ISSN online 2545-2819
ISSN print 0800-6377

DOI: 10.2478/ncr-2019-0012

Received: April 22, 2019
Revision received: June 7, 2019
Accepted: June 18, 2019

Plastic Shrinkage Cracking of Self-compacting Concrete: Influence of Capillary Pressure and Dormant Period

Faez Sayahi
Ph.D.
Div. of Building Materials
Luleå University of Technology, LTU
971 87 Luleå, Sweden.
faez.sayahi@ltu.se

Mats Emborg
Professor LTU/Head R&D Betongindustri AB
971 87 Luleå, Sweden. /Betongindustri AB, 100 74 Stockholm.
mats.emborg@betongindustri .se
mats.emborg@ltu.se

Hans Hedlund
Adjunct Professor LTU/Skanska Teknik AB
971 87 Luleå, Sweden/Skanska AB, 405 18 Göteborg, Sweden
hans.hedlund@ltu.se
hans.hedlund@skanska.se

Andrzej Cwirzen
Professor
Div. of Building Materials
Luleå University of Technology, LTU
971 87 Luleå, Sweden
Andrzej.cwirzen@ltu.se

ABSTRACT
This research investigates the effect of capillary pressure and the length of the hydration dormant period on the plastic shrinkage cracking tendency of SCC by studying specimens produced with different w/c ratios, cement types and SP dosages. A relationship between the capillary pressure rate and the length of the hydration dormant period is defined, which can explain the cracking severity of the concrete when the volumetric deformation is unknown.
The results show, that the cracking tendency of SCC was the lowest in case of w/c ratio between 0.45 and 0.55, finer and more rapid hardening cement, and lower dosage of SP. The dormant period was prolonged by increasing the w/c ratio, using coarser cement, and higher SP dosage. It was concluded that the cracking tendency of concrete is a function of the capillary pressure build-up rate and the length of the dormant period.

Keywords: plastic shrinkage, cracking, evaporation, capillary pressure, dormant period.

1. INTRODUCTION

Plastic shrinkage cracks in concrete may form at the surface shortly after casting and before the concrete gains enough tensile strain capacity [1, 2]. The aesthetics, durability and serviceability of a structure may be dramatically impaired, as cracks facilitate ingress of harmful materials into the concrete that may cause damage in a long term. The physical aspect of plastic shrinkage is manifested in evaporation of the capillary water and the consequent build-up of a hydraulic pressure, i.e. capillary pressure, in the liquid phase of the material [3]. Autogenous shrinkage, during which the pore liquid is consumed by self-desiccation, does not play a decisive role in plastic shrinkage cracking, when water/cement ratio (w/c) is more than 0.5 [4, 5]. However, for concretes with low w/c ratio and/or high cement content, the effect of autogenous shrinkage in early-age cracking should be considered [6]. In this paper, the term "plastic shrinkage" refers to the contraction induced by drying, i.e. evaporation.

After placing the concrete in the mould, its solid particles settle due to gravity, forcing the pore water to move upwards to the surface, i.e. *bleeding* regime [7]. This surface water eventually evaporates, after which menisci start to form inside the pores, i.e. *drying* regime [7]. At this point, a negative capillary pressure begins to build-up in the pore network, which in turn creates tensile forces applying on the solid particles. If the accumulated tensile stresses exceed the tensile strength of the young concrete, cracks will form [3].

Rapid and excessive moisture loss, mainly due to evaporation, is the main cause behind plastic shrinkage cracking. However, with constant w/c ratio, self-compacting concrete (SCC) is characterised by a higher risk of early-age cracking in comparison to vibrated concrete (VC) [8, 9]. The reason lies in the lower water/binder ratio (w/b) and higher cement content of SCC which lowers the bleeding capacity

The influence of different parameters on the risk of plastic shrinkage cracking has been investigated by a number of researchers. For example, Löfgren and Esping [10] found that the optimum w/c ratio for decreasing the plastic shrinkage cracking tendency of SCC is 0.55. Same authors also observed that increasing the cement content or decreasing w/c ratio increases the autogenous shrinkage [4]. They concluded that SCC with a w/c ratio lower than 0.4, most probably, cracks due to autogenous shrinkage, rather than plastic shrinkage. Other experiments also showed that the risk of plastic shrinkage cracking of SCC significantly decreases when w/b ratio is below 0.44 [11].

Furthermore, it has been observed that a normal hardening cement boosts the cracking tendency of SCC in comparison to a rapid hardening cement [4]. Finer cement particles, on the other hand, increase the cracking severity [12, 13], most probably due to autogenous shrinkage. However, coarser cements cause wider cracks, despite of lower cracking intensity [13]. Another study shows that superplasticizers (SP) increase the evaporation, delay the hydration, and lead to higher cracking risk [14].

Despite all the research done so far, the mechanism of plastic shrinkage is not yet fully understood, especially when considering the evaporation as the only driving force [13]. The main aim of this paper is to determine a relationship between capillary pressure and the hydration dormant period, which may explain the cracking mechanism. The findings of this research may then be utilized in developing new models to explain the phenomenon of plastic shrinkage.

2. MATERIALS AND METHODS

2.1 Materials and mixing process

The mix design of the concretes and composition of the cements are shown in Tables 1 and 2, respectively. A reference concrete (REF), with w/c ratio of 0.67 was produced using a Portland composite cement, (CEM II/A-LL 42.5R according to EN 197-1 [15]) known as Byggcement in Sweden and containing 11% of limestone. The reference mixture contained 60% of total aggregate mass of natural aggregates (0-4 mm and 0-8 mm) and 40% of total aggregate mass of mixed natural/crushed 8-16 mm aggregates. Limestone filler (Limus 40) with density of 2700 kg/m^3 and

SP (Sikament 56) based on polycarboxylate ether, with density of 1100 kg/m^3 and 37% of dry content were used.

Four mixtures with different w/c ratios (0.38, 0.45, 0.55 and 0.67) were produced and tested. The effect of SP dosage was investigated by changing its portion from 0.8% of cement weight in the REF mix, to 0.6% and 1.0% of cement weight in SP0.6 and SP1, respectively.

Table 1 - Mix design of the tested SCCs, in kg/m^3.

Name	REF	REFS	REFA	W/C38	W/C45	W/C55	SP0.6	SP1
Cement	300	300	300	420	380	340	300	300
Cem type*	Byggcement	SH-cement	Anläggni-ngscement	Byggcement	Byggcement	Byggcement	Byggcement	Byggcement
Water	200	200	200	160	171	187	200	200
Agg. 0-4	155	155	155	0	0	81	155	155
Agg. 0-8	771	771	771	1021	998	879	771	771
Agg. 8-16	628	628	628	694	678	651	628	628
Filler	220	220	220	40	100	160	220	220
SP	2.4	2.4	2.4	4.6	5.7	4.1	1.8	3
W/C	0.67	0.67	0.67	0.38	0.45	0.55	0.67	0.67

* According to Table 2.

All components were stored at the temperature at which the concrete mixing took place (20 ±1 °C). The aggregates, filler and cement were premixed in a pan type Zyklos mixer for one minute before the solution of water and the SP was added. The mixing process then continued for further five minutes. All the concrete mixtures were produced and tested twice to ensure the repeatability.

Table 2 - Composition of the cements (produced by Cementa AB, Sweden).

Name		CEM II/A-LL 42.5R (Byggcement)	CEM I 42.5N (Anläggningscement)	CEM I 52.5R (SH-cement)
CaO	(%)	61.7	63.9	62.9
SiO_2	(%)	18.4	21.3	19.3
Al_2O_3	(%)	5.0	3.6	5.2
Fe_2O_3	(%)	2.9	4.5	3.1
MgO	(%)	1.2	1.0	1.3
Na_2O	(%)	0.15	0.12	0.16
K_2O	(%)	1.3	0.66	1.3
SO_3	(%)	3.8	2.8	3.9
Cl	(%)	0.03	0.01	0.04
C_2S	(%)	7.6	12.8	8.6
C_3S	(%)	55.4	64.1	62.2
C_3A	(%)	7.7	2.1	8.6
C_4AF	(%)	8.4	13.6	9.4
Density	(kg/m^3)	3080	3189	3125
Blaine	(m^2/kg)	430	310	550

2.2 Method

The cracking tendency was measured according to the NORDTEST-method (NT BUILD 433) [16], also known as the ring test method. The test set-up included three identical moulds, each consisted of two concentric steel rings. Steel ribs (stress raisers), welded to the rings, provide crack initiation points, see Figure 1.

After casting the moulds were covered with a transparent air funnel attached to a suction fan, generating a wind of 4.5 m/s velocity across the specimen surface. The ambient temperature and the relative humidity were 20 ± 1˚C and 35 ± 3%, respectively.

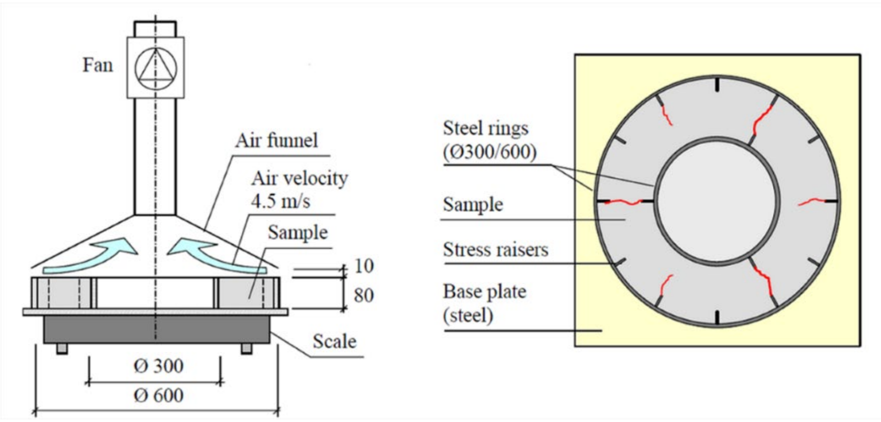

Figure 1 - The ring test set-up used to determine the plastic shrinkage cracking tendency, based on [10] (the dimensions are in mm).

One of the moulds was placed on three load cells (scales) in order to measure the weight loss (i.e. water evaporation), at 1 s intervals. The capillary pressure was measured every 15 s by two wireless pressure sensors (CPSS, manufactured by FTZ, HTWK Leipzig) filled with degassed water, see Figure 2. The sensors were inserted vertically, down to 4 cm from the concrete surface. The internal temperature was recorded at 1 s intervals with a thermo couple located 12 cm from the bottom of the mould. The measurements started 60 minutes after casting and ended 18 hours later.

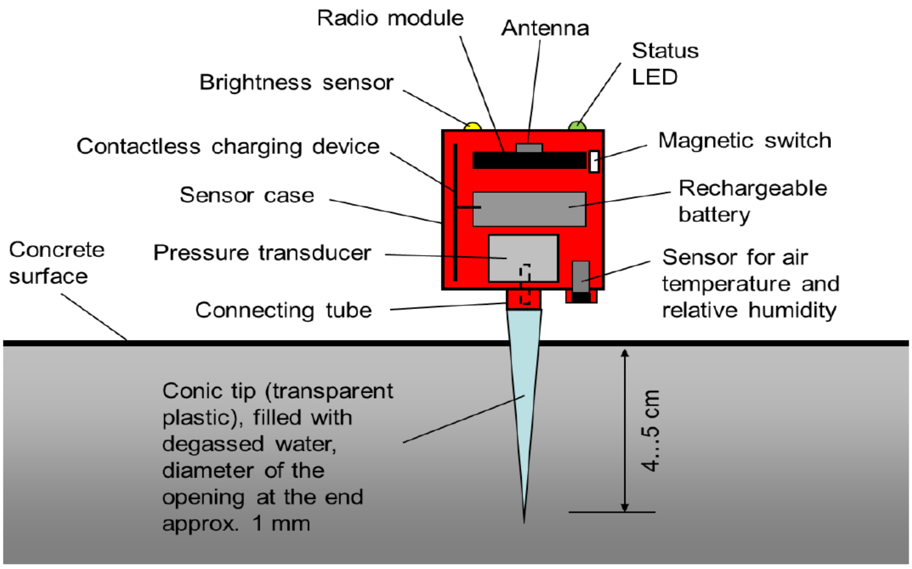

Figure 2 - Schematics of a wireless capillary pressure sensor, from [17].

The surface of the specimens was visually inspected every 30 minutes in order to determine the crack initiation time. The crack width and the crack length were measured by a digital microscope (Dino Lite AM-413T Pro) to an accuracy of 0.001 mm and a digital measuring wheel (Scale Master Pro) to an accuracy of ±1 mm, respectively. The average crack area of the three moulds was calculated, according to [14].

3. RESULTS

3.1 Concrete properties

Results of the slump flow test (according to EN 12350-2 [18]), associated with the density and air content, are presented in Table 3. Increasing the w/c ratio and SP dosage, increased the concrete flow, while no variation was detected by changing the cement type.

Table 3 - Concrete properties.

Name	REF	REFS	REFA	W/C38	W/C45	W/C55	SP0.6	SP1
Slumpflow (mm)	760	760	760	650	700	730	710	800
T_{500} (sec)	2	2	2	3	2.5	2	2.5	2
Density (kg/m^3)	2348	2380	2423	2146	2226	2292	2336	2350
Air content (%)	1.7	1.8	2	1.5	1.5	1.6	1.6	1.8

3.2 Effects of the w/c ratio

Figure 3 shows the influence of the w/c ratio on the average crack area and the crack initiation time. By increasing the w/c ratio from 0.38 to 0.45, the average crack area decreased from 34.3 to

9.2 mm^2. However, further increase of the w/c ratio, exhebited an opposite effect, as the average crack area started to increase, especially above the w/c of 0.55, where the crack area, eventually, reached 91.4 mm^2 in REF. On the other hand, the crack initiation time gradually decreased from 7 hours in W/C38 to 3 hours in REF, see Figure 3.

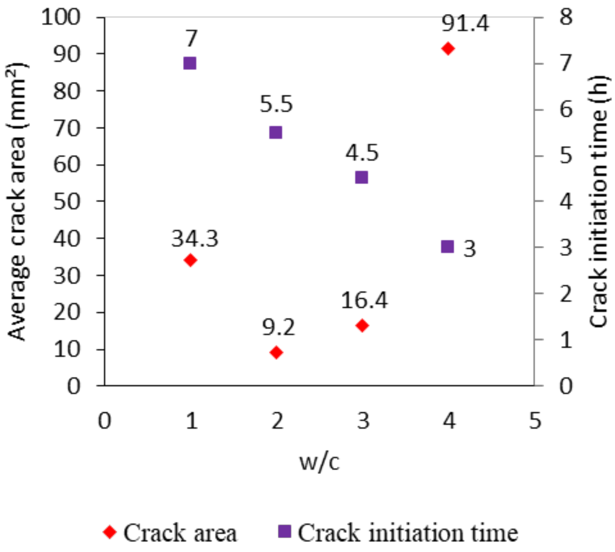

Figure 3 - Effect of w/c ratio on the average crack area and the crack initiation time (from mixing) of SCC.

Note that in this paper, the crack initiation time is the only parameter that was quantified from the concrete placement, while all the other measurements started 60 minutes after casting.

The total cumulative evaporation was raised by increasing the w/c ratio, see Figure 4. However, a notable difference was detected between the total evaporation of W/C38 and those of the other mixtures, where the evaporation of the former ceased after around 13 h, while the others exhibited ongoing evaporation, despite the falling rate.

With the exception of REF, increasing the w/c ratio did not significantly affect the capillary pressure build-up rate, see Figure 5. The onset time of the pressure evolution was not affected by the w/c ratio, as its absolut value started to increase simultaneously in all the specimens.

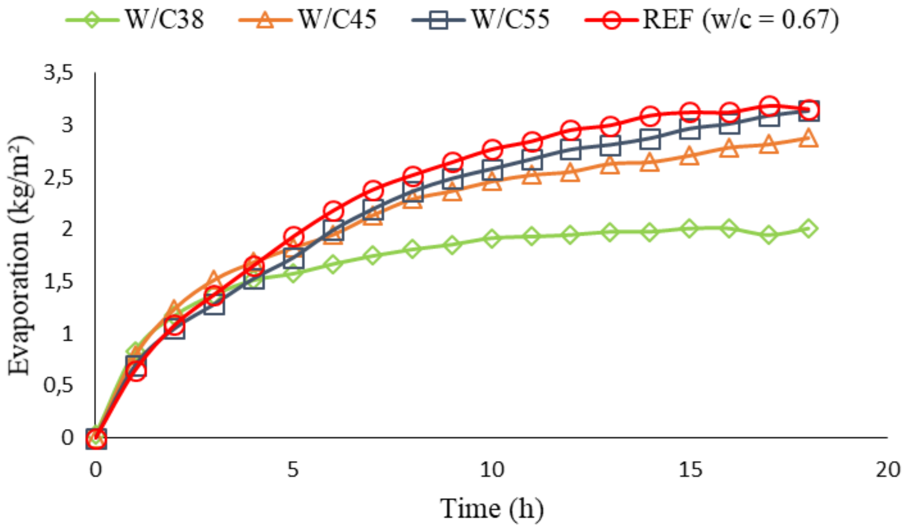

Figure 4 - Influence of w/c ratio on the cumulative evaporation (time after starting the measurement).

A gradual prolongation of the dormant period was observed, as the w/c ratio incread from 0.38 to 0.55 (see Figure 5 and Table 4). However, REF showed slightly shorter dormant period, compared to W/C55.

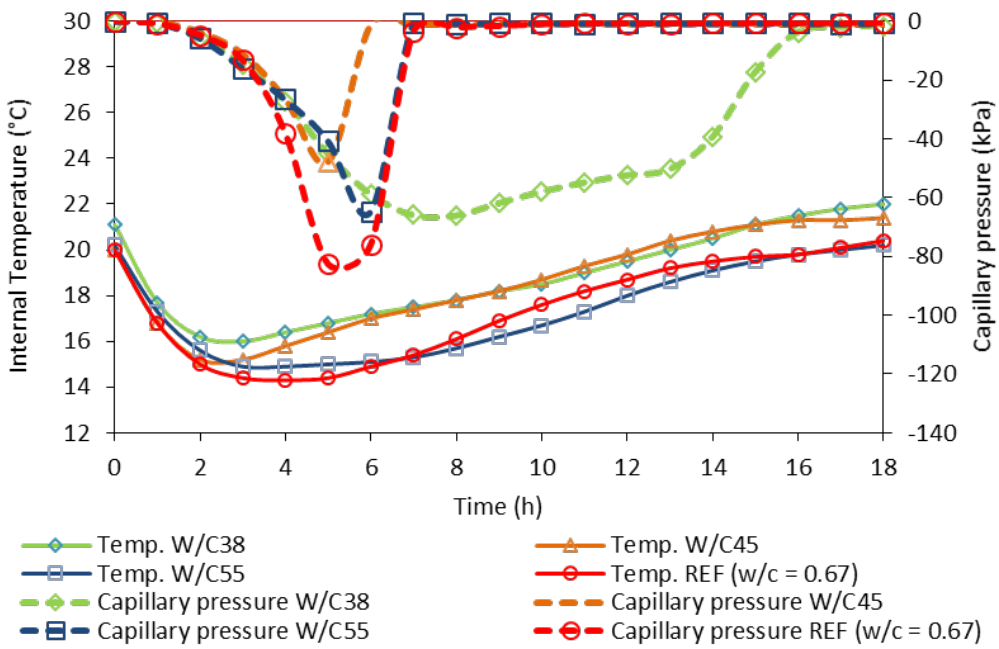

Figure 5 - Influence of w/c ratio on internal temperature and capillary pressure (time after starting the measurement).

3.3 Effects of the cement type

Crack areas of concretes produced with CEM II/A-LL 42.5R (REF) and CEM I 52.5R (REFS), were very close, see Figure 6. However, the crack area of REFA, produced with CEM I 42.5N, was around 50% larger in contrast to the other two mixes. The time of crack initiation was 3 hours after casting in the case of REF and REFA, whereas REFS showed the first crack after 7 hours.

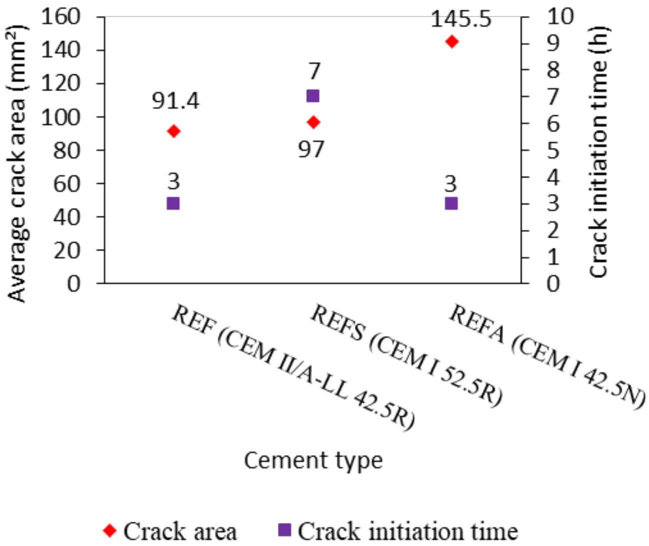

Figure 6 - Effect of cement type on the average crack area and the crack initiation time (from mixing) of SCC.

REFS showed a slightly less cumulative evaporation, compared to the reference concrete, see Figure 7. On the other hand, REFA had nearly 60% higher evaporation than that of REF. The difference was evident, even during the first hour. Figure 8 plots the maximum cumulative evaporation at the end of the test versus the blain size of the cements. The amount of the evaporated water, clearly increased when cements with coarser particles were used.

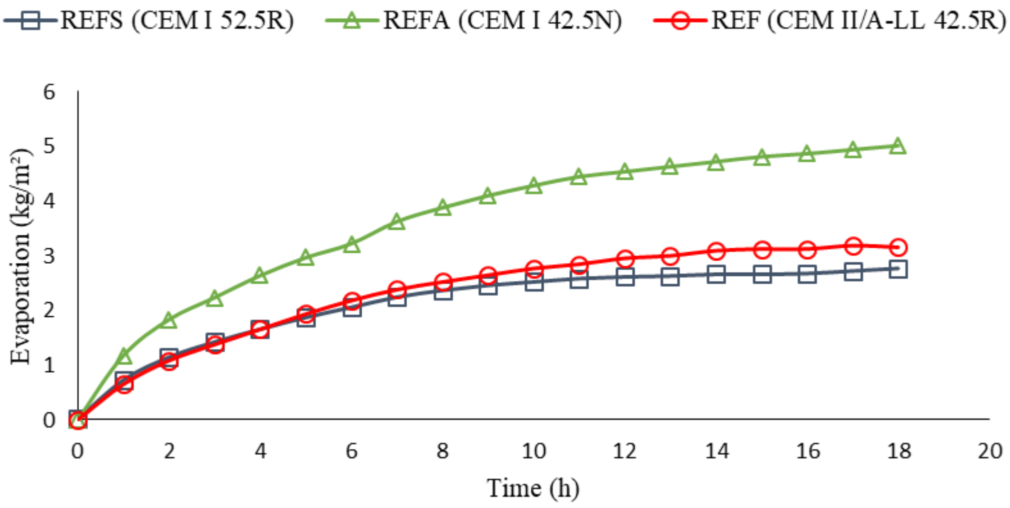

Figure 7 - Influence of the cement type on the cumulative evaporation (time after starting the measurement).

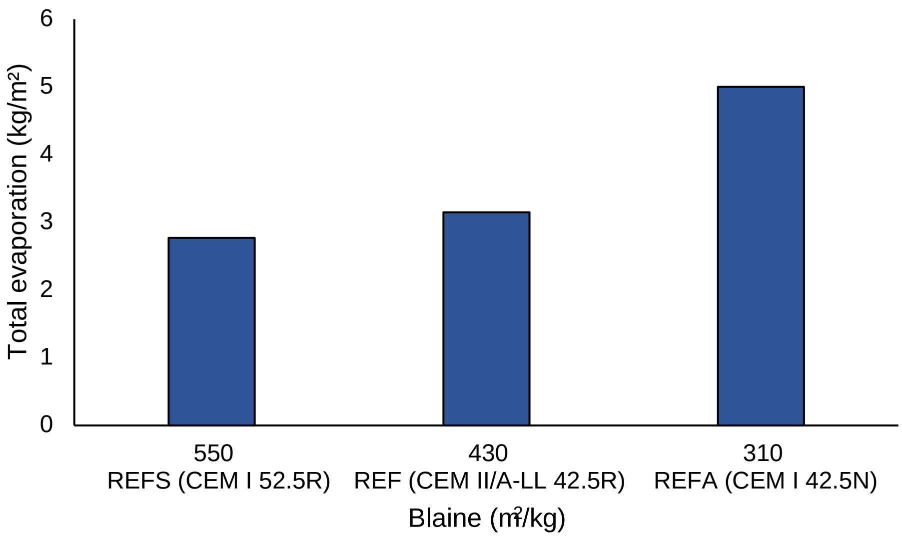

Figure 8 - Effect of cement fineness on the total evaporation.

The cement type did not have any noteworthy impact on neither the capillary pressure build-up rate nor its onset time, see Figure 9. On the contrary, significant difference was found in the internal temperature measurements, as the dormant periods of REFS and REFA were, respectively, shorter and longer than the one in the reference concrete. REFS was the only mixture to reach a maximum value of the internal temperature, among all specimens in this study, see Figures 5, 9 and 12.

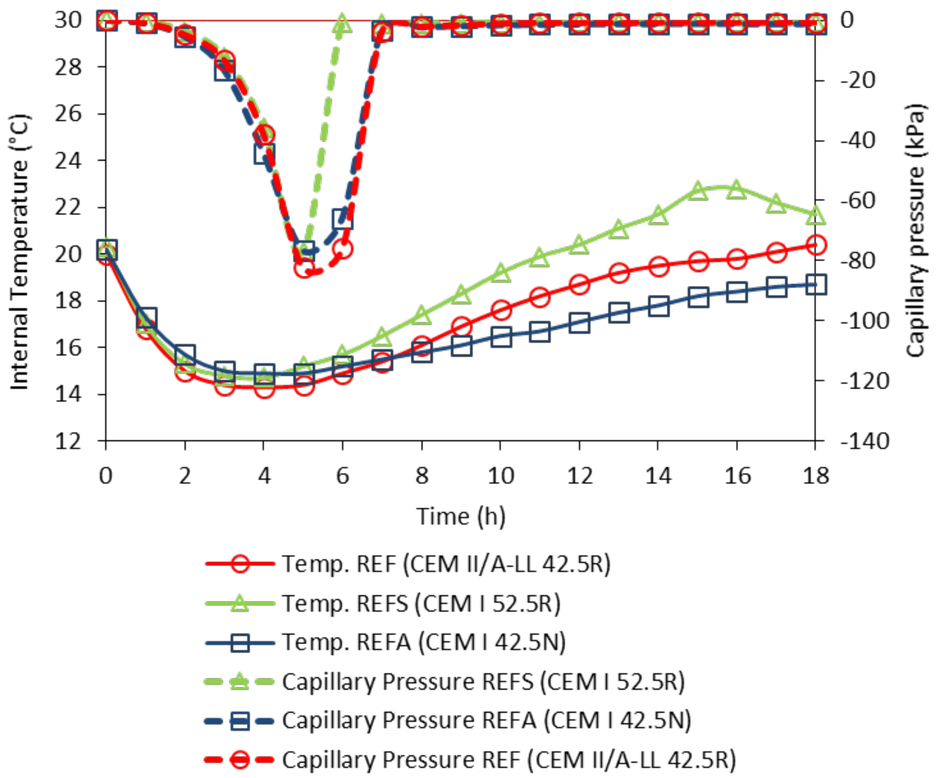

Figure 9 - Influence of cement type on the internal temperature and the capillary pressure (time after starting the measurement).

3.4 Effects of SP dosage

Increasing the SP dosage, increased the crack area almost at a constant rate, see Figure 10. The measured crack areas were 56.8, 91.4 and 112.4 mm^2 in SP0.6, REF (0.8%) and SP1, respectively. However, the amount of SP appeared to have no influence on the crack initaion time, as all the three specimens cracked at around 3 h after casting.

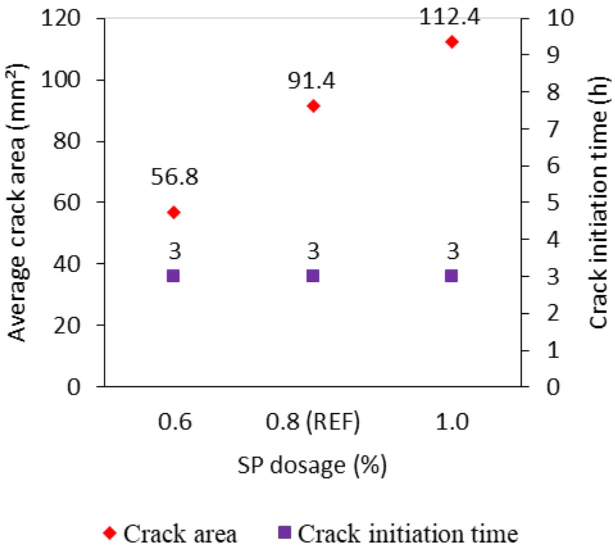

Figure 10 - Effect of the SP dosage on the average crack area and the crack initiation time (from mixing) of SCC.

Decreasing the SP dosage resulted in both lower evaporation rate and total amount of the lost water in SP0.6, compared to the reference mixture, see Figure 11. The opposite effect was observed when the SP content was increased to 1.0% of cement weight in SP1.

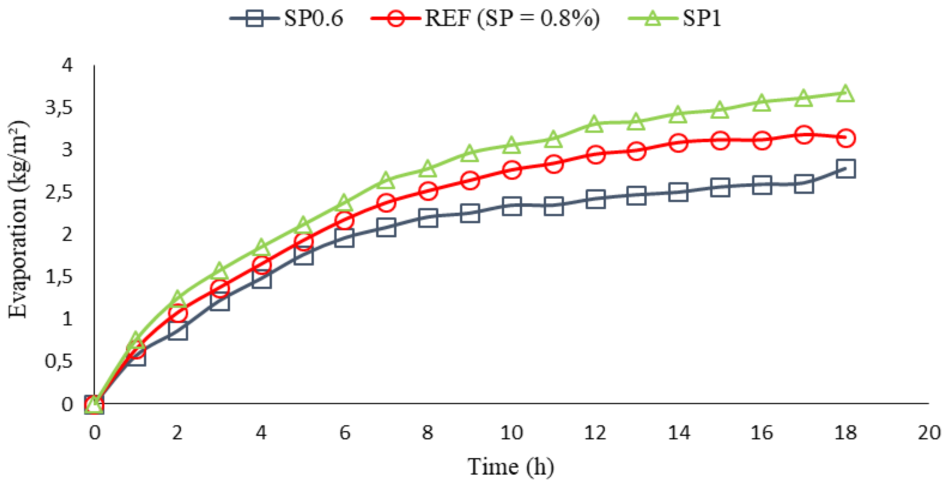

Figure 11 - Influence of SP on the cumulative evaporation (time after starting the measurement).

On the other hand, decreasing the SP content, caused higher capillary pressure build-up rate, see Figure 12. However, the pressure value in all the specimens started to increase almost simultaneously, regardless the SP dosage.

The amount of SP also affected the hydration rate, where SP0.6 and SP1, respectively, shortened and prolonged the dormant period, compared to the REF mix

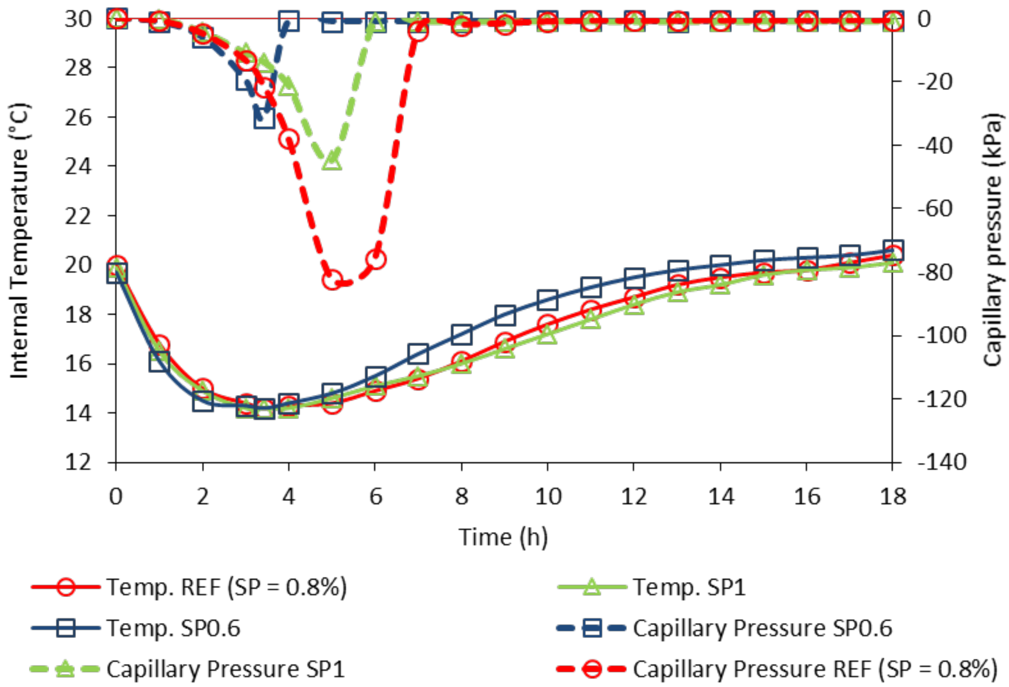

Figure 12 - Influence of SP dosage on the internal temperature and capillary pressure (time after starting the measurement).

3.5 Capillary pressure and dormant period characteristics

Table 4 gives the length of the dormant period (from the time of mixing) in addition to the rate and the onset time of the capillary pressure build-up, for all mixtures. The end of the dormant period was determined by calculating the inflection point of the internal temperature curve. In order to quantify the rate of the capillary pressure evolution, the lowest maximum absolute pressure value among all specimens, i.e. 31.56 kPa in SP0.6, was set as the upper limit. Then, for all mixtures, the pressure rate was calculated between the onset time, i.e. 1 h after starting the measurements (see Table 4), and the time at which the pressure reached the limit of -31.56 kPa.

Table 4 - Dormant period, capillary pressure build-up rate, and pressure build-up onset time of the tested mixtures.

Name	REF	REFS	REFA	W/C38	W/C45	W/C55	SP0.6	SP1
Dormant period* (h)	6.9	5.9	7.9	3.9	4.1	8.1	5.5	8.2
Pressure rate (kPa/h)	10.97	11.62	10.77	9.63	9.77	9.23	12.5	8.89
Pressure onset time* (h)	2	2	2	2	2	2	2	2

* time from mixing which was almost equal to the casting time.

4. DISCUSSION

The effects of w/c ratio, cement type and SP dosage on the plastic shrinkage cracking of fresh concrete, have been studied previously [4]. However, the present research focuses on the effects of these variables on the capillary pressure build-up and on the hydration rate. The results were used to define a relationship between the pressure evolution rate and the duration of the hydration dormant period. The determined relationship can contribute to explanation of the cracking mechanism, even without knowing the actual volumetric deformation. Thus, the vertical and horizontal deformations of the specimens are not reported in this paper.

4.1 Capillary pressure

After the concrete enters the drying regime, the progressive evaporation gradually reduces the radii of the water menisci, and leads to further increase of the capillary pressure absolute value, which in turn, increases the tension level in the concrete bulk [3]. These tensile forces act on the solid particles and shrink the concrete mass. In case the concrete member is restrained (internally and/or externally), the shrinkage can lead to accumulation of tensile stresses, which may cause cracking, if they exceed the low early age tensile strength of the concrete [19]. Thus, assuming constant restrain degree, higher capillary pressure increases the tensile stress in the concrete bulk, which may accelerate and facilitate surpassing of the still low tensile strength in the plastic state.

The maximum absolute pressure value in the concrete, however, differs by location, which can be attributed to the difference in the air penetration occurrence [3]. Accordingly, the maximum absolute value of the capillary pressure cannot be considered as a material property [10]. However, at a given depth, the rate at which the pore pressure increases (i.e. slope of the ascending part of the pressure-time curve) is the same, regardless the location [20], see Figure 13. Thus, the capillary pressure build-up rate may indicate the amount of the tension, applied on the solid particles of the mixture, and accordingly, the deformation of the concrete mass.

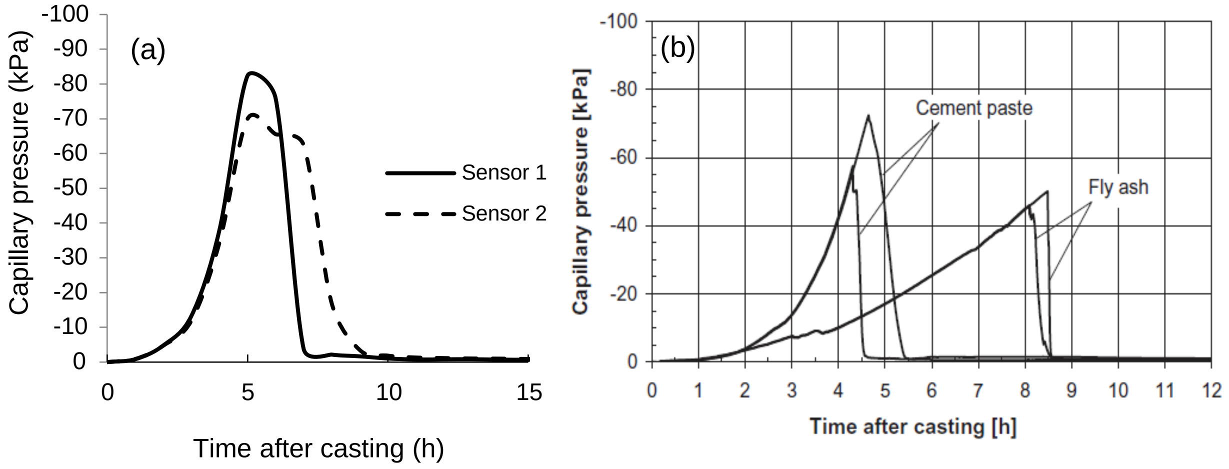

Figure 13 - Capillary pressure measured at 4 cm from the surface in two locations of one specimen: a) from [21]; b) from [19].

4.2 Tensile strength development

As stated before, the cracking potential should be evaluated based on a comparison between the tensile stresses and the concrete tensile strength, since cracking does not occur, unless this limit is passed. Earlier studies show that the tensile strain capacity of concrete gradually decreases after mixing, and reaches its lowest value at around the initial setting time [22], i.e. shortly after the end of the hydration dormant period. On the other hand, development of early age concrete tensile strength is consistent with the hydration degree [23, 24]. During the dormant period, when the hydrationis at its lowest level, the concrete possesses poor tensile strength [25], see Figure 14. However, it rapidly increases, as soon as the dormant period is over, when the hydration rate increases. Hence, the length of the dormant period may be assumed equal to the timespan at which the concrete is highly vulnerable to tensile stresses.

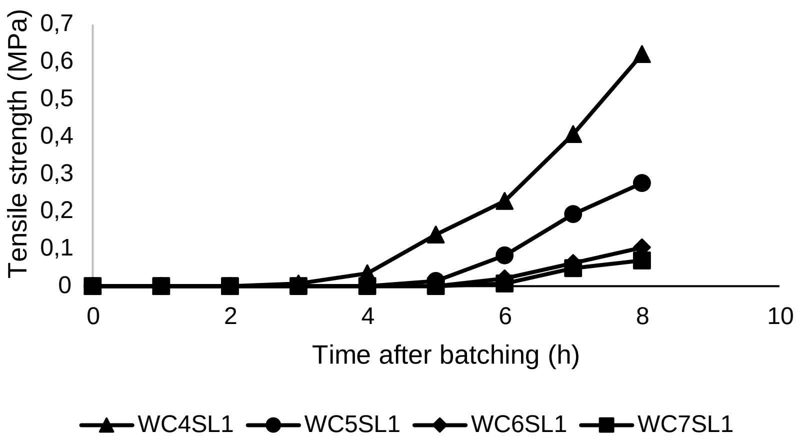

Figure 14 - Tensile strength development of concretes with 194 kg/m^3 water content (in the legend, the numbers after WC and SL denote the w/c ratio and the intended slump in inches, respectively), from [25].

In the following sections, an effort is made to explain the observed effects of w/c ratio, cement type, and SP dosage on plastic shrinkage cracking. The measured crack areas are then related to the capillary pressure build-up rate and the duration of the dormant period.

4.3 Influence of w/c ratio

According to the results, the total evaporation increased with higher w/c ratio, see Figure 4. However, the largest average crack area was measured in REF, with w/c ratio of 0.67, followed by W/C38, W/C55 and W/C45, respectively, see Figure 3. Evidently, this is not consistent with the evaporation trend. Subsequently, the substantial increase of the average crack area in REF cannot be explained, solely, based on the evaporation. Instead, it can possibly be related to the capillary pressure build-up rate and the length of the dormant period.

As mentioned, the tensile strength of the concrete is meagre during the hydration dormant period [23-25]. Increasing the w/c ratio, which in turn prolongs the dormant period, also delays the onset of the rapid increase of the tensile strength and decreases its rate [25], see Figure 14. Thus, SCC with high w/c ratio, such as REF in this case, has lower tensile strength for a longer period of time which can be easily exceeded by the tensile stresses.

Higher filler volume in SCC increases the risk of plastic shrinkage cracking [12]. Similarly, in the case of REF, a higher evaporation rate combined with presumably narrower pores rapidly increased the rate of capillary pressure development in comparison to the other mixtures, having lower fines content, see Figure 5. This implies that at any time, the amount of shrinkage in REF is higher than that in the other mixtures. For instance, the capillary pressure value at 4 hours after starting the measurement was -38 kPa in REF, versus -26.5 kPa in the other three, see Figure 5. The higher tensile stresses, induced by the faster pressure evolution, together with the concrete's lower tensile strength (i.e. longer dormant period), can explain the considerably higher average crack area of the REF mix. The crack width measurements complied with these results, where the cracks in REF (0.402 mm) were about 10 times wider than those in W/C45 (0.045 mm).

Since the cracking occurred before the end of the dormant period, see Figure 5 and Figure 3, it can be assumed that the plastic shrinkage was induced mainly by the drying contraction. This corresponds well to the general assumption that in a concrete having a w/c ratio exceeding 0.5, the evaporation is the governing mechanism of cracking [5, 6]. Moreover, higher amount of limestone filler, as in case of REF, decreases the autogenous shrinkage [26-28].

The lower evaporation measured in the W/C38 mix, presumably caused slower decrease of the radii of the menisci in the pores, which led to a somewhat lower capillary pressure build-up rate. However, the shorter dormant period was an indication of a faster hydration, which in turn reduced the intrinsic permeability of the mixture and blocked the paths through which water was transported to the surface. Consequently, the menisci curvature decreased faster, and increased the capillary pressure build-up rate to be almost the same as W/C45 and W/C55. Moreover, taking the late crack initiation time of W/C38 into account, it seems that the shrinkage and cracking of the SCCs with low w/c ratios was mostly related to the autogenous deformation, which agrees well with the conclusions made by other researchers [5, 29, 30].

Note that in order to maintain the integrity of the mixture and avoiding any segregation, in addition to the w/c ratio, the mix design of the specimens tested here was modified by changing the cement, filler, aggregate, and SP content, see Table 1. This was made due to the broad range of the tested w/c ratios, i.e. 0.38 to 0.67. Thus, the reported results cannot be attributed to the effect of w/c ratio solely, and therefore, should be further investigated in future.

4.4 Influence of cement type

Evaporation rate decreases by increasing the specific surface area of the cement particles [13]. A finer cement makes the pore structure denser, which in turn, reduces the permeability [31], and impedes the transportation of the capillary water to the surface. Cement composition is another important factor that may explain the evaporation results. It has been observed that higher amount of C_3A in cement, reduces the bleeding of the concrete [32], due to the accelerated hydration and the consequent reduction of the intrinsic permeability of the matrix [33]. Hence, the significant increase in the evaporation of REFA, compared to REF (Figure 7), can be attributed to its presumably higher permeability due to the lower C_3A content and coarser particles, see Table 2. Same argument can be used to explain the lower evaporation of REFS, as its finer particles and higher portion of C_3A decrease the permeability.

Finer pores, according to the Laplace equation [34, 35], may increase the absolute pore pressure value. However, in these particular tests, changing the cement type had a minor effect on the capillary pressure build-up rate, see Figure 9 and Table 4. Hence, it seems that all mixtures should develop more or less equal ultimate shrinkage, assuming constant dormant period. However, this is not the case here, as REFS had a faster hydration and shorter dormant period, compared to REF, while REFA hydrated considerably slower. Higher specific area of the cement particles, i.e. finer cement, helps the dispersion of the particles which increases both the hydration rate and the hydration degree [13]. In addition, the presence of the higher amount of C_3A, which liberates a significant amount of heat when it comes into contact with water, is another reason behind the faster hydration of REFS [32]. Thus, the difference in the length of the dormant period is the key parameter here, as it reveals the lower tensile strength of REFA.

The cracking in REFA occurs before the end of the dormant period, compare Figure 6 and Table 4. The relatively longer dormant period in REFA, means that the rate at which the concrete gains stiffness is lower. In other words, the specimen will be subjected to higher tension, induced by the capillary pressure, while at the same time the tensile strength develops at a lower rate. This indicates that, in REFA, the concrete cracks mainly due to plastic, rather than autogenous shrinkage.

REFS cracked around the end of the dormant period. It has been observed that the accelerated hydration rate of finer cements leads to larger chemical shrinkage at early ages [36]. Moreover, the higher C_3A content of CEM I 52.5R also facilitates a more rapid early age chemical shrinkage.

Therefore, the cracks in the REFS seem to be partly autogenous, which complies well with the results of Esping and Löfgren [10].

Based on the discussion mentioned above, it can be concluded that when the capillary pressure build-up rates of different concretes are identical, the one with a longer dormant period is the most prone to plastic shrinkage cracking.

4.5 Influence of SP

The prolongation of the dormant period in SP1 (see Figure 12), can be attributed to the retarding effect of the polycarboxylate ether based SP [37]. The slower hydration, facilitates more upwards transportation of the pore water, which in turn results in a higher cumulative evaporation, see Figure 11. It ought to be remarked, that the measured initial evaporation rate was almost the same for all specimens, which indicates that the later difference in the evaporation rate, most occurs probably, due to the change of the intrinsic permeability.

As it can be seen in Figure 12, the capillary pressure build-up rate decreased by raising the SP dosage. The trend can be explained based on the impact of SP on the concrete pore, i.e. intrinsic permeability. As the initial porosity of the mix decreases because of the formation of hydration products, especially C-S-H, the lower hydration rate - in this case induced by the retarding effect of the SP - causes slower reduction of the initial porosity [37]. Consequently, the pore pressure increases at a lower rate.
However, lower hydration rate of SP1 prolongs the dormant period, which means that the specimens' tensile strength is very low and may easily be exceeded by the induced tensile stresses.
On the contrary, despite of the faster capillary pressure build-up in SP0.6, its tensile strength develops fast enough - due to its shorter dormant period - to withstand the rapidly increasing tensile stresses. Similar results have been observed previously by Esping and Löfgren [4].

4.6 Relationship of capillary pressure and dormant period

According to the results of this research, it is not possible to explain the cracking severity of the tested mixtures, only based on the evaporation. Instead, it seems that the risk of plastic shrinkage cracking tendency of concrete is a function of the capillary pressure rate and the length of the dormant period. Accordingly, the cracking tendency of concrete, or in this case the measured crack area, can be described as:

$$CA \propto \frac{dP}{dt} \times t_d \quad (1)$$

Where CA is the crack area, P is the capillary pressure, and t_d is the length of the hydration dormant period.

By plotting the crack area (Figures 3, 6 and 10) versus the product of the multiplication of the capillary pressure build-up rate and the length of dormant period (Table 4), a general similarity may be observed (i.e. both the crack area and the multiplication product increase or decrease simultaneously), see Figure 15. The only exception is W/C55, which is still in the range of 0.45 to 0.55 w/c ratio, at which the plastic shrinkage cracking risk does not change significantly [20]. Hence, for assessing the cracking severity of plastic concrete, without knowing its volumetric deformation, the combined effect of capillary pressure and hydration rate should be considered.

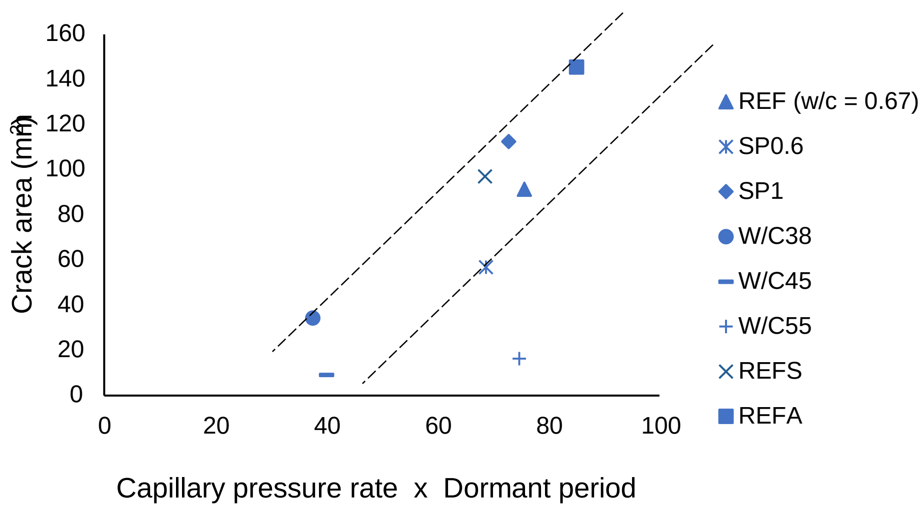

Figure 15 - Crack area versus capillary pressure build-up rate multiplied by the length of the dormant period.

Note that in all specimens, the capillary pressure started to increase around 1 hour after the beginning of the measurements (2 hours after the time of mixing), see Table 4, and thus, the effect of the pressure onset time can be disregarded. Otherwise, assuming constant capillary pressure build-up rate, the sooner the pressure starts to increase, the higher the cracking tendency, as the period between the tensile stress accumulation and the rapid tensile strength development – once the dormant period is ended – will be prolonged.

5. CONCLUSIONS

Plastic shrinkage cracking is a complex interaction of several variables that may change under different circumstances and conditions at early ages. These variables may influence the evaporation, in addition to the capillary pressure and hydration rate. Based on the results of this study, the following concluding remarks can be listed:

- Plastic shrinkage cracking tendency of concrete, in this study, is assumed to be directly proportional to the product of the capillary pressure build-up rate multiplied by the length of the dormant period.

- SCC with high w/c ratio (higher than 0.55), cracks mainly due to plastic shrinkage, while autogenous shrinkage is the main cause of cracking in SCCs with low w/c ratio (lower than 0.45).
- Cracks in SCC, produced by using fine rapid hardening cements are caused by plastic and partly autogenous shrinkage. On the other hand, coarse normal hardening cements result in cracking, induced mainly by plastic shrinkage.
- Higher SP dosage decreases the capillary pressure build-up rate, delays the hydration and increases the evaporation. Concretes with higher SP dosage are more prone to plastic shrinkage cracking, despite the slower capillary pressure development.
- Assuming constant length of the hydration dormant period, the rate of capillary pressure evolution must be reduced by decreasing the evaporation. This can be done, among others, by fogging and/or covering the concrete surface.

6. FUTURE WORK

The findings of this research gives a clearer picture about the role of capillary pressure and hydration rate in plastic shrinkage cracking. In future, the relationship discussed here can be used to develop new models to explain the phenomenon.

ACKNOWLEDGMENT

The authors would like to gratefully appreciate the financial support they received from the Development Fund of the Swedish Construction Industry, SBUF. Special thanks are also due to M.Sc. students and staff of the MCE and Thysell lab at Luleå University of Technology.

REFERENCES

1. Lerch, W: "Plastic Shrinkage", *ACI Materials*. Vol. 53, 1957, pp. 797-802.
2. Ravina, D & Shalon, R: "Plastic shrinkage cracking", *ACI Materials*, Vol. 65, 1968, pp. 282-291.
3. Slowik, V, Schmidt, M & Fritzsch, R: "Capillary pressure in fresh cement-based materials and identification of the air entry value", *Cement and concrete composites*, Vol. 30, 2008, pp. 557-565.
4. Esping, O & Löfgren, I: "Cracking due to plastic and autogenous shrinkage-investigation of early age deformation of self-compacting concrete-experimental study", Technical report, Chalmers University of Technology, Sweden, 2005.
5. Turcry, P & Loukili, A: Evaluation of plastic shrinkage cracking of self-consolidating concrete. *ACI Materials*, Vol. 10, 2006, pp. 272-279.
6. Esping O: "Early age properties of self-compacting concrete - Effects of fine aggregate and limestone filler". Doctoral thesis, Chalmers University of Technology, Göteborg, Sweden, 2007.

7. Lura, P, Pease, B, Mazzotta, G.B, Rajabipour, F & Weiss, J: "Influence of shrinkage-reducing admixtures on development of plastic shrinkage cracks". *ACI Materials,* Vol. 104, 2007, pp. 187-194.
8. . Persson, B: "Plastic shrinkage of self-compacting concrete". In: Jensen, O.M., Geiker, M., Stang, H. (eds.) *Proceedings of the Knud Hojgaard Conference*, Lyngby, Report R-155 DTU, 2005, pp. 43-57.
9. Gram, H.E & Piiparinen, P: "Properties of SCC: Especially early age and long term shrinkage and salt frost resistance". In: Skarendahl, Å., Petersson, Ö. (eds.) *Proceedings of the 1st International RILEM Symposium on Self-compacting Concrete*, Stockholm, RILEM Publications S.A.R.L., Bagneux, 1999, pp. 211-225.
10. Löfgren, I, Esping, O, Jensen, O, Lura, P & Kovler, K: "Early age cracking of self-compacting concrete". *International RILEM Conference on Volume Changes of Hardening Concrete: Testing and Mitigation*, Lyngby, Denmark, 2006, pp. 251-260.
11. Leemann, A & Lura, P: "Creep and Shrinkage of SCC". *In Mechanical Properties of Self-Compacting Concrete*, edited by K. H. Khayat and G. DeSchutter, New York, 2014, pp. 73–94
12. Hammer, T.A: "Cracking susceptibility due to volume changes of self-compacting concrete (SCC)". In: Wallevik, O., Nielsson, I. (eds.) *Proceedings of the 3rd International RILEM Symposium on SCC*, Reykjavik, RILEM Publications S.A.R.L., Bagneux, 2003, pp. 553-557
13. Yang, K, Zhong, M, Magee, B, Yang, C. Wang, C, Zhu, X & Zhang, Z: "Investigation of effects of Portland cement fineness and alkali content on concrete plastic shrinkage cracking", *Construction and Building Materials*, Vol. 144, 2017, pp. 279-290.
14. Esping, O, Löfgren, I, Marchand, J, Bissonnette, B, Gagné, R & Jolin, M: "Investigation of early age deformation in self-compacting concrete". *Proceedings* of the 2nd International Symposium on Advances in Concrete Science, Quebec, 2006.
15. EN 197-1, Cement: Composition, Specifications and Conformity Criteria for Common Cements, Br. Stand. Inst. London. 2000.
16. Johansen, R & Dahl, P: "Control of plastic shrinkage of cement". *Proceedings* of the 18th Conference on Our World in Concrete and Structures, Singapore, 1993.
17. CPSS- User Manual, manufactured by Research and Transfer Centre (FTZ) at the Leipzig University of Applied Science (HTWK Leipzig).
18. EN 12350e12352, Testing Fresh Concrete: Slump Test, Br. Stand. Inst, London. 2000.
19. Slowik, V & Schmidt, M: "Early age cracking and capillary pressure controlled concrete curing". *Advance in Cement-Based Materials*, Vol. 126, 2010, pp. 229-234.
20. Sayahi, F: "Plastic Shrinkage Cracking in Concrete", Licentiate thesis, Luleå University of Technology, 2016.
21. Sayahi, F., Emborg, M, Hedlund, H & Löfgren, L: "Plastic Shrinkage Cracking in Self-Compacting Concrete: A Parametric Study", *Proceedings*, International RILEM conference on Materials, Systems and Structures in Civil Engineering, MSSCE 2016, pp. 609-619
22. Boshoff, W.P & Combrinck, R:"Modelling the severity of plastic shrinkage cracking in concrete". *Cement and Concrete Research*. Vol.48, 2013, pp.34-39.
23. Dao, V.T.N, Dux, P.F & Horris, P.H: "Tensile properties of early-age concrete". *ACI Materials*, Vol. 106, 2009, pp. 483–492.
24. Hammer T.A & Fosså, K.T: "Cracking tendency of HSE: Tensile strength and self-generated stress in the period of setting and early hardening". *Materials and Structures*, Vol. 40, 2007, pp. 319-324.

25. Abel, J & Hover, K: "Effect of water/cement ration the early age tensile strength of concrete". *Transportation Research Record: Transport Research Board*, Vol. 1610, 1998, pp. 33-38.
26. Poppe, A.M & De Schutter, G: "Creep and shrinkage of self-compacting concrete". In: Yu, Z, Shi C, Khayat KH, Xie Y (eds) *Proceedings* of the 1st International RILEM Symposium on SCC. RILEM Publications S.A.R.L, Bagneux, 2005, pp. 329-336
27. Rozière, E, Granger, S, Turcry, P & Loukili, A: "Influence of paste volume on shrinkage cracking and fracture properties of self-compacting concrete". *Cement and Concrete Composites*, Vol. 29, 2007, pp. 626-636.
28. Pons, G., Proust, E & Assié, S: "Creep and shrinkage of self-compacting concrete: a different behaviour compared with vibrated concrete". In: Wallevik, Ó, Nielsson, I. (eds) *Proceedings* of the 3rd International RILEM Symposium on SCC, Reykjavik. RILEM Publications S.A.R.L., Bagneux, 2003, pp. 645-654
29. Darquennes, M.I.A, Khokhar, E & Rozière, A: "Loukili, F. Grondin, S. Staquet, Early age deformations of concrete with high content of mineral additions". *Construction and Building Materials*, Vol. 25, 2011, pp. 1836–1847.
30. Mora-Ruacho, J, Gettu, R & Aguado, A: "Influence of shrinkage-reducing admixtures on the reduction of plastic shrinkage cracking in concrete". *Cement and Concrete Research*, Vol. 39 2009, pp. 141–146
31. Ghourchian, S, Wyrzykowski, M, Baquerizo, L & Lura, P: "Susceptibility of Portland cement and blended cement concretes to plastic shrinkage cracking". *Cement and Concrete Composites*, Vol. 85, 2018, pp. 44-55.
32. Neville, A.M & Brooks, J.J: "Concrete Technology". Longman, London. 1990.
33. Ghourchian, S, Wyrzykowski, M, Baquerizo, L & Lura, P: "A poromechanics model for plastic shrinkage of fresh cementitious materials". *Cement and Concrete Research*, Vol. 31 2018, pp. 120-32.
34. Wittmann, F.H: "On the action of capillary pressure on fresh concrete". *Cement and Concrete Research*, Vol. 6, 1976, pp. 49-56.
35. Sayahi, F., Emborg, M, Hedlund, H: "Plastic shrinkage cracking in concrete: State of the art". *Nordic Concrete Research*, Vol. 51, 2014, pp. 95-16.
36. Dellinghausen, L.M., Gastaldini, A.L.G., Vanzin, F.J & Veiga, K.K: "Total shrinkage, oxygen permeability, and chloride ion penetration in concrete made with white Portland cement and blast-furnace slag", *Construction and Building Materials*, Vol. 37, 2012, pp. 652–659.
37. Gu, P, Xie. P, Beaudoin, J.J & Jolicoeur, C: "Investigation of the Retarding Effect of Superplasticizers on Cement Hydration by Impedence Spectroscopy and Other Methods". *Cement and Concrete Research*, Vol. 24, 1994, pp. 433-442.