internal relative humidity in the cementitious system drops, in a process called internal curing. Many SAP are available on the market in different shapes, with different polymeric compositions and different absorption capacities, and only a limited few are suitable for concrete. The SAP have to be able to absorb and retain water in a highly alkaline environment in the presence of calcium ions (Zhu et al. 2015; Schröfl et al. 2014, Zhong et al. 2019) and should not disintegrate during concrete mixing. SAP are normally added to the dry constituents. Usually, additional water is added to the concrete mixture to supply the SAP with water to be absorbed (Mechtcherine et al. 2019; Snoeck et al. 2018b; Wyrzykowski et al. 2018). If the water amount to be absorbed by the SAP during mixing is not accounted for in the mix design, the workability is substantially reduced, which can be compensated by increasing dosage of superplasticizer. Internal curing by means of SAP has been shown in numerous studies as an effective method against autogenous shrinkage. On the other hand, no systematic study regarding the effect of SAP on plastic shrinkage cracking has been reported so far. This paper addresses this issue.

Plastic shrinkage cracking is a phenomenon that occurs in the fresh state of concrete, normally within a few hours after the concrete has been placed and finished (Boghossian and Wegner 2008). The mechanism can be summarized as follows: Bleeding of the concrete water starts directly after the concrete is cast, which goes hand in hand with the consolidation/settlement of the concrete. This bleed water is vital for the protection of the fresh concrete as once the total evaporation exceeds the bleed water, the rapid drying of the concrete starts which causes high capillary pressures in the cementitious material whose stiffness increases rapidly at the same time (both due to hydration of cement and capillary pressure stiffening). This in turn leads to the build-up of self-induced stresses, which consequently cause cracking (Slowik et al. 2008; Wittmann 1976; Combrinck and Boshoff 2013; Ghourchian et al. 2018; Ghourchian et al. 2019). If sufficient bleeding water is available, the cracking can be reduced. However, if the evaporation rate is severe (typically more than 1 $kg/m^2/h$), bleeding is not sufficient and different means of preventing cracking are required (American Concrete Institute 2007; Ghourchian et al. 2017; Ghourchian et al. 2018).

The most common way to mitigate plastic shrinkage cracking is by reducing the evaporation locally at the surface of the concrete. These methods include covering the concrete with plastic sheets, adding windbreaks and sun protection, applying curing agents, and, lastly, using a fog spray over the surface of the concrete. The application of such methods is however often omitted in practice due to high workload and costs. Another popular way to mitigate plastic shrinkage is to reduce the cracking by an internal approach (so-called passive methods), namely adding micro polypropylene fibres (Banthia and Gupta 2006; Soroushian et al. 1993), natural fibres (Boghossian and Wegner 2008), shrinkage reducing agents (Leemann et al. 2014; Ghourchian et al. 2018; Lura et al. 2007).

Internal curing by means of pre-wetted lightweight aggregates has been shown to be effective in reducing plastic shrinkage cracking (Henkensiefken et al. 2010). Wyrzykowski et al. (2015) showed with neutron tomography that the lightweight aggregates were able to release internal curing water already in the plastic stage. Some results have been also published about internal curing by SAP. As the SAP possess the ability to induce internal curing, this feature can be used to mitigate plastic shrinkage as well. When spherical SAP with size of 150 µm in an amount of 0.6 % by mass of cement were added to cement pastes with a basic water-to-cement (w/c) ratio of 0.265 along with additional water corresponding to an additional w/c of 0.087, the capillary pressures and plastic deformations were reduced while the settlement deformations increased (Dudziak and Mechtcherine 2010). Serpukhov and Mechtcherine (2015) showed that the addition of SAP to both ordinary concrete and strain-hardening cement-based composite (SHCC) clearly reduced the capillary pressure within fresh materials under hot climate conditions as well as plastic shrinkage and cracking propensity.

In a recent study, Nuclear Magnetic Resonance was used to study the water release kinetics with SAP when plastic shrinkage conditions (i.e. rapid evaporation when the concrete was still plastic) were imposed (Snoeck et al. 2018a). The SAPs were able to reduce plastic settlement and plastic shrinkage but were not able to eliminate it (Snoeck et al. 2018a). The water release kinetics by the SAP were a key parameter when investigating plastic shrinkage. Besides, an investigation of the sorption kinetics of two distinct SAP samples by neutron radiography imaging of fresh, uncovered cement pastes disclosed a pronounced decrease of the cracking propensity. It was shown that the inherently desorbing SAP was slightly less efficient than the retentive SAP, which only desorbs its intaken liquid upon demand, i.e. upon severe drying or water consumption by the accelerating phase of cement hydration (Schröfl et al. 2019).

Some publications thus point to the possibility of using SAP to mitigate plastic shrinkage cracking. In this paper, the use of SAP in conventional concrete to mitigate plastic shrinkage is examined within a RILEM inter-laboratory test programme in which six laboratories participated. This paper presents the results of the test programme and makes inferences on the use of SAP for the mitigation of plastic shrinkage cracking in conventional concrete. The inter-laboratory test programme was commissioned by Working Group 2 of the RILEM Technical Committee 260-RSC, titled "Recommendations for Use of Super-absorbent Polymers in Concrete Construction". The participants from six countries and three continents are shown in Table 1. Initially, the effect of two different dosages of SAP compared to the control mix was tested and constituted Set 1 of the tests. At a later stage, second set of tests was carried out, where the effect of additional water (without any SAP) was studied. Because the second set of tests was carried out at a later stage, and a possible variation of the materials could have taken place, that set also consisted of the repeated control mix and the mix with the same amount of additional water and SAP. The scheme of the tests done in different sets is presented in Table 2. It should be noted that for Laboratory 6, all the tests of Set 1 and additional test of the control mix with extra water were done in one set of experiments on the same batch of materials in a short time window (about 1 month).

Table 1. List of participating laboratories

Laboratory Number	Institution	Country
1	Laboratório Nacional de Engenharia Civil	Portugal
2	National Research Council Canada	Canada
3	Stellenbosch University	South Africa
4	Technische Universität Dresden	Germany
5	University of Ghent	Belgium
6	Empa	Switzerland

Table 2. The test programme

	SAP (by mass of cement)	Set 1	Set 2
Control	0%	X	X
SAP 1	0.15%	X	
SAP 1	0.30%	X	X
Control + Add water 1*	0%		X
SAP 2	0.15%	X	
SAP 2	0.30%	X	X

Control + Add water 2*	0%	X

* Additional water is the same as that determined for the mix with 0.30% SAP

2. Specifications

The inter-laboratory tests were done in two sets, referred to as Set 1 and Set 2 in this paper. Set 1 consisted of five mixtures, namely a control mix, and mixes with 0.15% SAP 1 and SAP 2 and 0.30% SAP 1 and SAP 2 (all percentages of dry SAP are by mass of cement). Set 2 included a control, and mixtures with 0.30% SAP 1 and SAP 2 and an additional mixture that contained the same amount of extra water needed for the SAP mixtures, but with no added SAP. This extra set was aimed at indicating whether the change of plastic cracking behaviour of concrete containing SAP was due to the added SAP, or due to the net effect of additional water.

An important aspect of these SAP mixtures is that the additional water required for the SAP absorption was not determined beforehand by a tea-bag test or similar test (Snoeck et al. 2018b). Instead, the amount of additional water was ascertained by adding water to the SAP concrete mixture until the same slump was obtained as in the control mixture without SAP (Mechtcherine et al. 2019; Wyrzykowski et al. 2018).

The concrete mixture to be used only had a few limited specifications while the SAP were supplied to ensure all mixtures from the different participating laboratories used the same SAP. There were two SAP used, labelled as SAP 1 and SAP 2 in this paper. Slump, setting time, compressive strength, bleeding and plastic shrinkage cracking tests were also specified and are detailed in the following sections after the mixture specifications.

The SAP were distributed from a single source while all other concrete materials were locally sourced.

2.1 Mixture specification

A conventional concrete mixture was to be used with only the following specifications:

- The w/c of the control mix should be 0.5;
- Cement of strength 42.5 should be used and it can be either CEM I, CEM II or CEM III, or equivalent (depending on local availability);

- The maximum aggregate size should be between 13 mm and 16 mm;
- For the SAP mixtures, additional water should be added to the concrete "on top" of the mix design to ensure the same slump as the reference (0% SAP) mixture. This must be recorded and expressed as (g additional water) / (g SAP);
- The SAP must be added at both 0.15% and 0.30% concentrations (by mass of cement) for Set 1 and only 0.30% for Set 2;
- The mixtures with additional water without additional SAP (Set 2) should get the same amount of additional water as determined for the corresponding mixture with 0.30% SAP;
- The target slump should be 120 mm (±15 mm) for all mixtures, except the mixtures of Set 2 with just the additional water. The last mentioned mixture had no target slump (adding additional water without SAP should increase the slump considerably);
- The slump test should be done exactly 10 minutes after the water was added to the dry constituents;
- The mixture should exhibit limited bleeding to ensure plastic shrinkage cracking. The mixture should exhibit no visible segregation.

SAP 1 is a covalently cross-linked poly acrylate while SAP 2 is a covalently cross-linked poly(acrylate-co-acrylamide) with qualitatively intermediate crosslinking density. SAP 1 has higher cross-linking density than SAP 2. Both polymer materials were used "as-delivered" in their original form and size grading. SAP 1 shows self-releasing (non-retentive) behaviour; in free absorption tests it initially absorbs water and later releases most of the water. SAP 2 shows a retentive type of absorption behaviour; the absorbed pore solution is retained by the SAP over a long period. Supposedly, it is only released as a response to an external trigger, e.g. capillary suction when used in cement paste (Schroefl et al. 2015). It is hence expected that mixtures with SAP 1 will show increased bleeding compared to SAP 2. Please note that the denomination of SAP 1 and SAP 2 is the same in the present paper as in Schroefl et al. (2015) and Schröfl et al. (2019).

2.2 Test specification

A number of tests were specified to obtain a comprehensive understanding of the effect of SAP addition on fresh and hardened concrete properties. The tests are: plastic shrinkage cracking, bleeding, setting time, slump test, compressive strength and pore pressure development. The specifications for these tests are explained in the following paragraphs.

Plastic shrinkage cracking tests according to ASTM C1579 were specified. Variations of the mould geometry were allowed, e.g. increasing the restraint to increase the probability of occurrence and the magnitude of cracking. It was preferred that three to four samples be tested per mixture variation to obtain representative information on the crack widths or areas, respectively. The ASTM C1579 prescribes cracks to be measured 24 ± 2 hours after the mixing of the concrete, but another appropriate time and justified by physical reasoning, e.g. at final set, can be used if it is done consistently.

ASTM C232 or a similar method was recommended for the measurement of the bleeding. The setting times were to be tested on sieved concrete samples using the Vicat setup, penetrometer or any other appropriate method. The compressive strengths could be performed according to local standards, on either cylinders or cubes.

3. Actual Test setups

The recommended specifications were mostly followed, with few exceptions. Also, these results are included, but qualified where appropriate. The individual test setups used by each laboratory are presented in the following sections.

3.1 Setting time test setups

Laboratories 1, 2 and 5 all used the penetrometer approach of ASTM C403/C403M for the setting times. The containers used for Laboratory 1 were 150 mm cubic moulds while Laboratory 2 used 250 mm cubic moulds. All three laboratories stored the specimens in the same conditions as for their plastic shrinkage cracking tests.

Laboratory 3 used a Vicat test method for determining the setting time of the concrete. The concrete was first sieved through a 4.75 mm sieve to obtain a mortar and placed in the same environmental conditions as the plastic shrinkage tests.

3.2 Bleeding test setup

Laboratories 1, 2, 3 and 5 all used the bleeding test setup prescribed by ASTM C232/232M. The container dimension for Laboratory 1 is 200 mm in diameter and a height of 270 mm, and for Laboratory 2 the diameter was 255 and a height of 280 mm. Laboratory 3 used containers with the same height as the plastic shrinkage cracking moulds. The containers used by Laboratory 5 were exactly 1 litre in volume and the same height as the plastic shrinkage tests. All moulds were exposed to the same environmental conditions as the plastic shrinkage tests, however using a cover to prevent evaporation. Laboratory 6 measured bleeding according to the standard EN 480-4:2005. The container used had a diameter of 250 mm and a height of 250 mm and it was filled with 12 litres of concrete.

3.3 Plastic shrinkage cracking test setups

A summary of the environmental conditions of the plastic shrinkage cracking environments can be seen in Table 3.

Table 3. The environmental conditions of the plastic shrinkage cracking tests for each laboratory [L#] for each Set [S#]

	L1S1	L1S2	L2S1	L3S1	L3S2	L4S1	L5S1	L5S2	L6S2
Temperature [˚C]	38-42	39	24-32	40	40	30	30-35	30-35	33±0.5
Wind speed [m/s]	6.2	6.2	2.5-2.9	6.25	6.25	5.8	5.5-6.5	5.5-6.5	7.5
Relative humidity [%]	31-34	23.5 - 30.5	37-51	10	10	40	35-45	35-45	35±5
Concrete temperature at start of test [˚C]	19-24	18-19	23	22	22	35	23-24	23-24	19.3-21.4
Evaporation rate [kg/m^2/h]	1.07-1.16	0.85 - 0.98	0.42-0.80	1	1	2	1.03-1.14	1.46-1.82	0.60-0.64

All laboratories ran their plastic shrinkage tests based on the ASTM C1579-13 standard with the following exceptions or modifications. Laboratories 1, 5 and 6 used a walk-in chamber with precisely controlled climate rather than an enclosed environmental chamber. The airflow was created by a fan on the same level as the samples. The rest of the setups were climatic chambers as illustrated in ASTM C1579-13. Two additional 10 mm steel reinforcing bars were inserted in the prescribed mould with risers by Laboratory 3 to increase the restraint, thus increasing the plastic shrinkage cracking.

Laboratories 1 and 2 used a crack comparator to measure the crack at at least ten points over the stress riser in a progressive order from one side of the panel to the other, avoiding measurements within 25 mm of test panel boundaries. The cracks were measured every 10 mm along the length of the crack using a C & D crack-scope with an optical magnification of 40× and a 0.02 mm resolution. Laboratory 3 used high-resolution photos which were scaled in CAD software using a ruler on the samples. The crack width for every 10 mm of crack length was measured and the average reported. Laboratories 4 and 6 used a digital image processing approach where high resolution photos of the cracked surfaces were taken and processed to measure the crack widths. The crack widths were determined by Laboratory 6 at 10-mm intervals (neglecting the zones 25 mm from the edges of the samples) along the cracks formed over the stress risers. The cracks were measured every 20 mm along their length by Laboratory 5 using a crack microscope.

3.4 Capillary pressure test setup

Laboratory 6 measured the evolution of capillary pressure in the concrete. This was measured by tensiometers with ceramic heads (T5-10 by UMS). The tensiometers were placed in fresh concrete through holes in one of the moulds with stress risers at mid-height of the concrete layer. Two tensiometers for each concrete mixture were used.

3.5 Summary of test configurations

Table 4 shows a summary of which sets and tests were done by the different laboratories.

Table 4. Summary of which laboratory performed which sets and tests

	Laboratory					
	1	2	3	4	5	6
Set 1	X	X	X	X	X	X
Set 2	X		X		X	X
Slump	X	X	X	X	X	X
Setting times	X	X	X		X	
Bleeding	X	X	X	X	X	X
Compressive strength	X	X	X	X	X	X
Plastic Shrinkage cracking	X	X	X	X	X	X
Pore pressure						X

4. Test results

The specifications for the mixture design were on purpose not stringent, so relatively large variations were found in the mixture designs of the different laboratories. However, the results were always compared to the control of the specific laboratory, so the normalised results can still be compared between laboratories, increasing the data set to verify the extent of mitigation of plastic shrinkage by the SAP. Not all laboratories took part in both Sets 1 and 2.

4.1 Actual mixture designs

The actual mixture designs of each laboratory are shown in Table 5. The mixing water content of the concretes varied from 142 kg/m^3 to 230 kg/m^3 while the cement content also varied accordingly to ensure a constant water/cement ratio of 0.50. Laboratory 1 used a retarder while Laboratories 4 and 6 used a superplasticiser to control the slump. The mixtures also varied slightly between Set 1 and Set 2 of the participating laboratories. The additional water added to compensate for the absorption of the SAP was not included in the mixture designs shown in Table 5. This amount was determined in order to obtain the same workability as the reference mixture, i.e. the same slump flow value at the time specified for this test. The SAPs and the additional water were added to the concrete on top of the mixture design.

Table 5. The mixtures used by each laboratory [L#] for each Set [S#]. This excludes the SAPs and additional water added for the SAP, which were added "on top", which means extra water was added without being taken into account in the mix design.

[kg/m^3]	**L1S1**	**L1S2**	**L2S1**	**L3S1**	**L3S2**	**L4S1**	**L5S1**	**L5S2**	**L6S1**	**L6S2**
Water	142	178	220	230	223	175	172	172	175	175
Cement	357[1]	346[1]	440[2]	460[3]	445[4]	350[5]	344[6]	344[6]	350[5]	350[5]
W/C	0.4	0.52	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Coarse aggregate	1291	1229	880	1000	1000	903	1352	1352	914.5	914.5
Sand	662	737	660	665	730	922	552	552	915	915
Admixture	3.21[7]	3.11[7]				3[8]			0.7[8]	0.7[8]

[1]CEM I 42.5 R

[2]OPC GU (Type 1)

[3]CEM II 42.5 N B-M (L-S)

[4]CEM III 42.5 N B-M (L-S)

[5]CEM II 42.5 N A-LL

[6]CEM I 42.5 N

[7]Retarder

[8]Superplasticiser

The additional water required for each mixture to ensure the same slump after SAP is added is shown in Table 6. Laboratories 1, 3 and 6 adjusted each mixture to ensure the same slump while Laboratories 4 and 5 used one value for both SAP volumes and types, but still obtained similar slump values. Laboratory 2 did not add any additional water.

It is interesting to note that for both Laboratories 1 and 3, the water required for SAP 1 in the second set was significantly reduced compared to Set 1 while Laboratory 5 required the same additional water for both sets. It is however similar to Set 1 results of other laboratories. This decrease in additional water means the absorption capacity of SAP 1 was reduced during the time from Set 1 to Set 2. Laboratories 5 and 6 stored the SAP in opaque and moisture-sealed containers to prevent preliminary absorption and UV degradation (Mechtcherine et al. 2018). The negligible reduction of Laboratory 5 SAP 1 absorption capacity compared to the other laboratories supports the recommendation to store SAP in the in the absence of light and moisture.

Table 6. The additional water added to the mixtures to compensate for the loss of water due to the SAP absorption. It is indicated as the additional water (g) per mass dry SAP (g) that was added.

[g/g]	**L1S1**	**L1S2**	**L2S1**	**L3S1**	**L3S2**	**L4S1**	**L5S1**	**L5S2**	**L6S1**
SAP 1 0.15%	22.8		0	25			27	27	
SAP 1 0.30%	19.7	6.85	0	22	10	27	27	27	
SAP 2 0.15%	15.2		0	23			27	27	25.63
SAP 2 0.30%	19.2	18.67	0	22	23	27	27	27	35.95

The actual slump values are shown in Table 7. All the laboratories, except Laboratories 2 and 5, were close to the specified 120 ± 15mm. Laboratory 2, who only did Set 1, did not add any additional water to their mixtures with SAP, therefore it is expected that the slump values would decrease, as they did, with an increase of SAP dosage. Note that the Ctrl + Add water 1 and 2 mixtures were supposed to have higher slump as additional water was added to the concrete without any addition of SAP. This is the same amount of water that would have been added if the respective SAP were added at 0.30% by mass of cement.

Table 7. The slump values of each mixture

Slump Values [mm]	L1S1	L1S2	L2S1	L3S1	L3S2	L4S1	L5S1	L5S2	L6S1
Control	105	130	225	120	125	170	130	160	110
SAP 1 0.15%	110		225	120			140	160	
SAP 1 0.30%	110	125	210	120	130	210	150	165	
Ctrl + Add water 1		180			155			215	
SAP 2 0.15%	110		218	120			130	160	110
SAP 2 0.30%	100	120	148	120	120	200	140	160	115
Ctrl + Add water 2		205			190			215	220

4.2 Setting times

The initial and final setting times are shown in Table 8. The long setting times found by Laboratory 1 were due to the retarder added. The effect of SAP on the setting times is shown to be small and no clear trend could be found.

Table 8. The initial and final setting times of the different concrete mixtures (the missing entries were not reported).

Initial / Final [min]	L1S1	L1S2	L2S1	L3S1	L3S2	L5S1	L5S2
Control	825/1280	1100/1180	276/348	145/190	140/180	163/255	226/368
SAP 1 0.15%	1015 / 1145		228/312	140/190		163/255	253/385
SAP 1 0.30%	1075 / 1240	1095/1150	258/336	145/210	160/180	167/265	265/397
Ctrl + Add water 1		1140/1200			140/160		257/396
SAP 2 0.15%	n/a / 1140		258/354	150/210		165/258	252/388
SAP 2 0.30%	n/a / 1340	1280/1360	210/294	130/190	140/180	166/263	262/391
Ctrl + Add water 2		1060/1120			160/180		257/396

4.3 Bleeding

The bleeding results show a significant difference between concrete with and without SAP, although there was quite some variability between the participating laboratories. The bleeding results are shown in Figures 1 and 2 for SAP 1 and SAP 2 respectively. These are expressed as a percentage of the control.

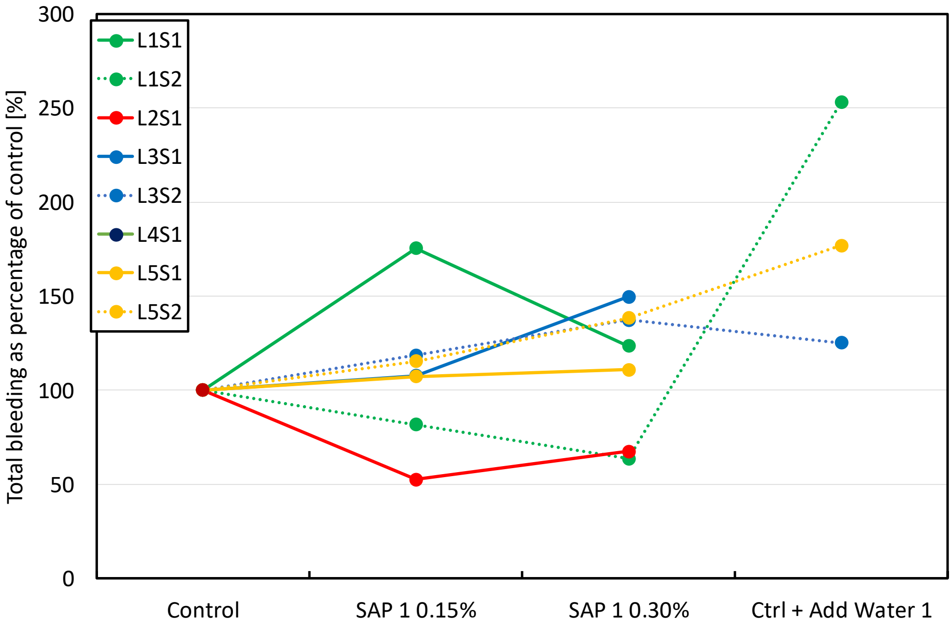

Figure 1. The bleeding for SAP 1 expressed as a percentage of the control.

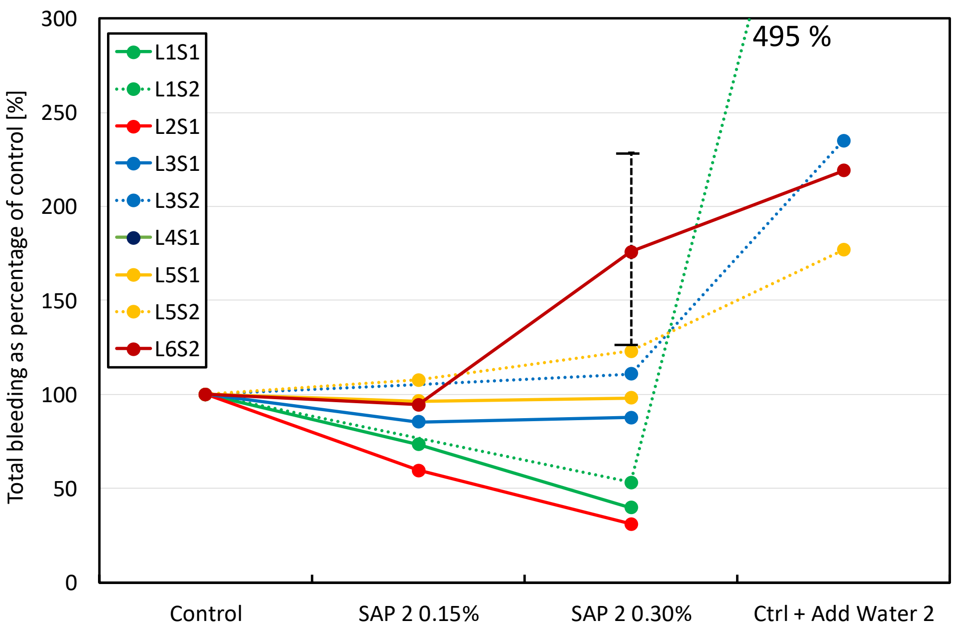

Figure 2. The bleeding for SAP 2 expressed as a percentage of the control. The error bars are showing the minimum and maximum values for a specific test result.

SAP 1 (Figure 1) showed more erratic bleeding results compared to SAP 2 (Figure 2). In most cases, the addition of SAP 1 at increasing dosage increased the bleeding, which is expected due to the inherent sorptivity behaviour of SAP 1, which easily releases the absorbed water again (so-called self-releasing SAP). This resulted in a smaller difference with the mixes including the additional water without the SAP, compared to the case of SAP 2. Note that Laboratory 3 did not show this increase for SAP 1, but rather for SAP 2. This can be ascribed to the reduced additional water required for SAP 1 in Set 2 to ensure the same slump.

The bleeding results of SAP 2 (Figure 2) looks fairly consistent between the laboratories. There is a gradual decrease of the amount of bleeding water as the SAP volume is increased with a large spike in the bleeding when only the extra water was added without the SAP. This is expected. However, Laboratories 1 and 2 showed the lowest bleeding for the mixtures with SAP. For Laboratory 2 this is expected, as no additional water was added to compensate for the water absorbed by SAP 2. For Laboratory 1 this decrease could be ascribed to the significantly lower amount of additional water to compensate for SAP that was added compared to the other laboratories, see Table 6.

Increased bleeding was observed for SAP 2 0.30% in Laboratory 6 who did two tests for each data point, as shown in Figure 2. Most likely part of the additional water could not be absorbed by the SAP in the concretes tested in Laboratory 6. The two test results also indicate the possible scatter of these tests with the error bars indicating the minimum and maximum values. The main reason for the large scatter is due to a likely shift in the time at which concrete was cast in the test vessel (for later casting, the amount of bleeding is reduced).

4.4 Compressive strength

The compressive strength values are shown in Table 9. Note that all the laboratories performed their tests using cubes except Laboratory 2, which used cylinders. The compressive strength as a percentage of the control is shown in Figures 3 and 4 for SAP 1 and SAP 2, respectively, and the average of the compressive strength as percentage of the control is shown in Table 10. The compressive strength values of Laboratory 2 were not included in Table 10, as they did not add any additional water for their SAP mixtures which is not in line with the test program prescribed here.

Table 9. The compressive strength values at 28 days (average ± standard deviation)

[MPa]	**L1S1**	**L1S2**	**L2S1**	**L3S1**	**L3S2**	**L4S1**	**L5S1**	**L5S2**	**L6S2**
Control	53.9±0.3	60.0±0.4	44.0±1	42.3±0.8	44.8±0.2	45.5±2.5	39.5±2.3	43.6±2.1	39.1±0.4
SAP 1 0.15%	56.6±1.0		46.3±0.6	42.3±0.5			37.3±1.3	39.8±1.5	
SAP 1 0.30%	51.5±0.3	55.2±2.3	45.0±2.2	38.7±1.2	42.8±0.8	32.3±1.5	30.9±1.1	36.1±1.1	
Ctrl + Add water 1		55.5±1.1			41.3±1.5			37.6±7.2	
SAP 2 0.15%	54.3±2.8		45.3±1.0	41.1±1.6			38.2±0.9	40.1±1.3	37.6±0.7
SAP 2 0.30%	57.0±1.0	56.0±2.3	45.4±0.6	39.7±1.0	39.7±0.8	41.9±0.6	33.4±1.8	36.7±1.8	40.9±0.5

Ctrl + Add water 2	51.6±1.1	35.2±0.5	37.6±7.2	30.9±0.3

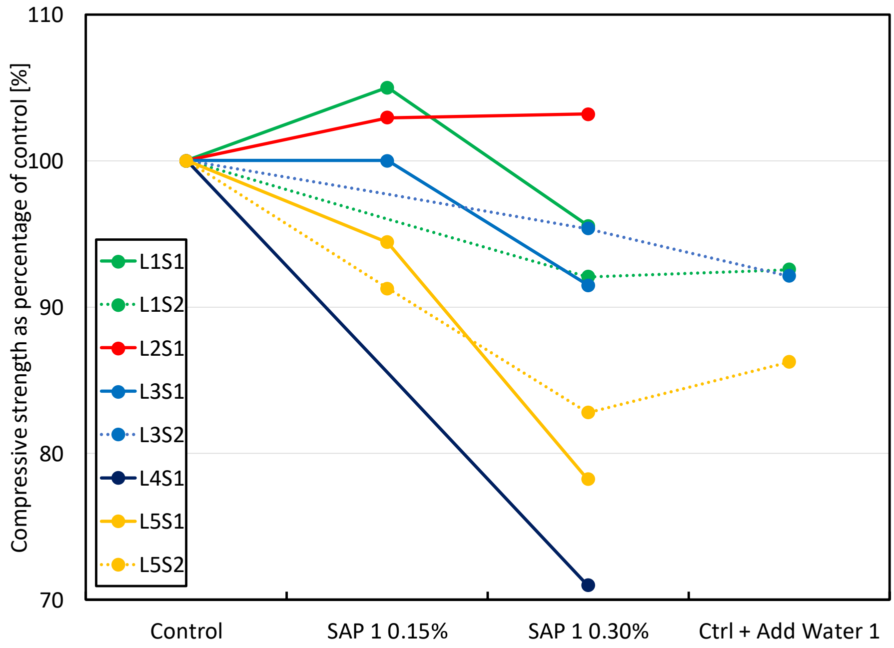

Figure 3. Compressive strengths as a percentage of the control for SAP 1.

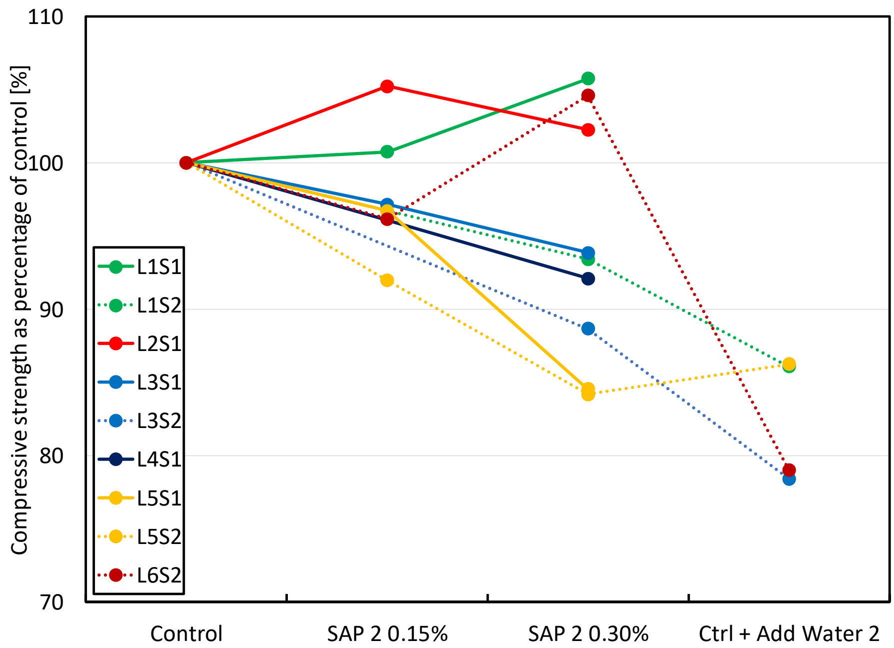

Figure 6. Compressive strengths as a percentage of the control for SAP 2.

Table 10. The average of the compressive strengths as a percentage of the control. Note that the results of Laboratory 2 are not included as mentioned earlier in this section. Standard deviation is calculated between the average values of different laboratories

	[%]	Standard deviation [% points]
Control	100.0	-
SAP 1 0.15%	97.7	6.1
SAP 1 0.30%	86.6	9.5
Ctrl + Add water 1	90.3	3.5
SAP 2 0.15%	96.6	3.1
SAP 2 0.30%	93.4	8.2
Ctrl + Add water 2	82.4	4.3

In general, adding SAP and additional water leads to a reduction in the compressive strength which is fully in line with the vast majority of results reported to date. The reduction is more prominent for SAP 1 with the compressive strength of 0.30% SAP 1 at 86.6% of the control, while for SAP 2 this value is 93.4%. This can be explained based on the nature of the different SAP. SAP 2 retains water for a longer time, only releasing it to compensate for drying. The major effect of SAP 2 on strength would be in such case just by introduction of the macroscopic pores (remnants of initially swollen SAP). On the other hand, SAP 1 is known to release the absorbed water without any external force during free absorption tests. When used in a concrete mixture, it is possible that such premature release could have led to actual increase of the basic w/c compared to SAP 2. In a previous study (Mechtcherine et al. 2017), it was shown that a reference concrete and concrete with SAP, both with the same w/c, had similar mechanical properties. Hence, the effect of additional porosity, either in form of large pores (corresponding to SAP 2 concrete) or higher capillary porosity (corresponding to SAP 1 concrete), can be expected to be similar with regard to strength. At the same time, the earlier release of water could also contribute to segregation which can also result in a more pronounced decrease of compressive strength in concrete SAP 1. The problems related to a premature absorption could be especially acute if the premature release took place before casting or vibration. This was likely the case in the tests presented here. When adding just the additional water without the SAP, the compressive strength dropped by 10% and 18%, for the amounts of additional corresponding to those in concretes with SAP 1 and SAP 2, respectively.

4.5 Plastic shrinkage cracking

The plastic shrinkage cracking tests were all quantified in terms of either crack widths or crack areas. Due to the difference in the mixtures between the laboratories, the different test setups and environmental conditions, the crack widths and areas cannot be compared between laboratories. However, the effect of SAP on the crack areas can be compared if all the results are normalised with regard to the control concrete within each laboratory. The plastic shrinkage cracking results, as a percentage of the control, are shown in Figures 5 and 6 for SAP 1 and SAP 2 respectively. These values are also presented in Table 11 with the standard deviation. The average crack areas / widths are shown in Table 12. Note that the results of Laboratory 2 are neglected in this calculation as their evaporation rates varied significantly between the different tests.

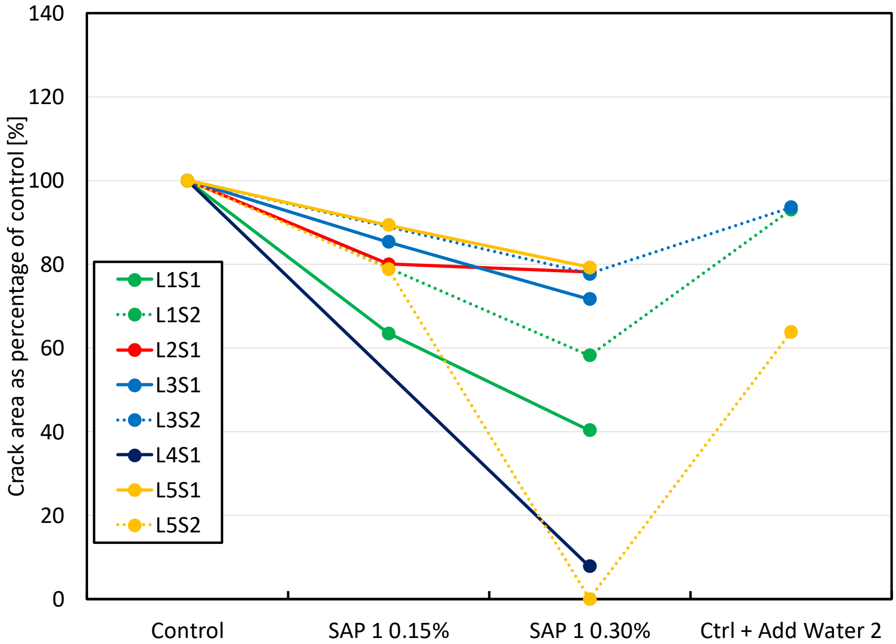

Figure 5. The plastic shrinkage crack area / width as a percentage of the control for SAP 1

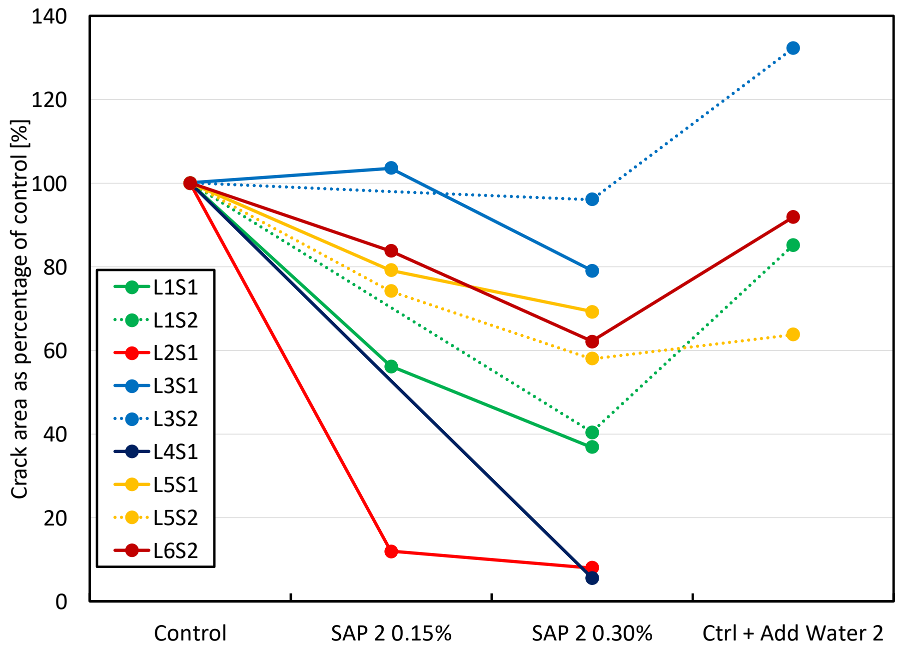

Figure 6. The plastic shrinkage crack area as a percentage of the control for SAP 2

Table 11. Plastic shrinkage cracking area/width as a percentage of the control with the standard deviation included.

	L1S1	**L1S2**	**L2S1**	**L3S1**	**L3S2**	**L4S1**	**L5S1**	**L5S2**	**L6S1**
Control	100±20	100	100±18.4	100±20.2	100±19.2	100	100±11.3	100±21	100±37.8
SAP 1 0.15%	63.4±30		80±38.5	85.3±17		53.895	89.3±11.4	78.8±24.6	-
SAP 1 0.30%	40.3±40	58.2	78±26.3	71.6±0.2	77.6±13.4	7.79	79.2±14	0±0	
Ctrl + Add water 1		92.9			93.5±30.5			63.8±35.4	
SAP 2 0.15%	56.2±29		12±33.3	103.6±9.72		52.83	79.2±12	74.2±35.9	83.8±45.2
SAP 2 0.30%	36.9±40	40.4	8±0	79.1±10.2	96±25.4	5.66	69.3±12.7	58±37.5	62.2±73.9
Ctrl + Add water 2		85.1			132.2±21.3			63.8±35.4	91.9±52.9

Table 12. The average plastic shrinkage cracking area / width as a percentage of the control.

	[%]	Standard deviation [% points]
Control	100	-
SAP 1 0.15%	79.2	11.4
SAP 1 0.30%	47.8	32.9
Ctrl + Add water 1	83.4	17.0
SAP 2 0.15%	79.4	17.1
SAP 2 0.30%	55.9	28.0
Ctrl + Add water 2	93.3	28.6

Except for one data point that was slightly higher (103.6 % for L3S1 SAP 2 0.15%), all mixtures with SAP showed a reduction in plastic shrinkage cracking when compared to the control. For both SAP 1 and SAP 2, this reduction increased with an increase of dosage of SAP. This was obtained for SAP 2 even though the bleeding of the SAP 2 mixtures was smaller than the control. A decrease of bleeding would normally be expected to increase the plastic shrinkage cracking.

For the Ctrl + Add. water 1 and 2 mixtures, the plastic shrinkage cracking was mostly also reduced when compared to the control. This is expected, as additional water without SAP would increase the bleeding, hence reduce the plastic shrinkage cracking. However, for both SAP 1 and SAP 2, (in conjunction with their respectively added amount of extra water) reduced the plastic shrinkage cracking significantly more compared to the Ctrl + Add Water mixtures. This result clearly demonstrates that the decrease of plastic shrinkage cracking when SAP are added is not due to just the additional water, as the additional water on its own does not reduce the plastic shrinkage cracking as much. In conclusion, SAP plays an important role in reducing the plastic shrinkage cracking, other than just supplying extra water.

The mechanism of how SAP reduced plastic shrinkage cracking is not yet fully clear. It is not due to the uncontested release of the water, as the bleeding did not increase for mixtures with SAP 2. Therefore, the cracking is not reduced due to the increase of bleed water. First results related to water migration in this context have most recently been published (Schröfl et al. 2019) but further investigations are due.

The volumetric change that results in plastic shrinkage cracking is caused by capillary action, which builds up the negative internal pore pressure, thus causing a reduction in volume of concrete. If this reduction of volume is restrained, cracking occurs. One mechanism that could be the reason for the improved performance with SAP, is that the SAP release the water when the capillary pressure is building up. By compensating for the lost water, they reduce the capillary pressure and decrease the volume change. On the contrary, the internal curing water would normally not be released during the bleeding tests, as there is no capillary pressure build up during this test. The hypothetical action of SAP during plastic shrinkage is supported by the additional results of Laboratory 6, where capillary pressure evolution in concrete was measured, see Figure 7. Average curves of two measurements per sample are shown with standard deviation at chosen time points. It was observed that the concretes SAP 2 0.15%, SAP 2 0.30% and Ctrl + Add water 2 experienced slower evolution of capillary pressure between the time of about 3 h from casting and setting time, and the effect was particularly visible for the higher dosage of SAP. With respect to the effect of SAP addition on capillary pressure and plastic shrinkage, these results agree with those reported earlier by Serpukhov and Mechtcherine (2015).

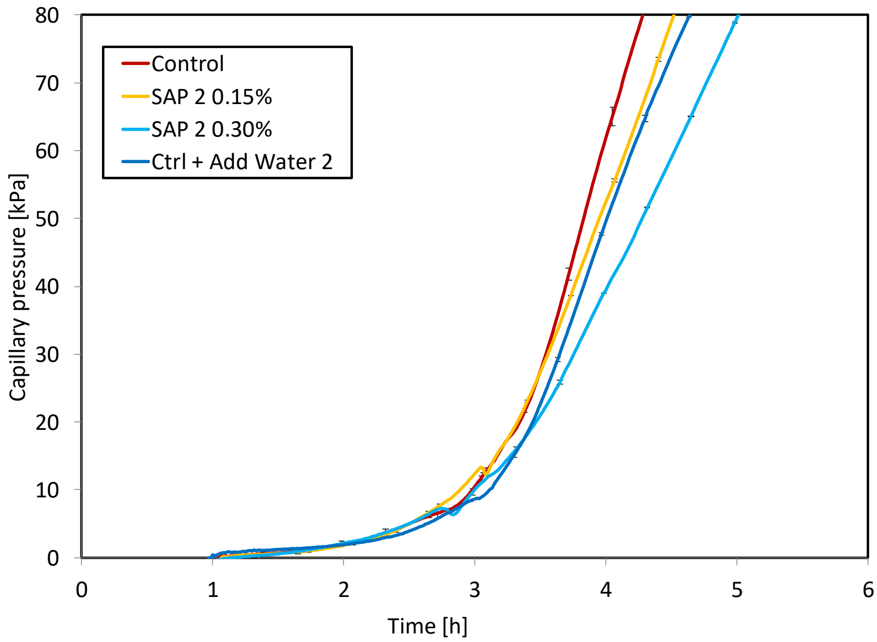

Figure 7. The capillary pressure development as determined by Laboratory 6 for SAP 2.

Another phenomenon that may result in cracking of fresh concrete is plastic settlement, in particular differential settlement that occurs over reinforcement or where the height of the concrete section changes (Kwak et al. 2010, Moradllo et al. 2019). In many cases, cracking in fresh concrete may result from the superposition of stresses caused both by settlement and drying (Qi et al. 2005). As shown in Figure 2, the addition of retentive SAP (SAP 2) reduces bleeding and thereby also is expected to reduce consolidation and settlement of fresh concrete (though no measurements of settlement are reported in this paper). At the same time, the internal curing water stored in SAP 2 is released into the matrix as well as to the ambient air according to a “demand-and-supply” mechanism (Schröfl et al. 2019). This supply of water mitigates plastic shrinkage cracks (Figure 6). The faster pressure buildup of Ctrl + Add. water 2 comparing to SAP 2 0.30% may be caused by different permeabilities of the fresh concretes. Obviously, adding water directly affects the permeability of the fresh concrete more than the same amount of water stored inside SAP and released in time.

5. Conclusions

This paper presents the results of an inter-laboratory test programme to determine the effect of superabsorbent polymers (SAPs) on the plastic shrinkage cracking of conventional concrete. The following conclusions were made:

- The majority of tests (26 out of 27) revealed that adding SAP to conventional concrete, together with the appropriate amount of additional internal curing water, reduced the severity of plastic shrinkage cracking. This occurred both for SAP that retain the absorbed water(so-called retentive SAP) and for SAP that release their water prematurely.
- When just the same amount of additional water was added, but without SAP, the plastic shrinkage cracking was more significant than for the mixtures with both SAP and additional water. It can be concluded that SAP does indeed reduce plastic shrinkage cracking and that it is not just due to the additional water.
- Bleeding is influenced not only by the addition of SAP, but also by the type of SAP employed. The SAP with higher long term fluid retention ability by itself reduced the bleeding compared to the other SAP which only had only short-term absorption capacity. The latter increased the bleeding, contrarily to the first type.
- When SAP is added to conventional concrete with just enough additional water to ensure the same slump as the control, a slight decrease of the compressive strength can be found. In this study, the compressive strength was found to be on average 97% of the control for the 0.15% SAP mixtures and 90% of the control for the 0.30% SAP mixtures. This will have to be determined for each mixture made with SAP for the mitigation of plastic shrinkage cracking.

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Declaration on conflict of interest

The authors declare that they have no conflict of interest.

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