Capillary pressure monitoring in plastic concrete for controlling early age shrinkage cracking

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ABSTRACT

Cracking of concrete in its plastic stage is mainly caused by the build-up of a capillary pressure in the pore water of the material. Evaporation leads to the loss of water and, eventually, the solid particles at the surface can no longer be covered by a plane water film. The curved water surface between these particles leads to contracting forces and, possibly, to cracking. If the capillary pressure as the driving force for plastic shrinkage cracking is monitored by appropriate technical means, it would be possible to evaluate the cracking risk on site and to control curing measures accordingly. The measured capillary pressure captures the influences of the material composition, of the environmental conditions and of the member's geometry. Therefore, it is a direct indicator for the early age cracking risk. For the on-site capillary pressure measurement, a newly developed wireless sensor system is presented. Possible fields of application are the control of curing measures, the evaluation of their efficiency, and the characterization of concrete compositions with respect to their vulnerability to plastic shrinkage cracking.

1 INTRODUCTION

Planar concrete structures with an exposed surface, like floors, airfields, roads, and bridge decks, are especially prone to cracking in the plastic material stage, i.e., before final setting. Evaporation at the surface leads to the loss of water. By appropriate curing measures, the evaporation rate may be reduced significantly and cracking is normally prevented. Nevertheless and despite the advances in concrete technology, plastic shrinkage cracking is still a serious and not completely solved problem in the construction industry. This may be attributed mainly to the numerous influences on the early age cracking risk, which stem from the material properties, from the climatic conditions affecting the evaporation rate, and from the member’s geometry. It is therefore difficult to predict the cracking risk. The evaporation rate may reliably be determined by appropriate technical means. The other aforementioned influences, however, are not captured in this way.

It is well known that concrete cracking in the plastic stage is caused by the capillary pressure build-up in the liquid phase of the material (1-5). An attempt has been made to directly measure this pressure on site and to use the measurement results for evaluating the cracking risk as well as the efficiency of curing measures.

2 CAPILLARY SHRINKAGE CRACKING

It can be observed in nature that drying suspensions may crack as a result of water loss. Plastic concrete, i.e., concrete before hardening, exhibits a similar behavior. In Figure 1, the process of capillary pressure build-up which may eventually lead to cracking is shown schematically. After the placement of the concrete, all solid particles are normally covered by a plane water film the thickness of which may increase due to bleeding or decrease due to evaporation, see Figure 1, Stage A. If the evaporation rate is high enough, the plane water film will disappear after a certain time period. Then, a curved water surface is formed between the particles at the surface, see Figure 1, Stage B. As a consequence, a pressure difference between the water and the surrounding air is being built up. This difference results from the equilibrium of forces and is referred to as capillary pressure. While more water is removed from the system, the curvature of the water surface will increase and accordingly the capillary pressure, see Figure 1, Stages B through E. This leads to increasing contracting forces and a compaction of the material, the so-called plastic or capillary shrinkage. At some point in time, the curved water surface can no longer bridge all the pores and air penetrates the pore system which has been fully saturated up to this point. The air entry is a local event and starts at the largest pores. When the capillary pressure is measured exactly at a location where air entry occurs, it will “break through”, i.e., it will suddenly drop down, see Figure 1, Stage E. It has been shown experimentally (4, 5) as well as numerically (6, 7) that the pores where air entry has occurred are weak points at the concrete surface and may be the origin of cracks. This is due to the fact that in these pores the attracting forces between the solid particles have vanished leading to strain localization under the increasing capillary pressure. Consequently, cracking of drying suspensions may be prevented by avoiding air entry. Crack formation requires air entry. However, air entry does not necessarily lead to cracking (4-7). The latter requires also sufficient particle mobility.

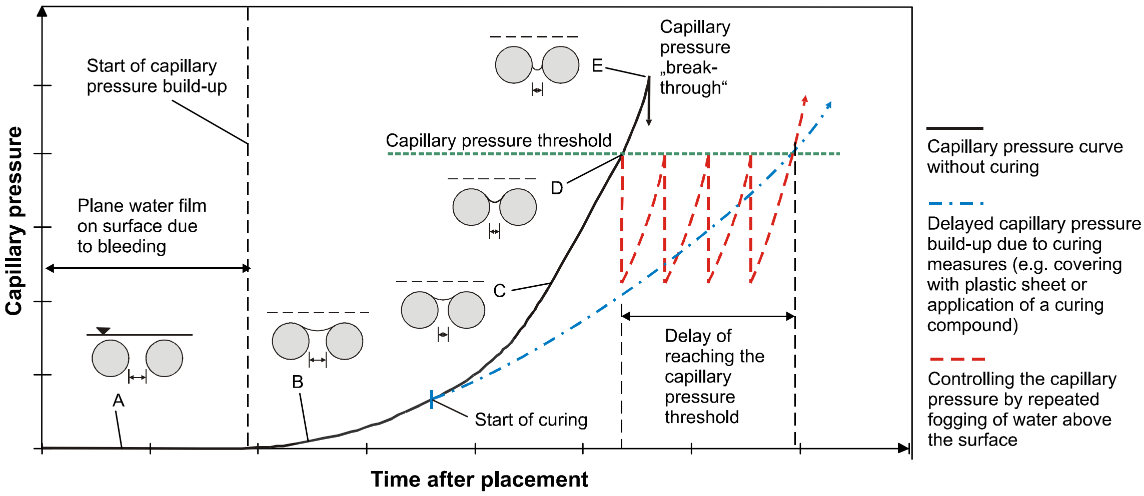

FIGURE 1 Capillary pressure development and effect of curing measures on the capillary pressure.

The capillary pressure at the first event of air entry is referred to as air entry pressure, a term which is also used in soil mechanics for describing a similar phenomenon (8). If in the plastic material stage the capillary pressure is kept below this limit, cracks will not be formed. In laboratory experiments (4, 5), a material-dependent critical capillary pressure may be identified and accordingly a pressure threshold, see Figure 1, which should not be exceeded in the plastic concrete.

It is possible to decrease the capillary pressure by rewetting, see Figure 1, red curve. Fogging of water above the surface results in a decrease of the curvature of the water surface and, consequently, in a pressure drop. The pressure will increase again, however, when the fogging is terminated. It has been shown in laboratory and field experiments that by a closed-loop capillary pressure controlled rewetting the measured pressure may be kept between two limits (4, 5, 9). When the upper threshold is reached, the rewetting is started, and at the lower limit the rewetting is stopped. It is not advisable to decrease the pressure down to zero since this would mean that a new water film is created on the surface. When the concrete has gained enough strength to withstand the capillary pressure, the controlled rewetting is no longer necessary for preventing capillary shrinkage cracks.

The monitoring of the capillary pressure build-up is also useful for evaluating the efficiency of concrete curing. The blue curve in Figure 1 shows schematically the effect of curing measures which reduce the evaporation rate. The slope of this curve is not as steep as in the uncured concrete. Hence, a previously defined threshold pressure is reached at a later age. At this age, the concrete has gained more strength and may presumably resist the capillary pressure.

In laboratory tests, the effect of a wax based curing compound was to be investigated. Two samples of size 30 cm×30 cm×10 cm (11.8 in.×11.8 in.×3.9 in.) were cast and subjected to constant drying conditions (25°C (77°F), 45 % relative air humidity, average wind speed 2.4 m/s (7.9 ft/s)). A concrete composition developed for road construction has been used. On one of the samples, the curing compound was applied when the surface appeared as pale damp. The other sample remained uncured. Figure 2, left, shows the evaporation rate which appears to be significantly reduced by the curing compound. The measured capillary pressure is presented in Figure 2, right. It may clearly be seen that the pressure build-up is decelerated, but not completely prevented. Nevertheless, delaying the pressure build-up will reduce the cracking risk since a critical pressure which might trigger crack initiation is reached at a later age when the concrete has developed more cracking resistance.

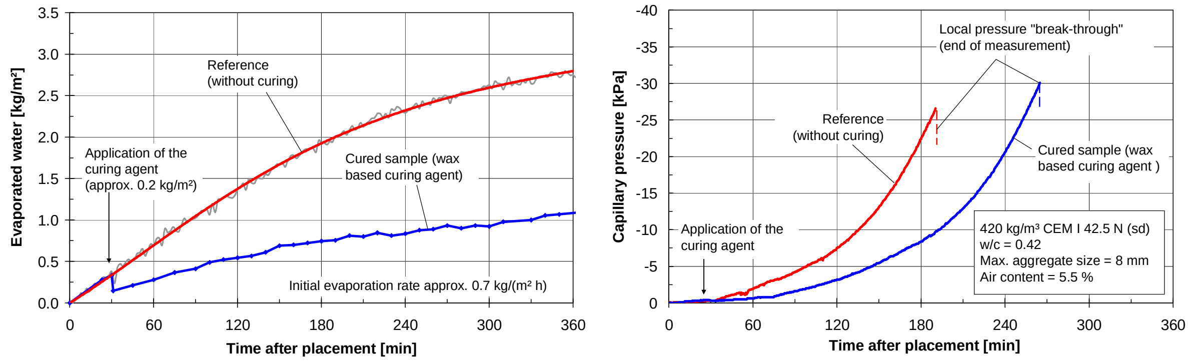

FIGURE 2 Water loss (left) and capillary pressure (right) versus time in cured and uncured concrete (1 kPa ≈ 0.145 psi, 1 mm ≈ 0.04 in., 1 kg/m² ≈ 0.205 lb/ft², 100 kg/m³ ≈ 168.5 lb/yd³).

The capillary pressure build-up may also serve for identifying the correct time for the application of curing compounds. Some of these agents need to be applied exactly when the surface appears as pale damp. This is the moment when the mirror-like plane water film on the concrete surface has vanished and the capillary pressure starts to build up. Hence, this point in time may reliably be determined by the capillary pressure measurement.

3 CAPILLARY PRESSURE SENSORS

The capillary pressure in fully saturated suspensions, also in cementitious ones, has been measured by several researchers under laboratory conditions (1-4, 10). Typically, a pressure transducer with a water-filled measurement tip is used. The latter connects the transducer to the water in the pore system of the material. For an accurate measurement, degassed water should be used and a bubble-free filling of the tip has to be ensured.

The challenge was to develop an easy-to-use sensor which would allow to reliably measure the capillary pressure also under site conditions. Figure 3, left, shows the concept. A manufacturer-calibrated pressure transducer is used which measures the pressure difference between the fluid at the measurement port and the atmosphere. It has a stable casing in order to protect the electronic components. A cable provides power supply and the connection to the data logger. The conic standardized pipette tip made of transparent plastic allows for a hydraulic connection between the sensor and the pore system of the material. Because of the transparent plastic, the tip may easily be checked for correct bubble-fee water filling. The conic shape allows inserting the capillary pressure sensor into fresh concrete surfaces after casting and compaction, see Figure 3, right. If the sensor tip is embedded deep enough in the concrete, approximately 4 cm to 5 cm (1.6 in. to 2 in.) for normal concrete compositions, the entire weight of the sensor is supported by the conic tip due to side friction. This ensures a stable position during the measuring process. The opening at the end of the tip has a diameter of about 1 mm (0.04 in.). It has to be noted that this type of sensor tip is applicable only for fully water-saturated suspensions, i.e., the pore system has to be almost completely filled with water. If air penetrates the pore system and reaches the sensor tip, the measured pressure breaks through, see Figure 1, E.

After the sensor has been extracted from the concrete surface, the remaining hole should be filled with an appropriate cementitious material.

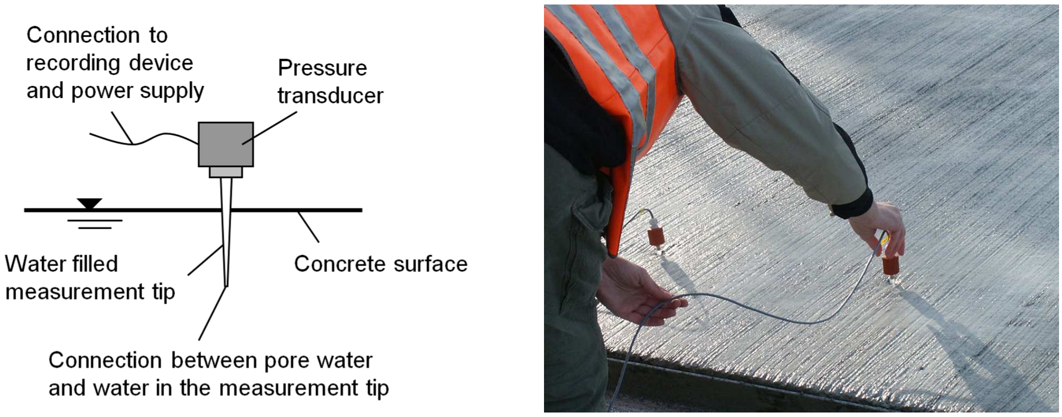

FIGURE 3 Schematic view of a capillary pressure sensor (left); application of capillary pressure sensors to a fresh concrete pavement in airfield construction (right).

During first practical applications, see Figure 3, right, it soon became clear that cable connections limit the applicability of the sensors. They hinder surface finishing and, if they are moved, the hydraulic connection between pore water and sensor may be lost. For this reason, a wireless capillary pressure sensor system has been developed. The sensors, see Figure 4, automatically connect to a base station. Their casings are completely sealed and, after the measurement, the built-in batteries are recharged by electromagnetic induction.

FIGURE 4 Wireless capillary pressure sensors applied to a bridge deck.

Figure 5 shows the newest prototypes of wireless capillary pressure sensors. In addition to the capillary pressure, the sensor in Figure 5, left, will allow to monitor environmental conditions, as are air temperature, relative air humidity, and sun radiation. Figure 5, right, shows a three-legged prototype which measures also the concrete temperature. On the basis of the measured data, the evaporation rate may be estimated and it is possible to keep records on the environmental conditions.

An advantage of the three-leg design is the reduction of the embedded depth of the sensor tips which is required for a stable sensor position. Hence, the remaining holes in the concrete surface will be smaller. An embedded depth between 1 cm and 2 cm (0.4 in. to 0.8 in.) is recommended.

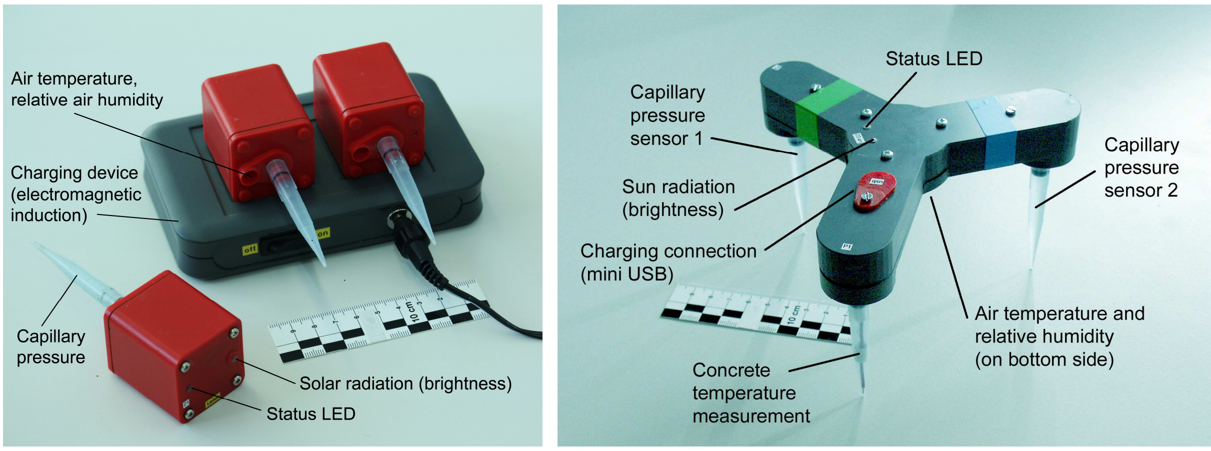

FIGURE 5 Prototypes of an enhanced capillary pressure sensor (left); prototype of a capillary pressure sensor in three-leg design (right); total length of the ruler is 10 cm (3.94 in.).

Possible fields of application for the capillary pressure sensors are the characterization of concrete compositions with respect to the cracking risk, the evaluation of the efficiency of curing measures, and the identification of the correct time for their application. In this context, a closed-loop capillary pressure controlled curing by rewetting of concrete surfaces was also discussed and tested (4, 5, 9).

4 APPLICATION

Several on-site measurements in bridge and pavement construction have been performed with the wired as well as with the wireless capillary pressure sensors (5, 9, 11, 12).

Figure 6 shows the capillary pressure measured with two sensors in a 0.4 m (1.3 ft) thick bridge coping. It should be mentioned that with both sensors almost the same pressure was obtained. This is usually the case during such measurements. All the pores are interconnected at this age. Nevertheless, it is recommended to use under site conditions multiple sensors, i.e., at least two sensors in each concreting step for bridge decks or floors, in order to enhance the reliability and robustness of the instrumentation. In concrete road construction, a sensor spacing between 20 m and 40 m (22 yd and 44 yd) is appropriate whereby a minimum distance of about 25 cm (10 in.) from the edge is recommended.

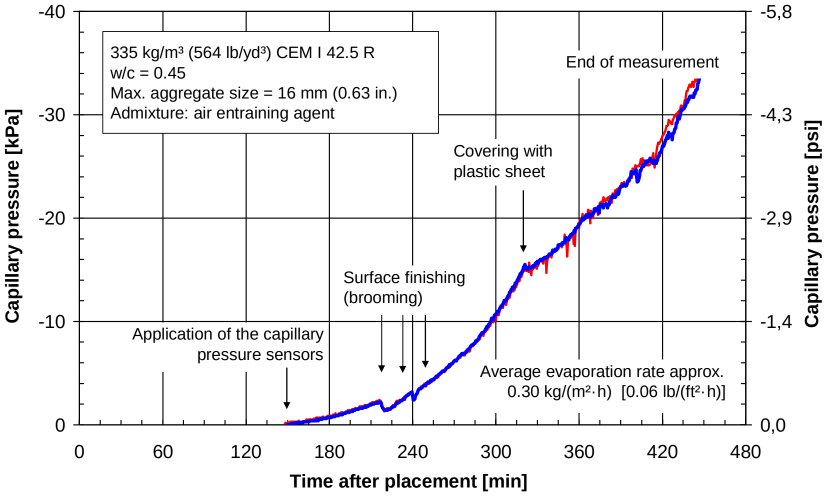

FIGURE 6 Capillary pressure versus time, measured in a bridge coping.

The concrete had a cement content (Portland cement CEM I 42.5 R) of 335 kg/m³ (564 lb/yd³) and a water-binder ratio of 0.45. An air-entraining admixture was used. For the unprotected concrete surface, a nearly constant evaporation rate of about 0.30 kg/(m²·h) (0.06 lb/(ft²·h)) was measured by using a Curing Meter, a measurement tool developed by Jensen (13).

The capillary pressure sensors had a distance of about 40 cm (16 in.) and were applied approximately 150 minutes after placing and compacting. After sensor application, the measured pressure values were zeroed. Because of the immediate, but comparatively slow pressure build-up, it is assumed that the formation of menisci started approximately at the time of sensor application. About 3.5 hours after placement, the concrete was textured by using a broom in order to obtain a slip-resistant surface. During this process, the particles at the surface were probably rearranged and the measured capillary pressure was temporarily influenced. After the brooming, the absolute pressure value continued to rise continuously. At about 5 hours and 20 minutes, a plastic foil was placed on the surface. As a consequence, the slope of the capillary pressure curve decreased because of the significantly reduced evaporation rate. Due to some space between the concrete surface and the foil, evaporation of water could not completely be prevented. The external water loss and also the internal water consumption by the beginning chemical reactions resulted in a continuing rise of the absolute capillary pressure value. After placing the foil, some discontinuities in the measured capillary pressure curves were observed which may be attributed to sporadic contact between plastic foil and sensors. In this particular case, the discontinuities did not influence the overall result. It should be noted, however, that the sensors should generally not be moved during the measurement process. Due to the cables, this could not be completely avoided here. Wireless sensors were not yet available at that time.

In summary, protecting the concrete surface by the plastic foil had a noticeable effect on the capillary pressure build-up. The latter was delayed resulting in a reduced early age cracking risk.

5 CONCLUDING REMARKS

Shrinkage of plastic concrete is mainly caused by the build-up of a capillary pressure in the pore system of the material. If a critical pressure value is reached, the plastic material may crack. By appropriate curing measures, the capillary pressure build-up is prevented or delayed. The delay reduces the cracking risk since the resistance of the concrete is increasing in time.

It has been shown that the capillary pressure can easily be measured under site conditions with wireless sensors. Unlike the evaporation rate, the measured capillary pressure captures not only the environmental influences on the cracking risk, but also those stemming from the material composition and from the member's geometry. On the basis of the measured capillary pressure, it is possible to make decisions concerning the correct timing of curing measures and to evaluate the effect of such measures. This allows to reduce the early age cracking risk.

The measured capillary pressure may also serve as feedback for a closed-loop controlled rewetting of concrete surfaces in order to reliably prevent plastic shrinkage cracking.

ACKNOWLEDGMENTS

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