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An advanced experimental setup to study plastic shrinkage cracking of concrete

P. Lura[1], C. Di Bella[1], P. Fontana[2], W. Trindler[1], B. Münch[1] and A. Leemann[1]

[1] Empa, Swiss Federal Laboratories for Materials Testing & Research, Dübendorf, Switzerland
[2] Bundesanstalt für Materialforschung und –prüfung (BAM), Berlin, Germany

ABSTRACT: The term plastic shrinkage cracking indicates cracks that form between the time when concrete is placed and the time when concrete sets. High temperatures, low relative humidity and high wind velocities in the first hours after placing accelerate evaporation from the fresh concrete surface and increase the cracking risk.

In this paper, the mechanisms by which evaporation of water produces underpressure within the fresh concrete, and ultimately shrinkage and cracking, are briefly discussed. The bulk of the paper describes an experimental setup for studying plastic shrinkage on concrete mixtures, which was recently developed at Empa. The integrated setup allows performing simultaneous measurements of evaporation rate, bleeding rate, pressure in the pore fluid, settlement and cracking on the same samples, while controlling precisely the temperature, the wind velocity and the relative humidity.

The influence of cement fineness on plastic shrinkage cracking of a concrete mixture is presented to show the potential of the integrated setup.

1 INTRODUCTION

One of the age-old problems in concrete is cracking. In addition to being unsightly, cracks may act as weak planes for further distress or may accelerate the ingress of aggressive agents and thereby reduce durability. In particular, fresh concrete is susceptible to plastic shrinkage cracking, which occurs between the time of placement and the time of initial set (Powers 1968).

Concrete pavements subjected to fast evaporation during the first hours after concrete placing are especially prone to this type of cracks (Figure 1). When the bleeding water on the surface of the concrete is consumed by evaporation, water menisci form. These menisci produce capillary stresses that put the whole concrete under compression and cause it to shrink (Lura et al. 2007). As long as the concrete remains plastic, the capillary stress manifests as settlement of the concrete surface.

The settlement of the plastic concrete continues until a critical point is reached a couple of hours after casting. At this critical point, the settlement suddenly stops and cracks may develop. It has been shown that the extent of plastic shrinkage cracking is directly related to the evaporation rate, to the settlement and to the magnitude of the developed underpressure, see e.g. Wittmann (1976), Radocea (1994), Lura et al. (2007), Slowik et al. (2008).

Figure 1. Concrete deck seen from above (left) and from below (right), showing through-going plastic shrinkage cracks.

With the aim of assessing the susceptibility of different concrete mixtures to plastic shrinkage cracking, an experimental setup was recently developed at Empa. The integrated setup allows performing measurements of evaporation rate, bleeding rate, pressure in the pore fluid, settlement (by non-contact lasers) and plastic shrinkage cracking (according to ASTM C-1579) simultaneously on the same samples. The temperature, the wind velocity and the relative humidity of the concrete are controlled and monitored, allowing precise and repeatable tests. The obtained cracks are quantified by automatic image analysis and a distribution of crack widths is obtained, which facilitates comparison between different mixtures.

To illustrate the application of this integrated setup, the results of three concrete mixtures with different cement fineness (CEM I 32.5 N, CEM I 42.5 N and CEM I 52.5 R) are presented in this paper.

2 MATERIALS

Three concrete mixtures with water to cement ratio (w/c) 0.5 were produced (Table 1). The aggregate used was alluvial sand and gravel, about 71% by volume. Superplasticizer (Viscocrete 3082 by Sika) was added at a rate of 0.2% by mass of cement to control workability. The three mixtures differed for the Blaine fineness of the Portland cement: 2530 cm^2/g for CEM I 32.5 N, 3150 cm^2/g for CEM I 42.5 N and 4510 cm^2/g CEM I 52.5 R. A volume of 60 litres was produced for each mixture in an Eirich mixer (maximum batch size of the mixer was 80 litres).

Table 1. Mixture composition and some properties of concrete with different cement fineness

Type of cement	CEM I 32.5 N	CEM I 42.5 N	CEM I 52.5 R
Aggregate 0/16 mm [kg/m^3]	1858	1858	1858
Cement content [kg/m^3]	352	352	352
w/c	0.5	0.5	0.5
Superplasticizer [mass-% of cement]	0.2	0.2	0.2
Air content [volume-%]	4.0	3.9	3.4
Flow [cm]	40	40	40
Density [kg/m^3]	2333	2336	2358

3 METHODS

3.1 Fresh concrete properties and bleeding

Concrete flow was measured according to EN 12350-5 immediately after mixing. The density was measured according to EN 12350-6. Air content was measured according to EN 12350-7. Bleeding was measured according to European Standard 480-4 for 5 hours. It is noticed that bleeding was measured on samples covered with a lid to prevent evaporation from the surface.

3.2 Plastic shrinkage cracking

Plastic shrinkage cracking according to ASTM C1579-06 was measured on two samples per mixture. Two moulds (355×560×100 mm^3), provided with steel inserts to initiate cracking (Figure 2), were filled with concrete and vibrated on a vibration table until compaction. The moulds were moved to a climate chamber with temperature 30±1°C and relative humidity (RH) 45±5%, provided with a wind tunnel (Figure 3). Temperature, RH and wind velocity (7±0.5 m/s) were monitored at the concrete surface by coupled temperature/RH sensors and by anemometers. This allowed verifying that the parameters governing evaporation rate from the fresh concrete remained constant throughout a test and comparable between different tests. Figure 4 shows an example of temperature and RH measurements during a typical test (left) and a measured distribution of the wind velocity at the concrete surface (right).

The age at cracking was determined by visual inspection every 30 minutes. The crack width distribution was obtained from image analysis of the cracked concrete surface (Qi et al. 2003) at the end of the experiment, about 6 hours after casting. The crack width was measured using an automated image analysis approach, which retrieved the thickness of the whole plastic shrinkage crack (or the cumulated thickness of multiple, parallel cracks) along the path over the stress riser. The minimum detectable crack width was about 0.02 mm. The obtained crack-width distribution for two specimens was then averaged to obtain the distribution of a single mixture.

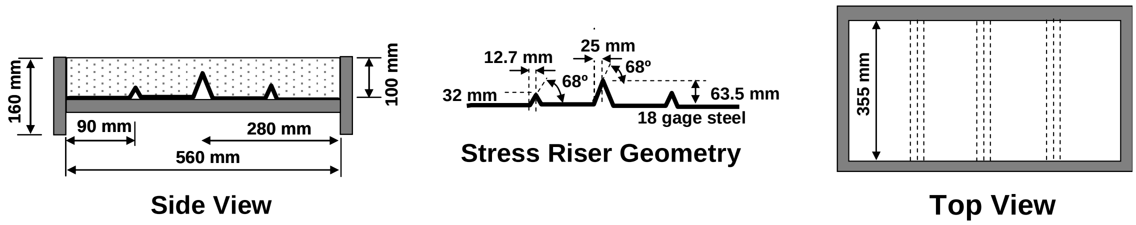

Figure 2. Moulds for measurements of plastic shrinkage cracking according to ASTM C1579-06 (from Lura et al. (2007)).

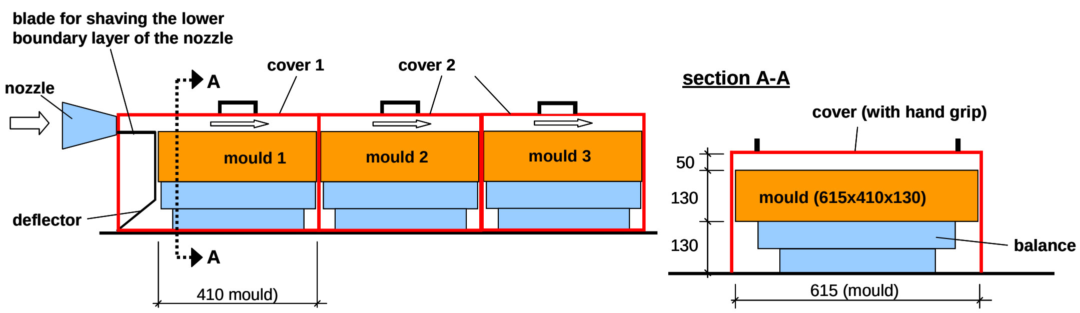

Figure 3. Schematic view of the setup for studying plastic shrinkage cracking of concrete mixtures.

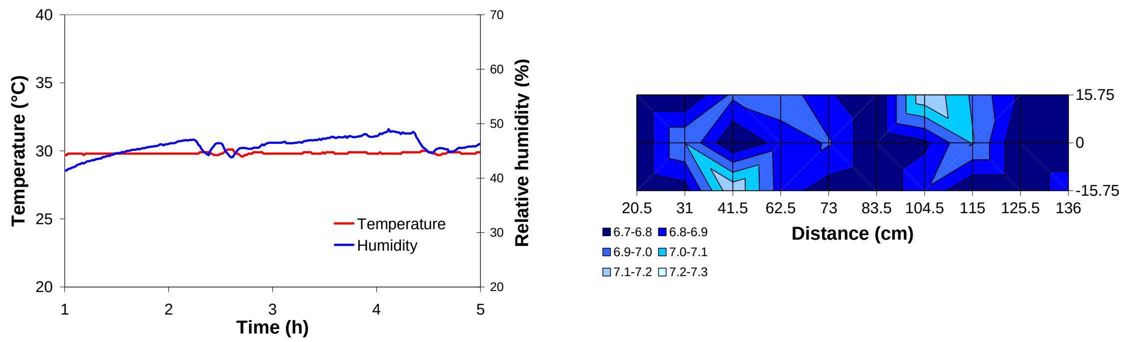

Figure 4. Temperature and relative humidity measurements during a typical test (left) and wind velocity measured at the surface of the concrete in the plastic shrinkage molds (right).

3.3 *Rate of evaporation, settlement and pore pressure*

Rate of evaporation, settlement and pore pressure were all measured directly on the same samples used to measure plastic shrinkage cracking.

One of the two moulds employed for the plastic shrinkage cracking test (see section 3.2) was placed on a balance equipped with automatic data logging. The evaporation from the concrete surface was obtained simply by dividing the mass loss by the surface exposed to evaporation.

Measurements of settlement of the fresh concrete surface were performed with non-contact lasers (Kayir & Weiss 2002, Lura et al. 2007) on the surface of the plastic shrinkage cracking specimens (Figure 5, left). The vertical displacement of the surface of the concrete was measured every 30 seconds from the time of finishing (about 15 minutes after water was added). The non-contact laser measurement devices consisted of a laser beam projected at a small angle from the vertical direction toward the specimen surface. The distance from the laser head to the surface is calculated by measuring the horizontal displacement of the reflected beam. Two measurements were taken on one mould and one on the second mould for each mixture. The settlement was measured at locations far from the sides of the moulds or the stress risers.

Measurements of pore pressure were performed with tensiometers (Radocea 1994, Slowik et al. 2008), consisting of a pressure sensor connected to a metallic tube by a rubber hose. The sensor and the tube were filled carefully with degassed water to avoid the formation of air bubbles. The tubes were inserted into the plastic shrinkage cracking moulds through holes in the mould before casting (Figure 5, right). After casting, the pressure in the pore fluid of the concrete was transmitted by the water in the tubes to the pressure sensors.

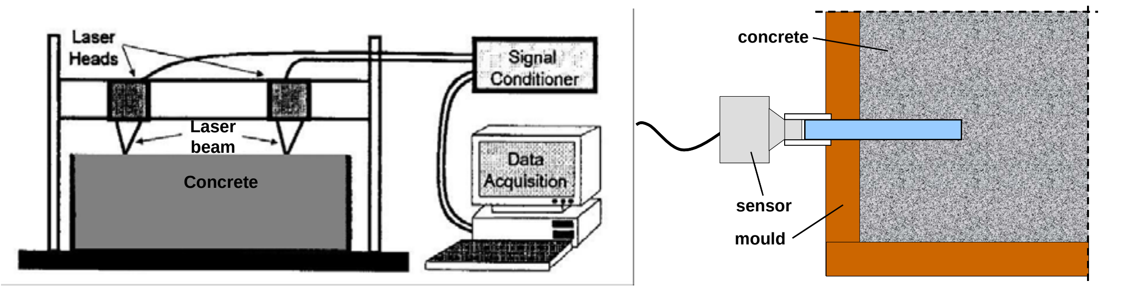

Figure 5. Schematic of settlement measurements by non-contact lasers (left) and of pore pressure measurements by tensiometers (right).

4 RESULTS AND DISCUSSION

4.1 Fresh concrete properties, bleeding and evaporation

Fresh concrete properties are reported in Table 1. Bleeding is shown in Figure 6, left, as a percentage of the total water content in the mixture; the bleeding measurements were repeated for CEM I 32.5 N and CEM 52.5 R. It is noticed that bleeding is inversely proportional to cement fineness. The mixture containing CEM I 32.5 N bleeds about twice as much as the mixture with CEM I 42.5 N and about eight times more than the mixture with CEM I 52.5 R. This effect was expected, as finer cement particles tend to settle less in the mixture and in addition cement hydration, which binds part of the water, is accelerated with finer cements. Evaporation from the concrete mixtures is shown in Figure 6, right. The evaporation rate is similar in all mixtures in the first 2 hours, after which the evaporation rate of the mixture with CEM I 52.5 R decreases.

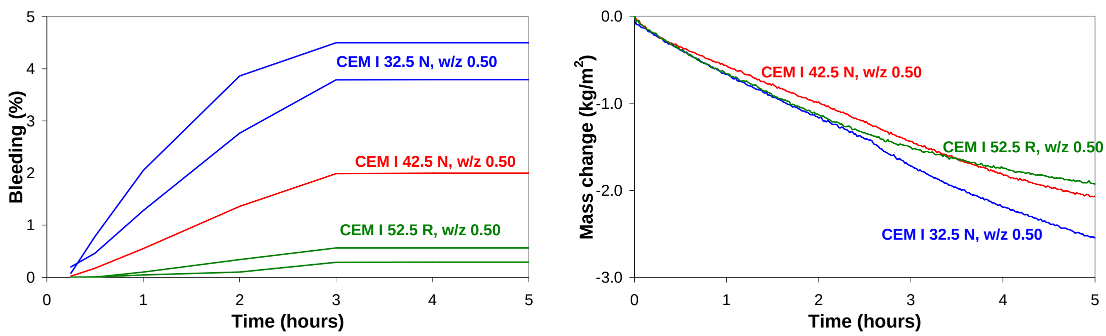

Figure 6. Bleeding (left) and mass change due to evaporation (right) of concrete mixtures with w/c 0.5 differing in the cement fineness.

4.2 Settlement and pore pressure

The settlement of the fresh concrete was measured by non-contact lasers at three different positions on the concrete surface. In Figure 7, left, the average of three measurements is shown for each concrete mixture. The settlement is highest for the mixture with CEM I 42.5 N and lowest for the mixture with CEM I 32.5 N. The underpressure in the pore fluid (Figure 7, right) appears to be directly proportional to the fineness of the cement. This is a consequence of the fact that the capillary forces in the fresh mixture are inversely proportional to the radius of the menisci that form between the cement particles (Lura et al. 2007).

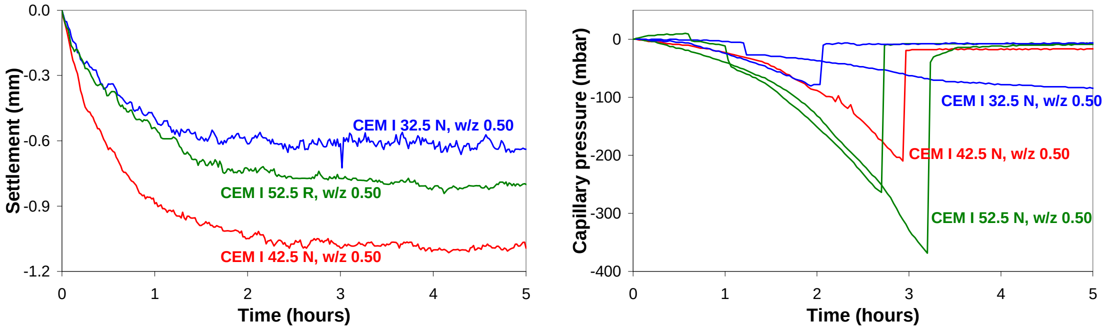

Figure 7. Settlement (left) and capillary pressure (right) of concrete mixtures with w/c 0.5 differing in the cement fineness.

4.3 Plastic shrinkage cracking

None of the four tested samples of the mixture with CEM I 32.5 N cracked. In the case of CEM I 42.5 N, 2 samples out of 2 cracked after 2.5 hours. 3 out of 4 samples showed plastic shrinkage cracks in the mixture with CEM I 52.5 R. The samples with CEM I 42.5 N had wider cracks than the samples with CEM I 52.5 R (Figure 8).

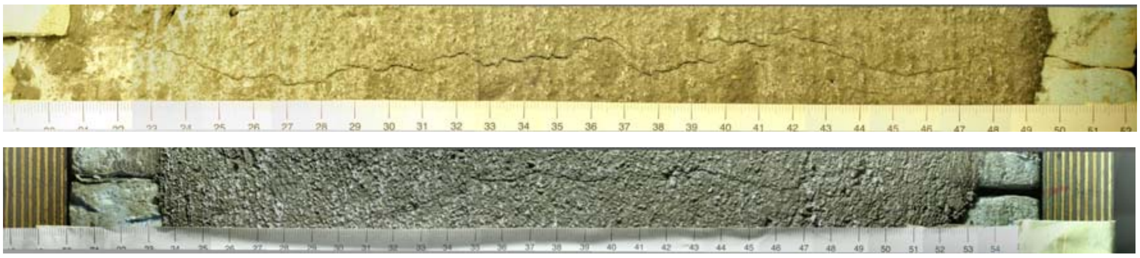

Figure 8: Example of plastic shrinkage cracks in concrete with CEM I 42.5 N (above) and in concrete with CEM I 52.5 R (below).

5 DISCUSSION

The fact that the specimen with CEM I 32.5 N did not crack can be explained by its higher bleeding (Figure 6, left) that retarded the onset of capillary stresses and decreased their magnitude (Figure 7, right). This reduced the settlement of the plastic concrete (Figure 7, left) and avoided plastic shrinkage cracks. On the other hand, the other two mixtures with finer cements showed consistently lower bleeding, higher capillary stresses and settlement, and consequently developed plastic shrinkage cracks.

It is more difficult to explain why the mixture with CEM I 52.5 R showed lower settlement and smaller plastic shrinkage cracks than the mixture with CEM I 42.5 N, despite the higher capillary stresses measured for this mixture. A possible explanation is that due to the higher cement fineness, some cement hydration had already taken place in the mixture with CEM I 52.5 R. As a consequence, the concrete may have developed some tensile strength (besides the cohesion of the particles in the mixture) that allowed it resisting in part the capillary stresses and reducing the extent of cracking. A possible confirmation of this hypothesis is that the evaporation rate progressively decreased in this mixture after 2 hours (Figure 6, right), which might be due to the onset of hydration.

6 CONCLUSIONS

This paper presented an integrated setup which was recently-developed at Empa with the aim of assessing the susceptibility of different concrete mixtures to plastic shrinkage cracking. Measurements of evaporation rate, bleeding rate, pressure in the pore fluid, settlement and plastic shrinkage cracking are performed simultaneously on the same samples. At the same time, the temperature, the wind velocity and the relative humidity of the concrete are controlled and monitored, allowing precise and repeatable tests.

An application of the setup for studying plastic shrinkage cracking of mixtures with cement of different fineness showed that concretes made with finer cements are more sensitive to plastic shrinkage cracking. This can be explained by their lower bleeding, higher capillary stresses and higher settlement.

The integrated setup is currently being applied for studying the influence of different parameters on plastic shrinkage cracking, including water to cement ratio, volume of cement paste in the mixture, cement type (different blended cements), admixtures (shrinkage reducing admixtures, viscosity modifiers, internal curing agents) and curing regimes (curing compounds, spraying with water).

The methods described in this paper are an important tool not only for understanding the mechanisms leading to plastic shrinkage cracking but also for optimizing the mix design of concrete in order to minimize cracking risk and prevent damages.

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