CAPILLARY SHRINKAGE CRACKING AND ITS PREVENTION BY CONTROLLED CONCRETE CURING

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Abstract

The build-up of a negative pressure in the liquid phase of a drying suspension may lead to cracking. In concrete construction, this effect results in damage processes taking place already in the very early age, i.e. within the first few hours after casting when the concrete has not yet reached a significant strength. For avoiding this type of damage, a method of controlled concrete curing has been proposed. It is based on in situ capillary pressure measurement and closed-loop controlled rewetting of fresh concrete surfaces. The capillary pressure is kept below a critical value and an uncontrolled application of too much water to the concrete surface is prevented. The method has been tested under laboratory as well as under site conditions.

1. INTRODUCTION

Under high evaporation rates, mainly caused by wind, low relative air humidity and high temperature, concrete may crack even before the material has reached a significant strength. Figure 1 shows a concrete slab which has been cast on a sunny and windy day. Since the curing was not started at the right time, cracks were formed within the first four hours after casting. These cracks had widths of about 1 mm and large depths. Some of them split the whole structure.

The process which leads to this type of early age cracking is the so-called plastic or capillary shrinkage. Water loss causes the build-up of a negative capillary pressure in the water filled pore system of the plastic material. Especially in high performance concrete with low water-binder-ratios, the capillary pressure development in the very early age is also affected by self-desiccation. If the capillary shrinkage is hindered cracks may occur.

In many cases, early age cracks are not as large and visible as shown in Figure 1. Sometimes these cracks are very small or they are temporarily covered during surface finishing. Nevertheless, they might have an effect on the structural durability. Numerical simulations have shown that early age damage may influence drying shrinkage cracking of the hardened concrete [1] as well as the cracking under the action of external forces.

Figure 1: Cracks in a concrete slab caused by capillary shrinkage

2. CAPILLARY PRESSURE DEVELOPMENT

After the placing of the concrete, its surface is normally covered by a thin film of water (Figure 2, A). Consolidation of the solid particles contributes into the accumulation of water at the concrete surface. This effect is called bleeding. When water on the surface evaporates and the surface is not completely covered by a plane water film anymore, menisci are formed between the solid particles, see Figure 2, B.

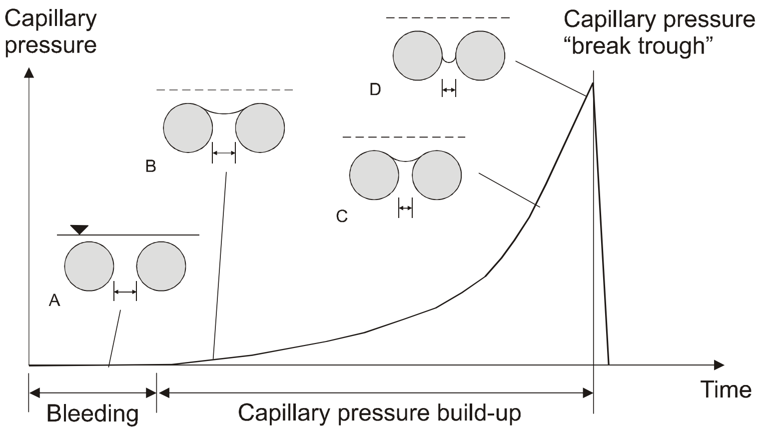


Figure 2: Capillary pressure build-up

The formation of the menisci results in a negative capillary pressure in the water filled pores. This physical process is described by the Gauss-Laplace-Equation:

$$p = -\gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{1}$$

with p = capillary pressure, γ= surface tension of the fluid and R_1, R_2 = main radii of the curvilinear fluid surface.

The capillary pressure is inversely proportional to the radii of the menisci. The smaller the spaces between the particles, the smaller the radii of the menisci and the higher the absolute capillary pressure value can become. Since the pressure acts on the solid particles of the drying suspension it results in a contraction of the material. Hence, the pores formed by the solid particles are becoming smaller (Figure 2, C). During this process, water is drawn out of the pores and transported to the surface where it evaporates. This happens until the particles can not get closer anymore due to restrictions like contact and friction or due to chemical processes like hydration. If not enough water is transported to the surface and the radii of the menisci become as small as the pore diameter (Figure 2, D), air penetrates into the pore system, at first into the lager pores. The capillary pressure “breaks through” locally. This phenomenon has also been observed in inert materials. In soil mechanics, the pressure at the start of air entry is referred to as air entry value [3].

The development of the capillary pressure and the air entry value are affected by several influences like particle size distribution, evaporation rate and mobility of the particles. Especially the amount of small sized particles like cement, fly ash or silica fume affects the observed process because these particles form a narrow pore system which allows for smaller menisci and higher pressure values.

Capillary pressure build-up and shrinkage can be numerically simulated on the particle level [4]. This allows to study the effects of different influences on the observed phenomena.

In cement paste, mortar, concrete, and also in inert materials like soils, the capillary pressure may be measured by using pressure sensors. Usually, a water filled tube connects the pore system of the material to the actual sensor element. The use of such sensors for cement based materials has been described by several authors, e.g. in [2] [5] [6].

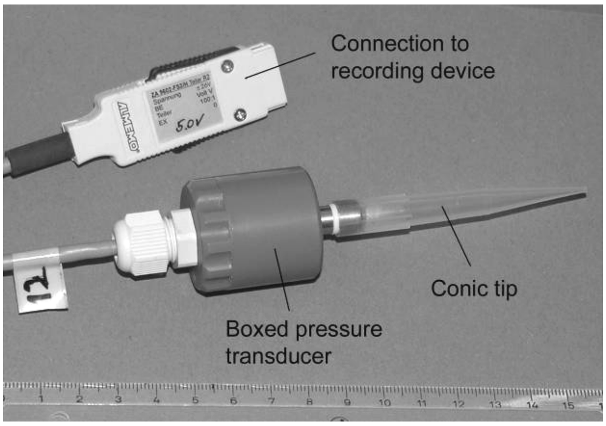
The pressure “break-through” shown in Figure 2 is taking place when air reaches the sensor tip. Because of material inhomogeneous, this is a local event. At other sensor positions, the break-through might occur earlier or later. Therefore, the local break-through can not be used as an indicator of reaching the air entry value. Previous experimental investigations have shown that the air entry value may be identified by deformation and electric conductivity measurements [7].

The aired pores are weak points in the system and the origin of strain localisation and cracking. If the described air entry takes place at a time when the material has not reached a significant strength yet, the cracking risk significantly increases.

3. CAPILLARY PRESSURE MEASSUREMENT UNDER SITE CONDITIONS

For measuring the capillary pressure under site conditions, optimized light-weight capillary pressure sensors were built, see Figure 3 (left). They have a conic water filled sensor tip and can be applied to the concrete surface after casting and compacting. The conic tip carries the sensor’s weight and provides the hydraulic connection between the pore water in the material and the sensor element. A cable connects the sensor with a digital recording device and supplies it with power.

The cable connection, unfortunately, limits the usability of the capillary pressure sensors under site conditions because the cables hinder surface finishing and, if they are moved, the hydraulic connection between pore water and sensor may be interrupted. Therefore, capillary pressure sensors with an integrated radio module were developed and prototypes have been tested successfully. These wireless sensors connect automatically to a base station within a radius of about 50 m and allow the monitoring of comparably large planar concrete structures like roads or bridge decks.



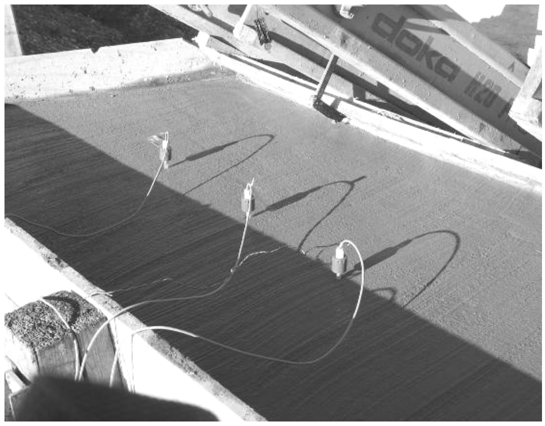
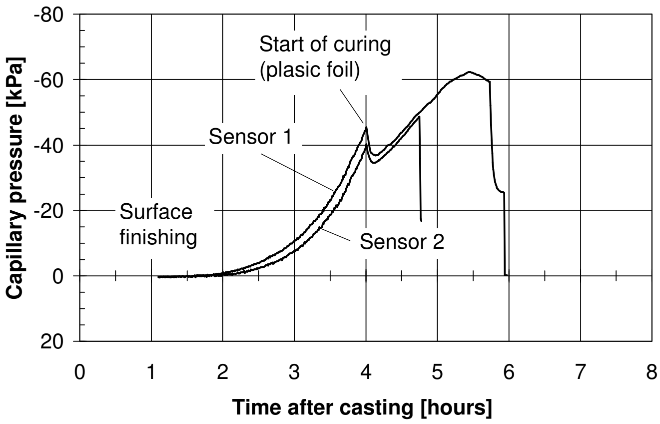


Figure 3: Capillary pressure sensor (left), on-site capillary pressure measurement (right)

The cable based capillary pressure sensors have been used for several measurements under site conditions. In Figure 3 the sensors may be seen applied to a real structure. The graph in Figure 4 shows the measured development of the capillary pressure. The concrete had a cement content of 335 kg/m³ and a water-binder ratio of 0.45. It contained air-entraining admixtures. The capillary pressure sensors were applied shortly after surface finishing (60 minutes after casting). After about 100 minutes, the bleeding water on the surface was evaporated and the absolute capillary pressure value started to rise. The average evaporation rate amounted to about 0.5 kg/(m² h). It was measured by using a curing meter [8].



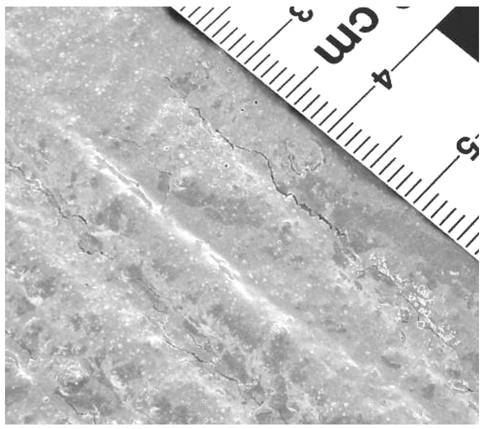


Figure 4: Capillary pressure development in concrete (left), small cracks on the surface (right)

Four hours after casting, the capillary pressure reached a value of about -45 kPa. At this time the surface was covered with a plastic foil. As a result, the absolute capillary pressure value temporarily decreased because the particles and the menisci on the surface were re-arranged due to the contact with the foil. It can be seen that covering the concrete surface does not prevent the continuing capillary pressure build-up which at this age is not only caused by evaporation, but also by the beginning cement hydration.

In experiments performed under laboratory conditions, air entry values between -10 kPa and -48 kPa were measured for cementitious materials [7]. It seems that for the structure shown in Figure 3 the curing was started too late since the capillary pressure amounted already to -45 kPa. This would also explain why small cracks were found on the surface before it was covered with the plastic foil, see Figure 4. Unfortunately, access to the structure was limited in this case and no further investigations could be undertaken.

After removing the sensors, conic holes with diameters of about 1 cm at the surface and depths of about 5 cm remain. They have to be closed by appropriate materials like cement mortar.

4. AUTOMATED CONCRETE CURING

Experiments reported by Wittmann [2] [10] and Radocea [5] have shown that the capillary pressure build-up can be reversed by adding water to the surface. After the added water is evaporated, however, the absolute pressure value starts to rise again, but can be reduced by repeatedly rewetting the surface. Figure 5 shows the capillary pressure development in a rewetted concrete sample. It can be seen that the absolute pressure value drops down to zero after rewetting the surface.

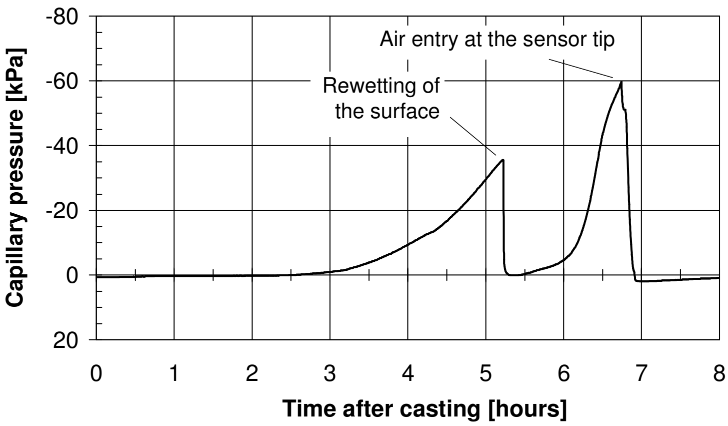


Figure 5: Capillary pressure development in a rewetted concrete specimen

On the basis of surface rewetting, an automated closed-loop controlled concrete curing system was proposed [9]. An uncontrolled flooding of fresh concrete surfaces with water is likely to cause damage to the surface layer and is not considered to be an applicable method. Therefore, experiments with commercially available fogging equipment were undertaken, see Figure 6 (left). Above the concrete surface, water is dispersed into very fine drops which tend to sink down to the surface. The fog also increases the local air humidity. A very small amount of water is sufficient to enlarge the radii of the menisci and to reduce the absolute capillary pressure value.

The fogging system is connected to the capillary pressure sensors. Fogging starts automatically when a defined capillary pressure is reached. The absolute value of this upper threshold should be lower than the one of the material’s air entry value in order to prevent plastic shrinkage cracking. For avoiding a closed water film on the surface of the concrete, fogging is stopped when the capillary pressure reaches a lower threshold and resumed not before the upper threshold is reached again. In this way, the capillary pressure is kept automatically between two previously defined limits which prevent both capillary shrinkage cracking and deterioration of the concrete surface.

Figure 6: Fogging device (left), concrete slab instrumented for controlled rewetting (right)

The closed-loop controlled curing system was tested under laboratory as well as under site conditions. In a field experiment, two quadratic slabs with edge lengths of 2.70 m were produced, see Figure 6 (right). They had a thickness of about 12 cm and were cast on a rough concrete subgrade in order to restrain early age shrinkage. The concrete had an equivalent water-binder-ratio of 0.47 and contained 290 kg/m³ of slag cement, 60 kg/m³ of fly ash, as well as plasticizer.

The two slabs were cast simultaneously and instrumented with the capillary pressure sensors shown in Figure 3. One of the slabs was cured by applying fog to its surface when the capillary pressure had reached a threshold of -10 kPa. The second one was left uncured as a reference sample. The average evaporation rate measured by a curing meter amounted to approximately 0.34 kg/(m² h).

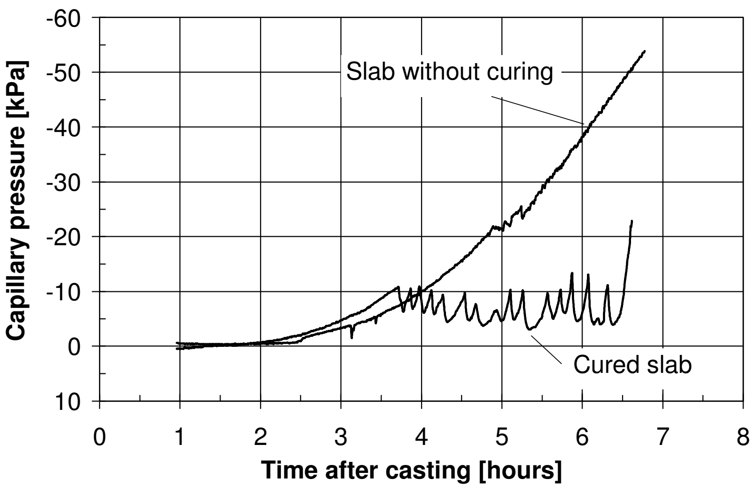


Figure 7: Capillary pressure versus time in a cured and in an uncured concrete slab

Figure 7 shows the capillary pressure versus time for the two concrete slabs. About 120 minutes after casting, the absolute capillary pressure value started to rise. After about 220 minutes, the pressure in the slab prepared for curing reached the predefined threshold of -10 kPa and the rewetting with the fogging system started. It can be seen that the capillary pressure is not completely relieved by the rewetting. In the uncured slab, the capillary pressure reached a value of about -53 kPa. After about 400 minutes, the curing system was deactivated and the absolute capillary pressure value in the previously cured slab started to rise rapidly. The rapid increase may be attributed to the narrower pore system in this age. It was assumed that by this time the concrete had developed sufficient resistance to withstand contracting forces caused by capillary pressure.

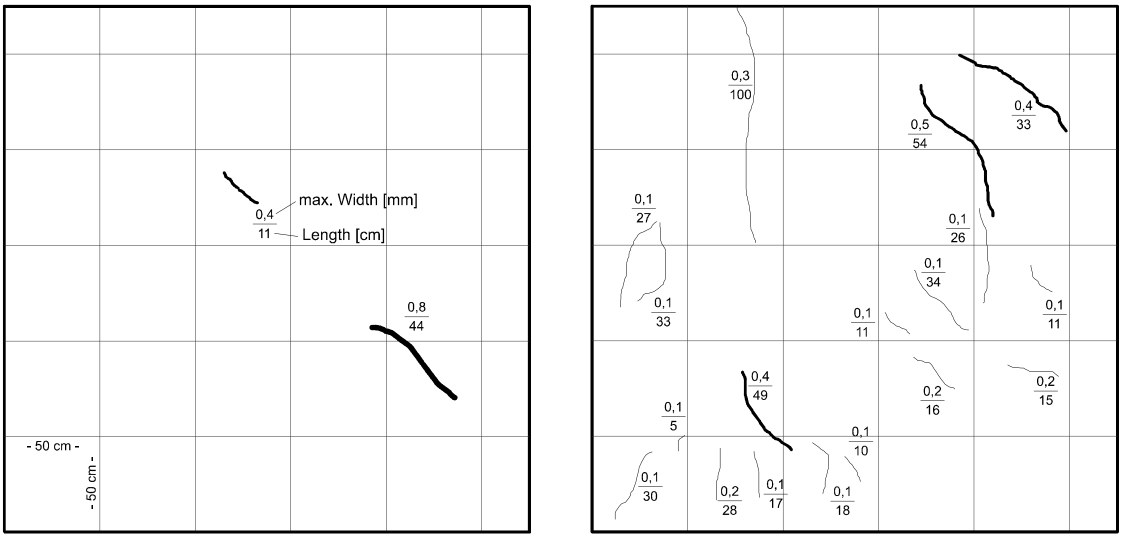


Figure 8: Crack pattern after 24 hours in a cured (left) and an uncured concrete slab (right)

After 24 hours, all cracks with widths larger than 0.1 mm were documented. Fig. 8 shows the lengths and widths of the observed cracks. Unfortunately, the early age cracking risk for this material was underestimated. Already before the curing was started, two cracks were found in the surface of the slab which had been prepared for curing (at a capillary pressure of about -9 kPa). Despite these unexpected cracks, it could be clearly demonstrated that the capillary pressure controlled rewetting significantly reduces the early age cracking risk.

5. CONCLUSIONS

- Plastic shrinkage of concrete results from the build-up of a capillary pressure in the pore system of the material and occurs mainly under high evaporation rates.
- The capillary pressure can be easily measured under site conditions with special pressure transducers.
- On the basis of the measured capillary pressure, it is possible to make decisions concerning the timing of curing measures and to evaluate the effect of such measures. This allows to reduce the early age cracking risk.
- It appears to be possible to use the measured capillary pressure as feedback value for a closed-loop controlled concrete curing based on surface rewetting. The capillary pressure is automatically kept within certain limits in order to prevent early age damage.

ACKNOWLEDGEMENTS

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