Early Age Cracking and Capillary Pressure-Controlled Concrete Curing

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Early age cracking and capillary pressure-controlled concrete curing

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ABSTRACT: Due to the evaporation of water at fresh concrete surfaces, a capillary pressure is built up in the pore system of the material leading to shrinkage deformations, ie the so-called capillary or plastic shrinkage, and possibly to cracking. By influencing the capillary pressure build-up, the risk of cracking in the very early age, ie within the first few hours after casting, may be reduced significantly. A method of controlled concrete curing is proposed. It is based on in situ measurements of the capillary pressure by using wireless sensors. If the measured pressure reaches a previously defined threshold value, the concrete surface is rewetted. Experimental and numerical results concerning the physical behaviour of drying suspensions are presented and observations made and discussed during on-site capillary pressure measurements.

1. INTRODUCTION

The presented work is aimed to reduce the early age cracking risk in concrete construction. Cracks in concrete structures may occur approximately within the first four hours after casting, ie when the material is still in its plastic stage and before it has reached a significant tensile strength. Similar phenomena as those leading to concrete cracking in this age may also be observed in drying suspensions with inert solid particles, for instance in silt. Physical processes rather than chemical reactions are the predominant reason for volume changes and cracking in plastic concrete (Wittmann 1976, Cohen et al. 1990, Schmidt et al. 2007, Slowik et al. 2008a). Therefore, drying suspensions consisting of fly ash and water may serve as model materials for studying these processes (Slowik et al. 2008a, Slowik et al. 2009). Such suspensions are characterised by a cement-like particle size distribution and by spherical particle shapes.

Planar concrete structures such as floors and roads are particularly prone to shrinkage and cracking in the plastic stage. This may be attributed to their large surface subjected to the evaporation of water. After casting, the fine solid particles, ie, those of the cement and additives are covered by a plane water film at the top face of the concrete where evaporation usually takes place. The self-weight of the solid particles may lead to a settlement of the same and, accordingly, to the transport of additional water towards the upper surface, ie to the bleeding of the concrete. Due to evaporation, the thickness of the water film reduces and, eventually, the near-surface particles are no longer covered by a plane water film. Due to adhesive forces, a curved water surface with so-called menisci in the interparticle spaces, see Figure 1, is then formed. Accordingly, a negative capillary pressure is built up in the water, the magnitude of which may be calculated by using the Gauss-Laplace equation.

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

The pressure p depends on the surface tension γ of the liquid phase and on the main radii R of its curved surface. It has to be considered that in cement paste water loss is not only caused by evaporation but also by the cement hydration beginning later.

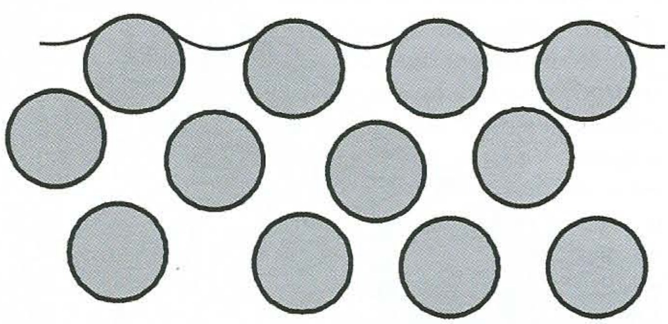

Figure 1: Curved water surface between near-surface solid particles in a drying suspension.

The negative capillary pressure results in inward forces on the particles at the surface. The microstructure is compacted, resulting initially in a measurable settlement or vertical shrinkage of the material. After the material has been separated from the side faces of the mould, or after cracks are formed, the contracting capillary forces lead also to a shrinkage strain in the horizontal direction. Up to this stage, the volume change of the material is approximately equal to the volume of the evaporated water (Grube 2003, Slowik et al. 2008a).

However, the expansion of entrapped air might cause a deviation, however. While water is evaporating, the curvature of the menisci is increasing, the absolute capillary pressure value continues to rise, and the material volume is getting smaller. Since this volume change is caused by capillary forces, plastic shrinkage of concrete is also referred to as capillary shrinkage.

At a certain material specific pressure, air penetrates suddenly into the pore system (Wittmann 1976, Slowik et al. 2008a). This is the case when the curvature of the water surface is too large for bridging all the spaces between the particles at the surface where evaporation takes place. According to the terminology used in soil physics, this pressure value is referred to as air entry value (Slowik et al. 2008a).

Air entry appears to be a local event because of the irregular particle arrangement it does not occur simultaneously in all pores. The latter are drained successively starting with the largest ones. The air entry value marks the first instance of air penetrating the pore system. If the capillary pressure is measured at a location where air entry takes place, the pressure 'breaks through' (Wittmann 1976), ie it drops down to zero.

Figure 2 shows measured curves of the capillary pressure versus time in a cement paste sample, as well as in a sample made of fly ash and water. Each of the samples was instrumented with two capillary pressure sensors at different locations, but at the same depth of 4 cm. Details of the experimental set-up are described by Slowik et al. (2008a). It may be seen that the curves obtained for different sensor positions follow the same path. The maximum absolute pressure values, however, are different.

This may be attributed to the air entry which does not happen simultaneously into all pores. For this reason, the maximum absolute pressure value measured at a certain location cannot be considered to be a material property. It depends on the sensor location. In addition, the pressure might 'break down' locally, due to air bubbles reaching the sensor tip.

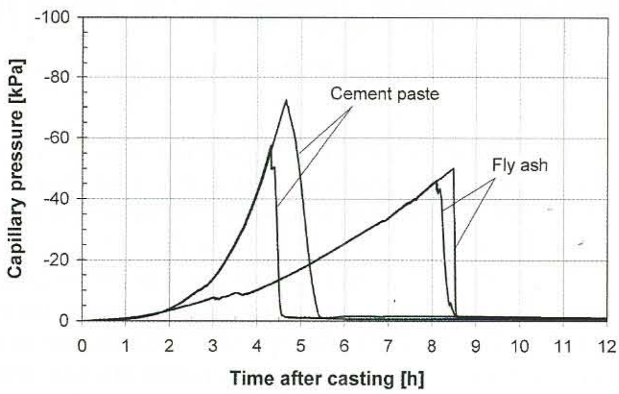

Figure 2: Capillary pressure versus time, measured at a depth of 4 cm, specimen height 6 cm.

When the concrete is in its plastic stage, all pores are interconnected and the capillary pressure is almost constant in the vicinity of the surface. According to the authors' experimental observations, this is the case up to a depth of at least 10 cm in common cementitious materials. Hydrostatic pressure differences are much smaller than the absolute value of the capillary pressure being built up.

When the air entry value is reached, the cracking risk increases significantly. The pores where air has penetrated into are weak spots at the material surface, and origins of crack initiation. This has been shown experimentally by electron microscopic observations (Slowik et al. 2008a, Schmidt et al. 2007) and by force measurements (Slowik et al. 2008b). In suspensions consisting of fly ash and water it was observed that shortly after air entry cracks were formed along a line connecting the weak spots mentioned above. Crack initiation requires air entry, whereas air entry does not necessarily result in cracking. Strain localisation and crack formation might be prevented by a limited mobility of the solid particles, although air entry takes place.

The causality between air entry and plastic shrinkage cracking led to an idea for a concrete curing concept. If the absolute capillary pressure being built up in the plastic concrete is permanently kept below the air entry value of the material, cracking can not occur. A corresponding curing method is described in section 4.

Early age cracks are not only an aesthetic problem. They also may degrade the durability of the structures. Even if they are not visible or if they have been temporarily closed during surface finishing, they do have an influence on damage processes taking place during the service life of the structure. Numerical studies into the drying shrinkage cracking of hardened concrete have shown that the obtained crack patterns are strongly influenced by pre-existing early age cracks (Slowik et al. 2008b). The latter may lead to distinct damage localisation and larger crack widths. Thus, the concrete permeability will be increased and the durability of the structure might be unfavourably affected.

2. MEASUREMENT OF THE CAPILLARY PRESSURE IN PLASTIC CONCRETE

In laboratory experiments, the capillary pressure build-up in drying suspensions has been studied (Slowik et al. 2008a). The test materials included cement paste as well as suspensions made of fly ash and water. In addition to the capillary pressure, deformations, the specimen temperature as well as the electrical conductivity in different depths were measured. For the capillary pressure measurement, miniature pressure transducers were installed outside the forms into which the specimens were cast. The connection to the water-filled pore system of the material was provided by metallic tubes having an inside diameter of 3 mm. The location of the tip of the respective tube is regarded as sensor location. In the following, some experimental observations are described.

The slope of the capillary pressure versus time curve depends on the evaporation rate and on the material characteristics. The higher the evaporation rate and the smaller the particle sizes, the steeper the increase of the absolute capillary pressure value. The last mentioned effect results from the smaller surface pores in the case of smaller particle sizes. Moreover, for smaller particle sizes higher absolute pressure values are reached. Air entry into the smaller pores requires a higher curvature of the water surface and, accordingly, a higher capillary pressure. Therefore, high-performance concrete compositions tend to be more vulnerable to early age shrinkage and cracking when compared to conventional structural concrete. This is due to the small particle sizes, the high binder contents and the low water-cement ratios. These characteristics lead to comparably high absolute capillary pressure values and shrinkage strains. Consequently, the early age cracking risk is higher. In addition, a more intense self-desiccation increases the water loss rate.

The slope of the capillary pressure versus water loss curve depends on the specimen height of the drying suspension. This effect has been extensively investigated by Radocea

(1992). The higher the specimen – the higher the potential for material consolidation. In other words, out of a higher specimen more water can be transported to the surface where evaporation is taking place.

As mentioned before, the maximum absolute capillary pressure value, the so-called 'break-through' pressure, measured in a drying suspension depends on the sensor location and may not be regarded as a material property. However, the pressure reached at the first instance of air entry into the pore system should be specific for a certain material. This pressure is called air entry value and mainly depends on the pore structure at the specimen surface and on the mobility of the particles. It has been found that under certain experimental conditions, reaching the air entry value is accompanied by a temporary maximum of the settlement, ie of the vertical shrinkage, by an increasing deviation between specimen volume change and evaporating water volume as well as by a sudden drop of electrical conductivity (Slowik et al. 2008a). On the basis of these observations, the air entry value may be identified in laboratory experiments as a material parameter for a drying suspension.

Capillary pressure measurements were also undertaken under site conditions. Figure 3 shows capillary pressure versus time curves measured on a road construction site. Two sensors were applied to an actual concrete member which was treated by using a curing agent. A third sensor was applied to an uncured reference specimen, which had the same height and was cast simultaneously. It may be seen that the capillary pressure rise was much faster in the case of the uncured concrete specimen. Obviously, the curing agent reduced the evaporation rate. Consequently, the capillary pressure increase was retarded, although not prevented. This retardation reduces the cracking risk. Due to the beginning cement hydration, the particle mobility starts to decrease resulting in an increasing mechanical resistance to the capillary pressure.

Figure 3 also shows that at two different sensor locations in the cured concrete member almost the same capillary pressure values were measured. This confirms the results obtained under laboratory conditions.

In view of a capillary pressure based concrete curing, the corresponding measuring technique had to be improved. Since cable connections usually cause technical problems during the construction process, a wireless capillary pressure sensor was developed, see Figure 4 consists of a conic

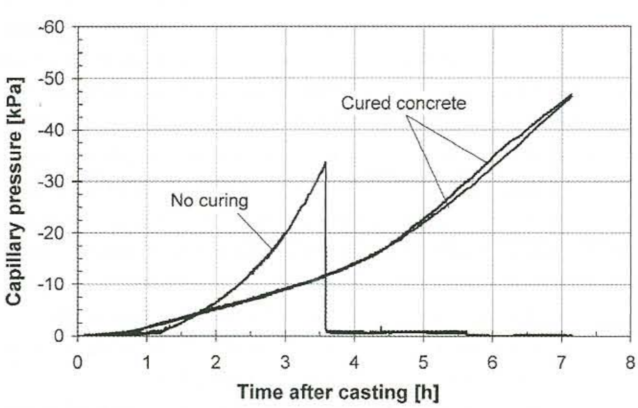

Figure 3: Capillary pressure versus time, measured at a road construction site.

Figure 4: Wireless capillary pressure sensor to be used for on-site measurements.

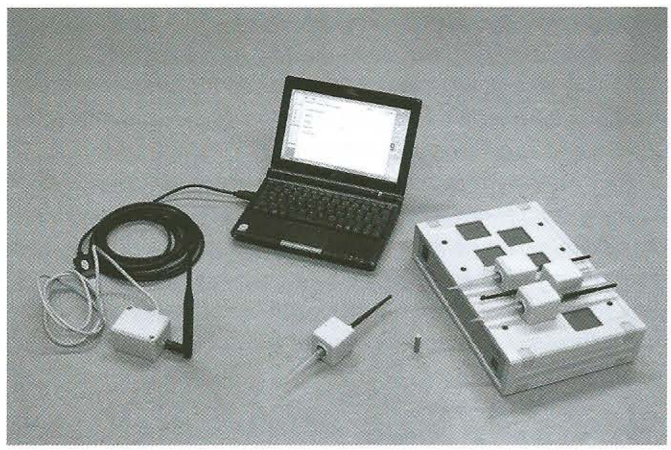

Figure 5: Measuring system for on-site capillary pressure measurements.

plastic tip, which is plunged into the concrete, a small cubic box containing the transducer as well as the radio module, and an antenna. The range of wireless transmission amounts to approximately 50 m. Prior to the sensor application; the plastic tip has to be filled with water in order to connect the sensor to the pore system of the material. After the measurement, usually after the final setting of the concrete, the sensor is simply extracted from the concrete surface and the remaining hole is closed. The plastic sensor tip may be replaced, if necessary.

Figure 5 shows the complete measuring system. It consists of the wireless sensors, the radio receiver box and a contactless battery charger. The receiver box may serve up to eight wireless sensors. In Figure 5, it is connected to a netbook via USB.

3. NUMERICAL SIMULATION OF CAPILLARY PRESSURE BUILD-UP AND CRACK INITIATION

The described capillary pressure build-up and the resulting crack initiation have been numerically simulated by using a 2D particle-based model (Slowik et al. 2009). It represents a drying suspension consisting of inert solid particles surrounded by water. Circular particles of different size are generated and placed in a rectangular specimen. The top face of the specimen is assumed to be open ie evaporation may take place. In order to simulate the loss of water, the absolute capillary pressure value is incrementally increased and the according course of the water front is calculated under the assumption of constant curvature of the water surface.

In addition to forces resulting from the capillary pressure, the solid particles are subjected to gravitational and interparticle forces. The latter mainly include electrostatic and van-der-Waals forces. By superposition of these forces, a resulting interparticle force is obtained, see Figure 6. In the short-distance range, however, a simplified force-distance function has been adopted for computational reasons (Slowik et al. 2009).

Figure 7 contains the results of a numerical simulation of the capillary pressure build-up in a drying suspension with circular (dark colour) solid particles having a size ranging from 4 μm to 32 μm. The absolute capillary pressure value in the

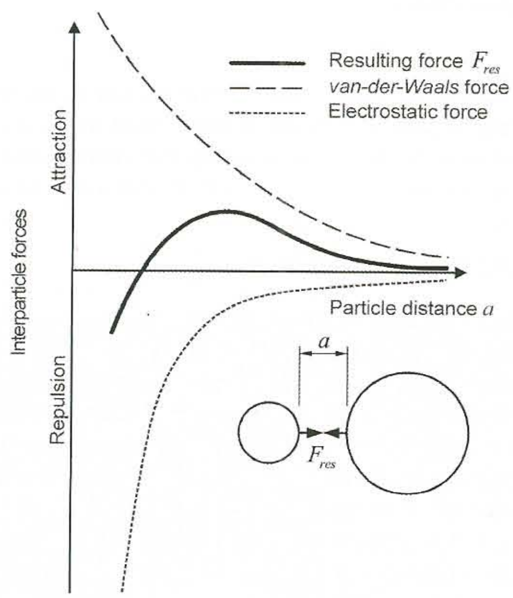

Figure 6: Interparticle forces versus particle distance (not to scale).

water (grey colour) is incrementally increased. The top figure shows the particle arrangement under zero pressure and the bottom figure for the maximum absolute pressure value reached. The latter amounted to 88 kPa. During the capillary pressure build-up ie under decreasing water content of the system, menisci are formed between the solid particles at the surface leading to downward forces and a settlement of the material. It may also be seen that the air entry into the material does not occur uniformly. Under certain conditions, strain localisation and crack initiation may be observed in such simulations. In the simulation shown in Figure 7, a 'gap' is formed on the right side of the specimen and widened by the rising capillary pressure. This phenomenon of strain localisation and separation is regarded as crack initiation.

By using the described 2D model, several influences on the capillary pressure build-up and on the early age cracking risk were investigated. The cracking risk is increased if the particle sizes are decreased. Furthermore, the capillary pressure versus water loss curve becomes steeper with decreasing particle sizes. The same effects could be observed when the portion of fine particles was increased. It was also found that the material appears to be more vulnerable to cracking in this case. These numerical results are in accordance with experimental observations.

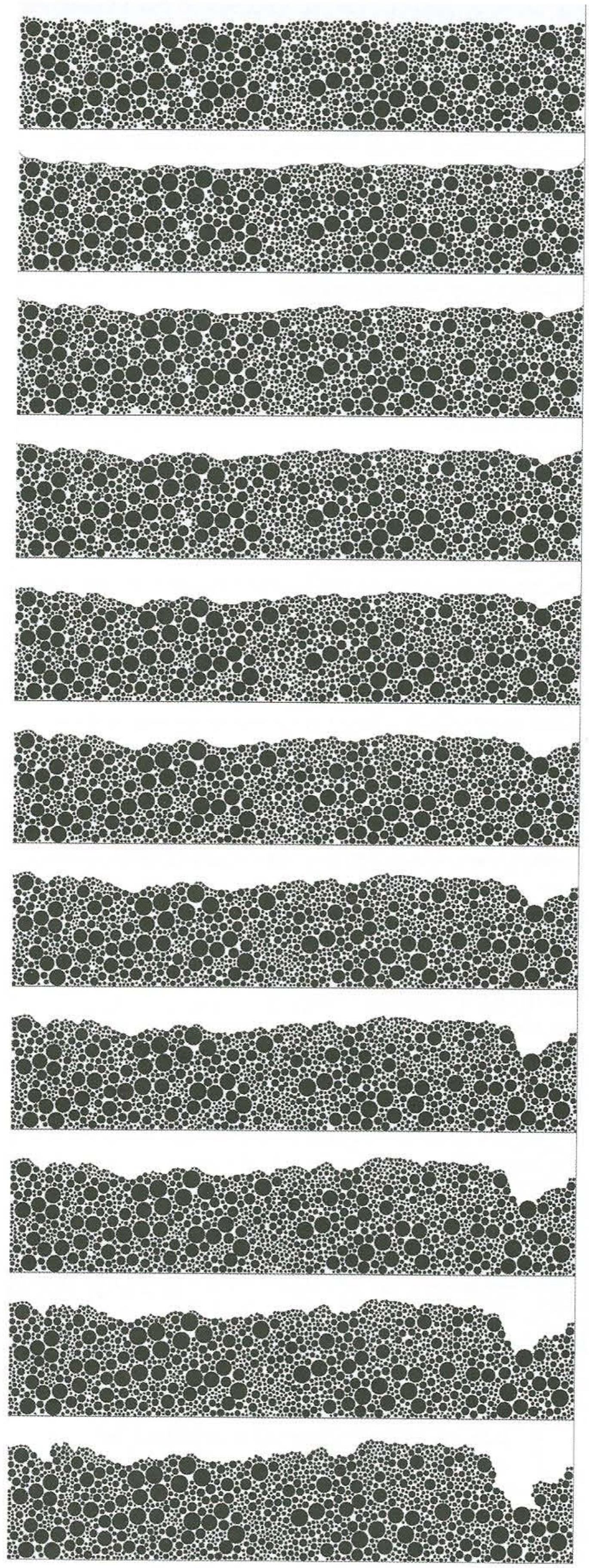

Figure 7: Simulation of the capillary pressure build-up in a drying suspension (absolute capillary pressure value increasing from top down, particles sizes ranging from 4 μm to 32 μm).

The capillary pressure values obtained in the simulations are in the same order of magnitude as those determined experimentally. The ongoing work on the simulation of capillary shrinkage cracking is aimed at a better understanding of the material based influences on the air entry value and on the early age cracking risk. Possibly, the numerical results can help to select an appropriate threshold pressure value for a closed-loop controlled concrete curing.

4. CONCRETE CURING BASED ON CAPILLARY PRESSURE MEASUREMENT

If the air entry value of a certain cementitious material is known, it is possible to define a critical absolute capillary pressure value which should not be exceeded during concrete processing. This value should be smaller than the absolute air entry value. In this way, the early age cracking risk may be significantly reduced since cracking requires air entry.

A method of closed-loop controlled concrete curing is proposed. It is based on the in situ measurement of the capillary pressure. If the measured absolute value reaches a previously defined threshold, the concrete surface is rewetted. This results in a temporary reduction of the capillary pressure. The rewetting is terminated when a lower limit is reached. It is recommended to always maintain a negative capillary pressure in order to prevent the formation of a water film on the concrete surface, which might have an unfavorable effect on the near-surface material properties. Furthermore, a moderate capillary pressure leads to an advantageous compaction of the microstructure.

Figure 8 shows the capillary pressure versus time curve measured in a concrete slab subjected to a controlled concrete curing. The corresponding curve measured in an uncured reference slab is also shown. It may be seen that the capillary pressure could be kept within a certain range between two limit values. The evaporation rate was monitored by using curing meters (Jensen 2006). An initial value of about 0.5 kg/ (m²h) has been measured, see Figure 9.

For the rewetting of the concrete surface, a commercially available fogging device was used, see Figure 10. Experience has shown that only a few seconds of fogging are required for reducing the absolute capillary pressure value down to its lower limit. The major advantage of the closed-loop control is that only the amount of water actually needed, for preventing early age cracks, is added to the concrete surface. Hence, the surface quality is not degraded by the rewetting.

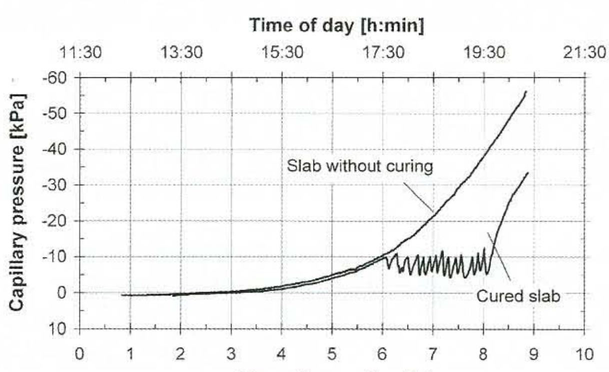

Figure 8: Capillary pressure versus time in a concrete slab under controlled curing.

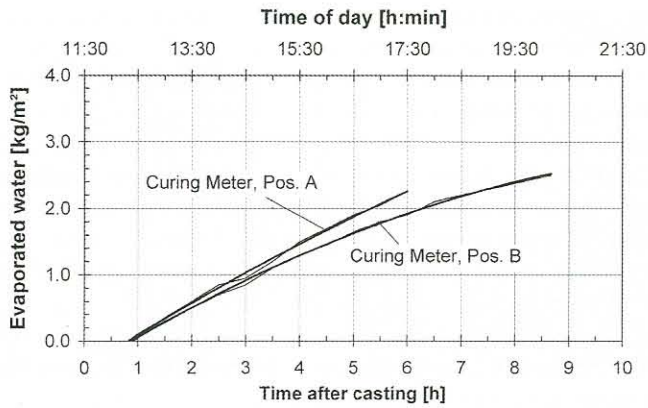

Figure 9: Evaporated water mass versus time, measured by using curing meters (Jensen 2006).

In field experiments, the effect of the proposed curing method on the crack pattern formed in the plastic stage could be demonstrated (Slowik et al. 2008b). The number of cracks as well as the total crack length was significantly reduced.

5. CONCLUDING REMARKS

Concrete in its plastic stage may be regarded as a drying suspension consisting of solid particles and water. The loss of water results in the build-up of a negative capillary pressure in the liquid phase of the material. Capillary pressure-induced local air entry into the material may then lead to crack initiation.

By keeping the absolute capillary pressure value below the value at which air entry takes place, crack initiation may be prevented. This concept requires the in situ measurement of the capillary pressure and the closed-loop controlled rewetting of the plastic concrete.

The material-dependent critical capillary pressure value and the required duration of the controlled curing will be subject to further research.

The application of the proposed curing method might be too expensive for many ordinary projects in concrete construction. Even in these cases, the wireless capillary pressure sensors might be utilised in order to obtain valuable information on the actual cracking risk and on the efficiency of curing measures. The sensors are comparably inexpensive and do not disturb the construction process.

Figure 10: Fogging device.

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