Capillary Pressure Controlled Concrete Curing in Pavement Construction

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ABSTRACT

Shrinkage of concrete in the plastic stage, i.e., within the first few hours after casting, is mainly caused by the build-up of a capillary pressure in the pore system of the material due to the loss of water. Early age cracks resulting from this so-called capillary shrinkage may have an unfavorable effect on the durability of concrete pavements. For avoiding this type of early age damage, it is proposed to measure the capillary pressure in situ during the first hours immediately after casting. 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. If the capillary pressure is kept below a critical value, shrinkage cracking in the plastic stage may reliably be prevented. The critical capillary pressure depends on the concrete composition and may be determined in laboratory experiments. Wireless capillary pressure sensors have been developed for this particular application. They were successfully tested under site conditions and do not influence the construction process.

INTRODUCTION

Concrete pavements, in particular those in road and airfield construction, are prone to so-called plastic shrinkage due to their comparatively large, exposed, and occasionally unprotected surface. For these structures, high durability standards have to be met. Early age cracks resulting from plastic shrinkage may degrade the durability of concrete pavements (*Breitenbücher* 2006). Hence, appropriate placement and immediate curing, usually by the application of curing agents, are necessary.

Plastic shrinkage is caused by the evaporation of water. It strongly depends on the bleeding rate. For estimating the extent of plastic shrinkage and the necessity for curing measures, technical means were proposed which are usually based on the determination of the evaporation rate – like the ACI nomogram (*ACI 305R-99*), the equation developed by *Uno* (1998), or the Curing Meter (*Jensen* 2006). Recommended critical threshold values for the evaporation rate are ranging from 0.25 to 1.0 kg/(m²·h) (*ACI 308R-01*).

The risk of plastic shrinkage cracking depends on a variety of influence parameters, including the environmental conditions, the material properties, and the bleeding rate. In the present paper, the in-situ measurement of the capillary pressure in plastic concrete is proposed as a new method to determine the necessity of curing measures and to monitor their effects. The build-up of this capillary pressure may lead to plastic shrinkage cracking. It depends on all the aforementioned influence parameters and, for this reason, it is a direct indicator of the cracking risk under the actual environmental and manufacturing conditions.

MECHANISM OF PLASTIC SHRINKAGE

Plastic or capillary shrinkage is a physical process which may be observed in cementitious as well as in inert materials like soils. It is caused by the loss of pore water mainly due to evaporation. This water loss results in the build-up of a negative capillary pressure in the pore system and leads to the contraction of the material. In concrete, plastic shrinkage occurs when the material is still in its plastic stage, i.e., in the time period between placing and final setting (*Cohen et al.* 1990). Figure 1 contains a schematic presentation of this process.

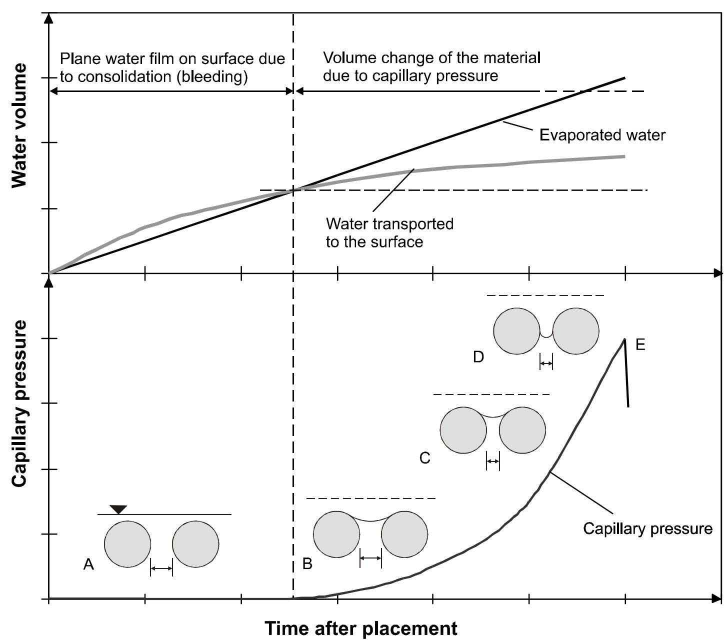

Figure 1. Capillary pressure development, bleeding, water evaporation, and menisci formation versus time (schematic view).

The capillary pressure development starts after the bleeding water on the surface has evaporated and the evaporation rate is higher than the rate of water transported to the surface, i.e., higher than the bleeding rate. If the particles at the surface can no longer be covered by a plane film of water, menisci are formed between these particles due to the surface tension of the water and adhesion effects. This process can be described by the Gauß-Laplace equation. If axi-symmetric pores at the surface are assumed, the following expression may be used for simplified considerations:

$$p = -\frac{2\gamma}{r} \cdot \cos \beta \qquad (1)$$

In this Equation, p is the pressure in the pore fluid, r the radius of the menisci, γ the surface tension of the pore liquid (for water 0.073 N/m), and β the wetting angle. The exact value of the latter is unknown. However, for siliceous materials, the assumption of full wetting, i.e., of a wetting angle of 0° ($\cos \beta = 1$), is justified.

The capillary pressure acts on the solid particles resulting in a contraction of the plastic material (*Wittmann* 1976). The pores are getting smaller and additional pore water is transported to the surface. If the radii of the water menisci become too small for bridging all the spaces between the particles at the surface, the pressure "breaks through" and air penetrates into the pore system, starting at the largest pores. When this pressure break–through occurs, the system becomes unstable and a relocation of the water in the interconnected pores will take place. The beginning of this process is the so-called air entry and the pressure reached at air entry is referred to as air entry value. This term is also used in soil mechanics describing a similar phenomenon (*Fredlund et al.* 1993).

Since the contracting forces between the particles in the air penetrated regions are considerably smaller than those in the water filled regions, strain localization takes place and cracking may occur. Crack initiation triggered by air entry has been observed in drying suspensions made of fly ash and water by using an Environmental Scanning Electron Microscope (*Slowik et al.* 2008a). This process was also numerically simulated with particle-based methods (*Slowik et al.* 2009, *Slowik et al.* 2011).

In the completely saturated pore system of a cementitious material, the maximum capillary pressure, and thus the air entry value, may be estimated by using Equation (2) (*Cohen et al.* 1990, *Dao et al.* 2010). It is based on Equation (1) and on the calculation of the hydraulic diameter of porous materials.

$$\Delta p = -\frac{\gamma \cdot S_m}{w/c} \cdot \rho_W \cdot \cos \beta \qquad (2)$$

The water-cement ratio *w/c*, the specific surface of the cement by mass S_m (Blaine value), and the density of water ρ_W are characteristic parameters which are known for most cementitious materials. It has to be considered, however, that air entry is controlled by the largest pores whereas Equation (2) is based on the average pore diameter. For this reason, the absolute air entry values are overestimated. Nevertheless, Equation (2) allows to explain some of the observed influences on capillary shrinkage. For example, the reduction of the *w/c*-ratio or the use of a finer-grained cement may result in a finer capillary pore system, in an earlier build-up of the capillary pressure and, consequently, in a higher shrinkage strain.

If the capillary pressure is kept below the air entry value, shrinkage cracking in the plastic stage may reliably be prevented (*Schmidt et al.* 2009). Crack initiation requires air entry in the material. An experimental investigation into the air entry value of cementitious materials with electric conductivity and strain measurements yielded values ranging from -10 kPa to -48 kPa (*Slowik et al.* 2008a).

CAPILLARY PRESSURE AS INFLUENCED BY CURING MEASURES

In a saturated particle system, a capillary pressure is built up when the particles are no longer covered by a plane water film and when, as a result, menisci are formed in the water surface between the particles. If this process is hindered or delayed, the capillary shrinkage is reduced. In the following, this correlation will be discussed on the basis of experimental results.

If a solid-liquid mixture is rewetted after menisci have already been formed, the pores at the surface are refilled and the radius of the menisci increases until eventually a plane water film is formed on the surface again. The capillary pressure in the pore system decreases and constraint stresses in the member are reduced. Furthermore, shrinkage strain and settlement may decrease. After the added water is evaporated, the capillary pressure starts to increase again. Although a decompression of the particle system may partially have occurred, the latter is already consolidated now and has a narrower pore system. Due to this fact, the capillary pressure increase will now be steeper under the same evaporation rate (*Wittmann* 1976, *Radocea* 1992).

Figure 2 (left) shows the capillary pressure development and the corresponding deformations for a repeatedly rewetted sample made of fly ash. The water to fly ash ratio amounted to 0.25. For monitoring mass changes, the specimen was placed on a scale. Shrinkage and settlement were measured by LVDTs. The experimental setup is described in *Slowik et al.* 2008a.

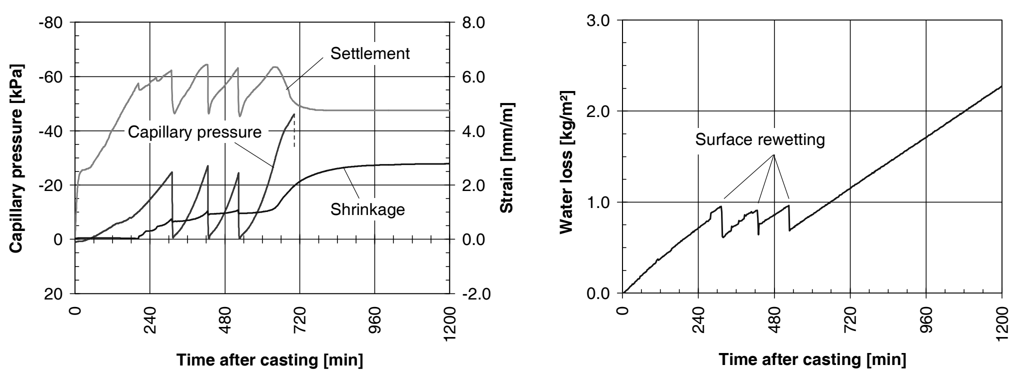

Figure 2. Capillary pressure, horizontal shrinkage, settlement, and mass change versus time, measured in a specimen made of fly ash under repeated rewetting.

Immediately after placing and compaction, the sample started to settle. When the capillary pressure was high enough to separate the material from the side faces of the mould, horizontal shrinkage also occurred. This happened about 185 minutes after casting. When a capillary pressure of -25 kPa was reached, the surface was rewetted. Thereby, exactly the amount of water which was necessary to reduce the pressure down to zero was applied. Since no plain water film could be formed, the capillary pressure started to increase again immediately after the rewetting.

Figure 2 (right) shows the change of the water mass due to evaporation and rewetting. By the time of the first rewetting, i.e., after about 300 minutes, almost 1.0 kg/m² of water had evaporated (evaporation rate approximately 0.2 kg/(m²·h)). In order to reduce the capillary pressure down to zero, about 0.30 kg/m² of water had to be added. This difference is attributed to the narrower pore system after 300 minutes. After the third cycle of rewetting, water was no longer applied to the surface and the capillary pressure increased monotonically. Starting at a pressure of -30 kPa, a significant increase of the shrinkage strain was observed. At the same time, the settlement reached a maximum. It is concluded that air entry occurred at this pressure (*Slowik et al.* 2008a). At -46 kPa, air reached the measurement tip of the pressure sensor and the locally measured capillary pressure broke through.

It was found that the rewetting may be repeated several times. However, especially in cementitious materials, the pore system may be comparatively dense after some time of hardening. Then, adding water to the surface will not reduce the capillary pressure immediately. Due to the reduced permeability of the material, it will take some time before the rewetting effect on the capillary pressure is observed.

Figure 3 shows the results of experiments performed with fresh concrete under laboratory conditions. Different curing measures were applied and the capillary pressure was measured with two sensors in each specimen. All samples were exposed to the same climatic conditions (20°C, 30 % relative air humidity). One sample was left uncured as a reference. Another one was cured by placing a plastic foil on its surface immediately after the compacting. The left graph in Figure 3 shows the measured capillary pressure in both of the samples. In the uncured sample, the build-up of the capillary pressure was observed about 2 hours after casting while in the covered sample the capillary pressure build-up started as late as 8 hours after casting. Since no water could evaporate due to the plastic foil, the capillary pressure build-up may be attributed in this case to internal water consumption, i.e., to the cement hydration. The slope of the capillary pressure increase is steeper in the cured sample. This may be explained by the narrower pore system and by the reduced particle mobility due to the beginning hardening process.

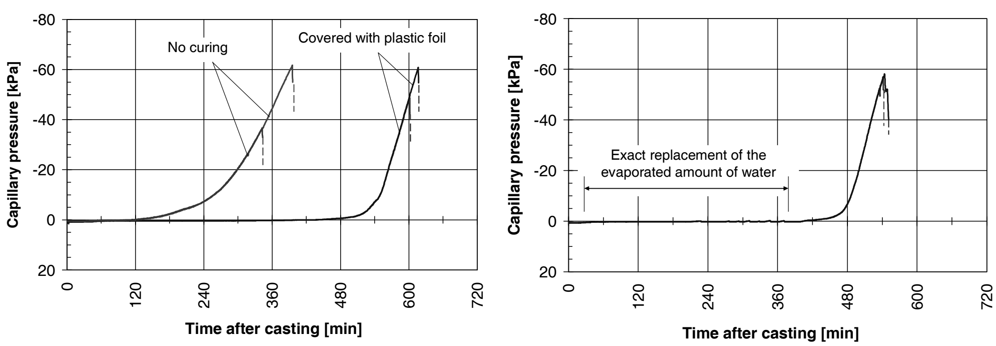

Figure 3: Capillary pressure versus time, measured in cured and in uncured concrete specimens.

At a third sample, the water loss due to evaporation was compensated by external rewetting (Figure 3, right). The total mass of the sample was held constant by continuously adding water to the surface. In this way, the build-up of a capillary pressure could be completely prevented. After about 6.5 hours, the rewetting was terminated. Only a few minutes later, the capillary pressure started to build up as a result of evaporation and also due to the chemical reactions.

CAPILLARY PRESSURE SENSORS FOR ON-SITE APPLICATIONS

The capillary pressure in cementitious materials may be measured with appropriate sensors. This has been proved under laboratory conditions by several authors (*Wittmann* 1976, *Radocea* 1992, *Scott et al.* 1997, *Slowik et al.* 2008a). Typically, small-sized electric pressure transducers are used with measurement tips like injection needles or small metallic tubes (diameter approx. 3 mm). These tips have to be filled with degassed water in order to provide a hydraulic connection between the pore water in the tested material and the sensor element. The capillary pressure can be measured as long as no air reaches the sensor tip and causes a local pressure break-through.

In order to reliably measure the capillary pressure also under site conditions, a mobile and easy to use sensor had to be developed. For this purpose, the pressure transducer used in the laboratory before was built into a stable casing which is protecting the sensor against splash water and a new type of measurement tip was attached. A cable provides the connection to a data logger as well as the power supply. Experience from on-site measurements has shown very soon that the cable connection limits the applicability of the sensors. The cables hinder surface finishing and, if they are moved, the hydraulic connection between pore water and sensor may be lost. Furthermore, it appears to be difficult to monitor the capillary pressure at different positions in large planar concrete structures, especially in concrete roads or in bridge decks. To resolve these problems, a radio module was integrated in the sensor.

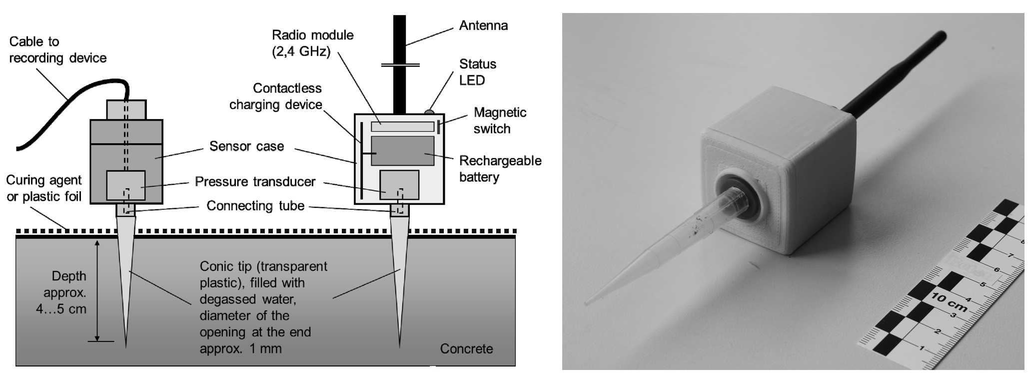

Figure 4. Schematic view of a wired and of a wireless capillary pressure sensor for on-site applications (left), wireless capillary pressure sensor (right).

Figure 4 shows a schematic view of a wired and of a wireless capillary pressure sensor with their components. The wireless sensors automatically connect to a base station within a radius of about 60 m. The casing of the wireless sensor is completely closed except for the ports for the measurement tip and for the antenna. It is turned on and off by a magnetic switch. Recharging is done contactless through electromagnetic induction.

In order to apply the capillary pressure sensors to fresh concrete surfaces, conic tips made of transparent plastic have proved to be suitable. The opening at the end of the tips has a diameter of about 1 mm. The transparent plastic is stiff enough to resist the negative internal pressure and the tip may easily be checked for correct bubble-fee water filling. The conic shape of the comparatively stiff measurement tip allows to insert the sensor into the plastic concrete after casting and compaction. If the sensor tip has been embedded deep enough in the concrete, approximately 4 cm to 5 cm for conventional concrete compositions, the entire weight of the sensor is carried by the conic plastic tip. The conic shape, the vertical orientation, and the weight of the sensor prevent the loss of the hydraulic connection between sensor filling and pore water, even under the action of wind and moderate vibrations. After the measurement, the sensor is extracted from the concrete surface. The remaining hole, see Figure 5 (right), may be filled with an appropriate cementitious material, if necessary.

FIELDS OF APPLICATION

Based on the results of laboratory investigations (*Slowik et al.* 2008a) and of on-site measurements (*Slowik et al.* 2010), the following fields of application for the capillary pressure measurement in plastic concrete may be identified:

- By in situ capillary pressure measurements, the demand for curing measures and their appropriate timing may be estimated under the actual environmental conditions. The recorded data will subsequently allow to evaluate the effect of these curing measures.
- Some curing agents, e.g. frequently used paraffin wax based compounds, need to be applied exactly at the time when the concrete surface appears as pale damp in order to activate their full efficiency (*Stark et al.* 2009). This point in time may reliably be identified on the basis of the onset of capillary pressure build-up.
- The slope of the capillary pressure increase versus time is an indicator for the efficiency of the applied curing measure. Even if the surface is covered with a foil or if a cuing agent is applied, a negative capillary pressure may be built up.
- In preliminary performance tests, a given concrete composition may be tested with respect to the early age cracking risk under consideration of the anticipated environmental conditions and of the planned curing measures. Furthermore, it is possible to experimentally investigate the influence of individual concrete components or admixtures on the capillary pressure development.
- The capillary pressure measured within the first hours after casting may be used to control the curing of the plastic concrete. Examples for an automated closed-loop controlled curing by using fogging devices have been reported by *Slowik et al.* 2008b and *Schmidt et al.* 2009.

In situ capillary pressure measurements have been undertaken at more than ten different construction sites. The method and the developed sensors have proved to be applicable. In the following, two practical applications in airfield and road construction are described.

TWO APPLICATIONS IN AIRFIELD AND ROAD CONSTRUCTION

Airfield construction. The capillary pressure development in a new concrete runway has been measured in situ. The intention was to gain experience with the sensor application under site conditions. The upper concrete layer of the pavement had a thickness of about 40 cm. The concrete contained ordinary portland cement (CEM I 42.5 N-NA) and an air entraining agent. The *w/c*-ratio was 0.42. For the casting process, a slipform paver has been used which was followed by a texturing and curing machine in a distance of about 10 m to 20 m. By this machine, the surface was textured with a steel broom and a membrane forming curing compound was applied.

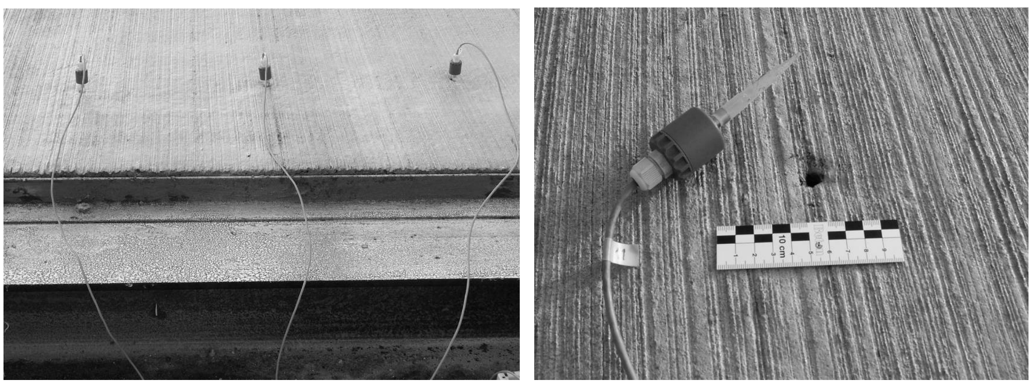

Figure 5. Capillary pressure sensors applied to a concrete runway of an airfield (left), typical surface damage remaining after the sensor has been removed (right).

Wired capillary pressure sensors were applied with a spacing of about 0.6 m after the curing agent had been sprayed on the surface, see Figure 5 (left). Between the placing of the concrete and the sensor application, about 45 minutes elapsed. Figure 6 shows the measured capillary pressure versus time. The capillary pressure started to build up about 170 minutes after the placing of the concrete. If the time required for the transport of the concrete is considered, the start of the pressure build-up corresponds approximately to the time of initial setting (typically 300 minutes for the cement used here). The measured absolute capillary pressure values increased until the sensors were removed and reached up to approximately -75 kPa. The curves measured with the three applied sensors exhibit the steepest slope about 6.5 hours after the placing of the concrete. A local capillary pressure break-through, which normally occurs at the steepest slope, could not be observed here. It is assumed that the sensor tips were jammed with cement paste. If air reaches the sensor tip, the pressure will not break through in this case. Instead, new menisci are formed at the cement “plug” in the sensor tip. Then, the pressure in the cement “plug” is measured and no longer the one in the surrounding concrete.

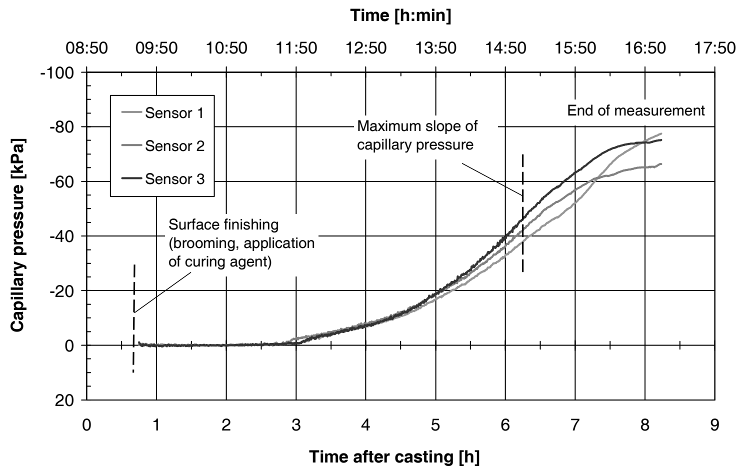

Figure 6. Capillary pressure versus time, measured in the runaway of an airfield.

It could be shown that the capillary pressure measurement in cured concrete pavements is generally possible by using the developed sensors. In addition, it was demonstrated that curing agents can not completely prevent the build-up of capillary pressure.

Road construction. Figure 7 shows a wireless capillary pressure sensor applied on a road construction site. For the pavement, exposed aggregate concrete has been used. This type of concrete is made with the help of an agent being sprayed on the smoothed concretes surface. The agent is a combination of a curing compound and a retarder. The retarder delays the chemical reactions in the near-surface mortar layer. After the core concrete has reached sufficient strength, the surface layer is removed by using a brush. In this way, the coarse aggregate particles are exposed in order to obtain a slip-resistant surface.

Figure 7. Wireless capillary pressure sensor applied to a concrete road (left), sensor during the application of the retarding and curing agent (right).

An uncured reference specimen with the dimensions of 0.5 m by 1.0 m and the same thickness as the concrete road (25 cm) was cast simultaneously and instrumented with a capillary pressure sensor. This reference specimen served for evaluating the effect of the applied concrete curing. The water loss from the unprotected concrete surface was estimated by using a Curing Meter (*Jensen* 2006). The measured average evaporation rate amounted to 0.29 kg/($m^2 \cdot h$).

Figure 8 shows the measured capillary pressure versus time. Approximately at the time when the curing agent was applied, the capillary pressure started to rise. The curing agent should have been applied to the concrete surface immediately after surface finishing. Due to technical problems it was applied comparatively late, about 1.5 hours after casting. When the capillary pressure development in the cured concrete road is compared to the one in the uncured reference specimen, it may be seen that the capillary pressure build-up was much faster in the uncured concrete. The curing agent reduces the evaporation rate and, thereby, retards the capillary pressure build-up, although it does not prevent it. This retardation reduces the cracking risk since the beginning cement hydration lowers the particle mobility resulting in an increasing mechanical resistance to the capillary pressure.

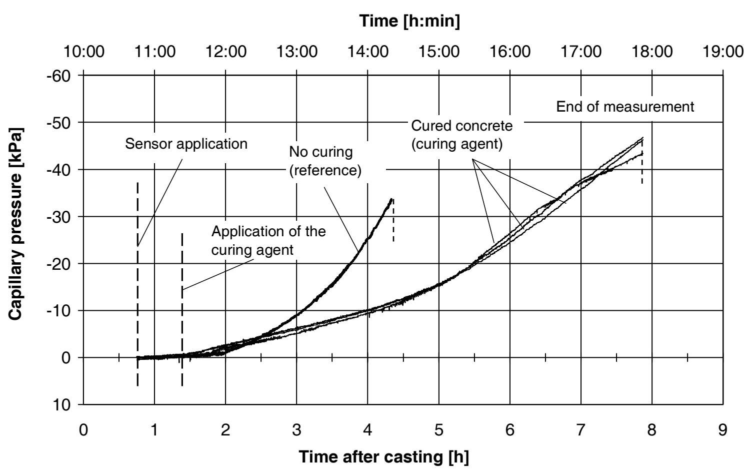

Figure 8. Capillary pressure versus time, measured in a concrete road and in an uncured reference specimen.

The distance between the individual sensors in the cured concrete pavement amounted to about 3 m. The graphs in Figure 8 show that at the different sensor locations almost the same capillary pressure was measured. About 8 hours after casting, the measurement was aborted because the upper layer of cement lime had to be removed according to the concept of exposed aggregate concrete.

CONCLUSIONS AND OUTLOOK

In concrete pavements, the capillary pressure build-up within the first few hours after casting may lead to cracks in the plastic material. On the basis of the actual capillary pressure measured on site, curing measures may be optimized in situ and decisions concerning the correct timing of these measures may be made. In addition, it is possible to document the efficiency of the curing. For these purposes, a wireless capillary pressure measurement system has been developed and tested successfully under site conditions in road and airfield construction.

The critical capillary pressure values which should not be exceeded in the plastic material stage should be based on the air entry value of the respective material. Ongoing research is focusing on practicable recommendations for identifying critical capillary pressure values.

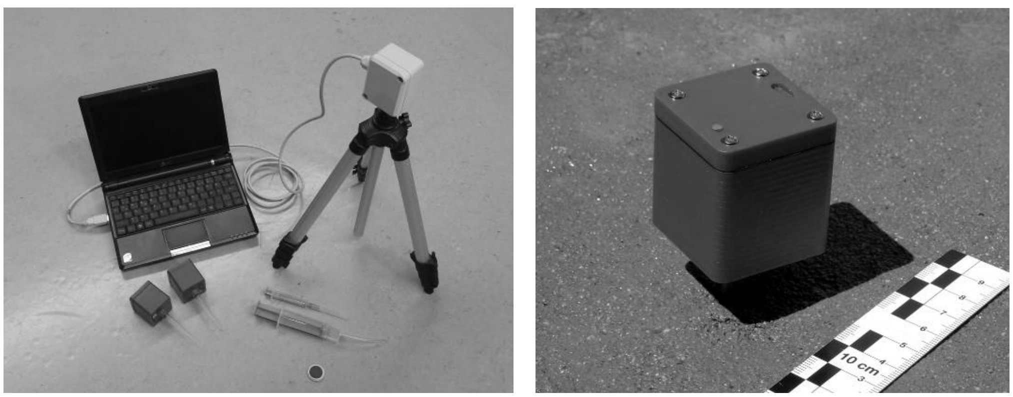

Figure 9: Prototype of an enhanced version of the capillary pressure sensor, base station (left), wireless sensor (right).

An enhanced version of the wireless capillary sensor with an extended radio range is under development. In addition to the capillary pressure, it will monitor the concrete temperature as well as the environmental conditions like air temperature, relative humidity, wind speed, and sun radiation. These parameters allow to estimate the evaporation rate, the amount of bleeding water, and the near-surface maturity. A prototype (without wind sensor) is shown in Figure 9. Based on the in situ measured parameters, the curing of fresh and hardening concrete may be controlled.

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