Fracture Mechanics of Concrete and Concrete Structures -
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Capillary shrinkage cracking – experiments and numerical simulation

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ABSTRACT: Crack formation in cementitious materials may start when the material is still in its plastic stage. Water loss in this very early age causes a curved water surface between the solid particles at open boundary faces. The resulting capillary pressure leads to the so-called plastic or capillary shrinkage. At a certain material specific pressure, air penetrates locally into the pore system and cracks may originate from these locations. If air entry is prevented; i.e., if the absolute capillary pressure value is kept below a critical limit, this type of crack initiation does not occur. Results of the capillary pressure measurement in plastic cementitious materials are presented and a method of capillary pressure controlled concrete curing is proposed. By using a discrete particle-based model, capillary pressure induced crack initiation may be simulated. Furthermore, it has been shown by Finite Element analyses that concrete cracks formed already in the plastic stage affect the behavior of the structures in the hardened stage. Capillary shrinkage cracks might degrade the durability of concrete structures.

1 INTRODUCTION

In concrete structures, cracks may already be formed at an age in which the material has still a negligible tensile strength; i.e., when the material is still in its plastic stage. Planar structures with a large surface area like floors or roads are especially vulnerable to this type of cracking, see Figure 1. If these structures are subjected to high evaporation rates within the first few hours after casting, the so-called plastic shrinkage cracking may occur. It is also referred to as capillary shrinkage cracking since it is caused by capillary forces. Crack widths of up to 1 mm may be reached and it is obvious that such cracks reduce the serviceability of the structure.

Although the physical processes leading to capillary shrinkage cracking are well known, the described type of damage may be observed at numerous newly-built structures. It seems that the problem of capillary shrinkage cracking is not appropriately accounted for in today's concrete technology. Another reason might be the trend towards high concrete strength. The respective materials tend to have a low water content and small particle sizes. Both of these characteristics increase the cracking risk in the plastic material stage.

It should also be pointed out that concrete cracks formed in the plastic stage are sometimes temporarily closed in the process of surface smoothing. At a later age, however, they are likely to appear again under the action of the various loads. Sometimes, causes of structural damage may only be found by considering the cracking processes taking place in the plastic concrete.

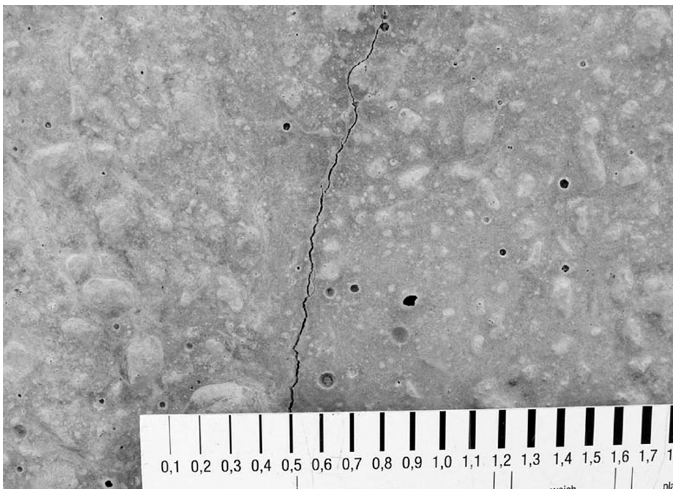

Figure 1. Capillary shrinkage crack in a concrete floor.

The costs for repairing cracked concrete surfaces usually exceed the original construction costs. It seems to be worthwhile to pay more attention to the prevention of capillary shrinkage cracking even if it increases the costs for concrete placing and curing. The authors were involved in a research project on capillary shrinkage cracking, its prevention and its effects on structural durability. The present paper is intended to give an overview of the research results.

2 EXPERIMENTAL INVESTIGATION OF CAPILLARY SHRINKAGE CRACKING

The physical processes leading to capillary shrinkage cracking of cementitious materials may also be observed in drying suspensions with inert solid particles. For this reason, experimental investigations were also performed with suspensions made of fly ash and water (Slowik et al. 2008). The chemical reactions starting already in the plastic stage of cementitious materials do have an influence on shrinkage and cracking; they are not the cause of these phenomena, however.

The reason for capillary shrinkage is the build-up of capillary pressure (Wittmann 1976, Radocea 1992, Holt et al. 2004). In the following, the behavior of a suspension consisting of water and solid particles is described. The material is cast into a form and then subjected to drying. Evaporation of the water may take place at the upper surface. After casting, all the solid particles are typically covered by a plane water film. It might happen that the solid particles settle because of gravitation. As a result, the material will “bleed”; i.e., the thickness of the water film might temporarily increase. Due to evaporation, the water film will eventually disappear and the particles at the surface will no longer be covered by a plane water film. Due to adhesive forces and surface tension of the water, a curved water surface will be formed in the spaces between the particles. This results in a negative water pressure which is referred to as capillary pressure and may be calculated by the Gauss-Laplace equation:

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

where p = capillary pressure; γ = surface tension of the water; and R = main radii of the curved water surface.

Figure 2 shows an experimental setup which has been used for the capillary pressure measurement in drying suspensions with cementitious as well as with inert solid particles (Slowik et al. 2008). Pressure transducers are connected to the pore system of the water saturated material by water filled tubes.

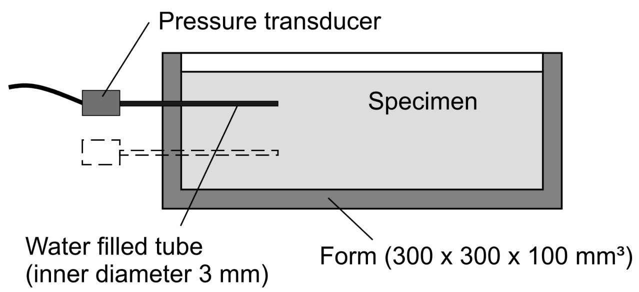

Figure 2. Experimental setup for the capillary pressure measurement in drying suspensions.

Figure 3 shows characteristic curves of the capillary pressure versus time measured in cement paste with different types of cement. The evaporation rate was monitored and found to be nearly the same in both tests and almost constant within the period of time in which the pressure build-up took place. Consequently, the corresponding capillary pressure versus water loss curves would have almost the same shape as the shown curves. The two types of cement paste are characterized by different grain sizes and, accordingly, by different sizes of the surface pores. The smaller the surface pores; i.e., the spaces between the particles at the surface, the steeper the increase of the absolute capillary pressure value in time will be. This also results from geometrical considerations and was confirmed by experiments.

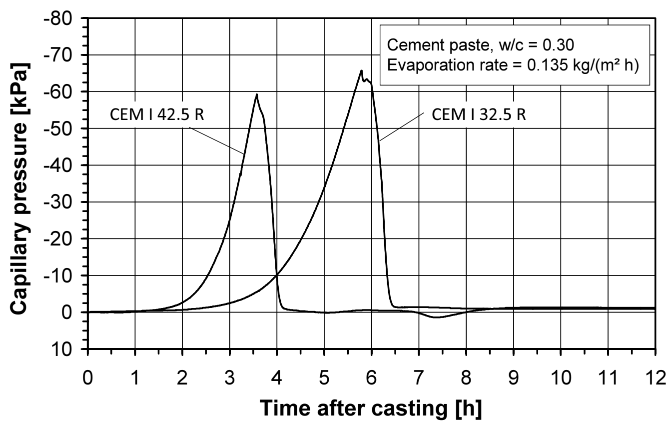

Figure 3. Capillary pressure versus time after casting in cement paste samples, measured with the setup shown in Figure 2.

The measured capillary pressure normally breaks down quite suddenly. While the capillary pressure curves measured at different locations follow almost the same path, the “break-through” pressure varies strongly with the sensor location and may not be considered to be a material property. This results from the irregular particle structure and from the non-uniform air entry into the pore system. Furthermore, air bubbles might reach the sensor tip and cause this local “break-through”.

Up to a depth of at least 100 mm, the capillary pressure appears to be almost depth independent since all the pores are interconnected in this age and the permeability is high.

The pressure at the first event of air entry is referred to as air entry value and may be regarded as a material property. It depends predominantly on particle sizes and content as well as on the particle mobility and may be estimated on the basis of experimental observations (Slowik et al. 2008). It could be shown that crack initiation is likely to occur when the capillary pressure reaches the air entry value. Because of the local air entry, weak spots are formed at the surface of the drying suspension and these spots might be the origin of cracks. Figure 4 shows electron microscopic images of the surface of a drying suspension made of fly ash and water. When the first image was taken, all the spaces between the particles were bridged by water menisci. In the second image, some dark spots may be seen on the left side. At these positions, air has penetrated the surface pores. The third image shows a crack which was formed along a path through the weak spots resulting from local air entry. It may be concluded that the cracking risk in drying suspensions may be significantly reduced by keeping the absolute capillary pressure value below the absolute air entry value. This concept is the basis of the capillary pressure controlled concrete curing described in section 4.

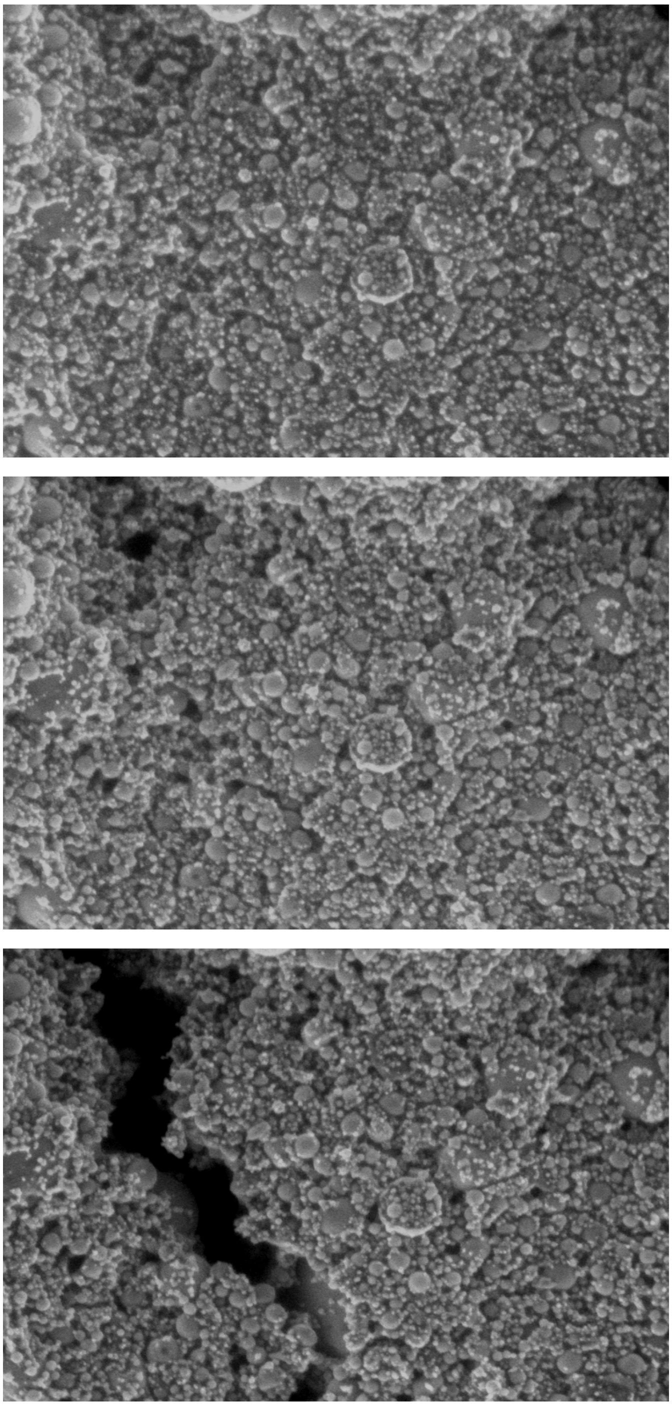

Figure 4. Electron microscopic images of the surface of a drying suspension made of fly ash and water, water content is reducing from the top down.

3 NUMERICAL SIMULATION OF CAPILLARY SHRINKAGE CRACKING

For modeling capillary shrinkage cracking, the concepts of solid fracture mechanics are not applicable. Instead, a discrete particle-based approach seems to be appropriate. The drying suspension is modeled in 2D as a two-component system consisting of circular solid particles and a liquid phase (Slowik et al. 2009). Particle interaction is described by interparticle forces which depend on the properties of the solid and liquid components. These properties are assumed to be constant in time; i.e., effects of chemical reactions on the particle interaction are not taken into account. Additional forces acting on the particles result from gravitation and from capillary pressure. Water loss is simulated by incrementally increasing the absolute capillary pressure value and calculating the course of the water front at an open surface under the assumption of constant curvature according to the respective pressure value.

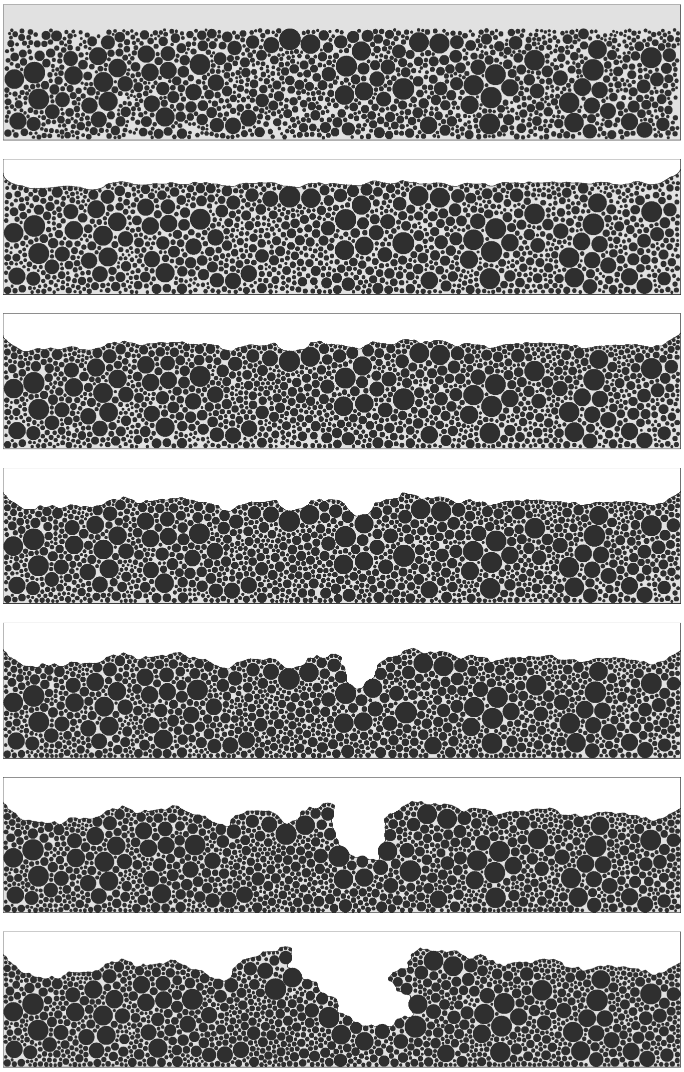

Figure 5. 2D simulation of capillary pressure build-up in a drying suspension, particle sizes ranging from 4 µm to 32 µm, absolute capillary pressure values from top to bottom in kPa: 0; 10; 20; 25; 30; 35; 40 (approximate values).

Figure 5 contains the results of a simulated drying process. The individual images correspond to different pressure levels. Initially, all solid particles (dark color) are completely surrounded by water (gray color). The upper surface is considered to be open. Due to drying, the water volume is decreasing. When the solid particles are no longer entirely below the water surface, menisci are formed in the surface pores and the particles are moving under the action of the forces resulting from capillary pressure. This leads to a consolidation or vertical shrinkage which appears to be non-uniform due to the irregular particle structure. Eventually, crack initiation may be observed. It starts with the formation of a local "breach" in the specimen surface. In the example shown in Figure 5, this happened at about 25 kPa. Later, the existing gap is widened by the horizontal components of the increasing absolute capillary pressure.

An implicit solution scheme has been applied for the drying simulations and some effects of the material composition on capillary pressure build-up and cracking risk could be studied (Slowik et al. 2009). As in the experiments, drying suspensions with smaller solid particles are characterized by a stronger capillary pressure build-up for a given water loss rate and by a higher cracking risk. An increase of the equilibrium particle distance also tends to raise the cracking risk.

Part of the ongoing work on the discrete modeling of capillary shrinkage cracking is the utilization of an explicit solution scheme.

4 CAPILLARY PRESSURE CONTROLLED CONCRETE CURING

It has been stated before that the risk of capillary shrinkage cracking may be significantly reduced by keeping the absolute capillary pressure value in fresh concrete below the absolute air entry value. Hence, a method of controlled concrete curing which is based on in situ measurements of the capillary pressure is proposed (Schmidt et al. 2007, Slowik et al. 2008, Schmidt et al. 2009). If the measured pressure reaches a previously defined threshold value, the concrete surface is rewetted. This may be conducted by commercially available fogging devices. The rewetting is stopped after the absolute capillary pressure value has reached a certain predefined minimum. Reducing the absolute capillary pressure value down to zero would mean that a new plane water film is created which might have negative effects on the surface quality and on the near-surface material properties of the structure.

Figure 6 shows the measured capillary pressure in two slabs on grade with a thickness of 200 mm. They were cast simultaneously and under site conditions. One slab was left uncured as a reference sample; the other one was rewetted by fogging water above the surface when the capillary pressure reached a threshold of -10 kPa. After a few seconds of rewetting, the measured absolute value had decreased to a predefined minimum value. It may be seen that the capillary pressure could be kept within a range defined by the two limits. After eight hours, the controlled rewetting was terminated and the absolute pressure value started to rise above the previously applied threshold. In this age, the concrete was expected to have gained enough resistance against capillary shrinkage cracking.

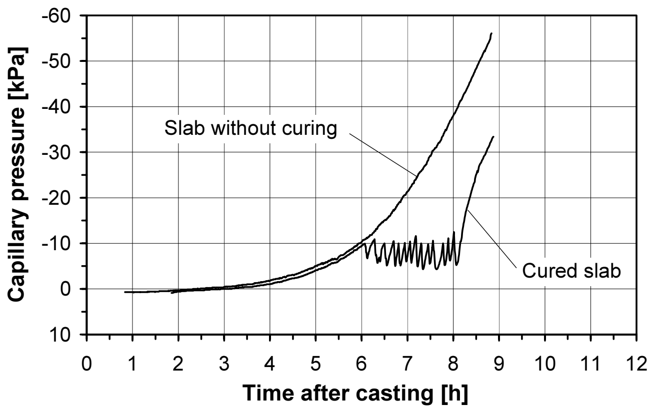

Figure 6. Capillary pressure versus time during controlled concrete rewetting of two slabs on grade, size approximately (3×3)m², thickness 200 mm.

The controlled concrete curing requires the in situ measurement of the capillary pressure and the specification of a critical capillary pressure value. The latter may be defined on the basis of the experimentally determined air entry value of the material (Slowik et al. 2008). An adequate safety margin should be considered.

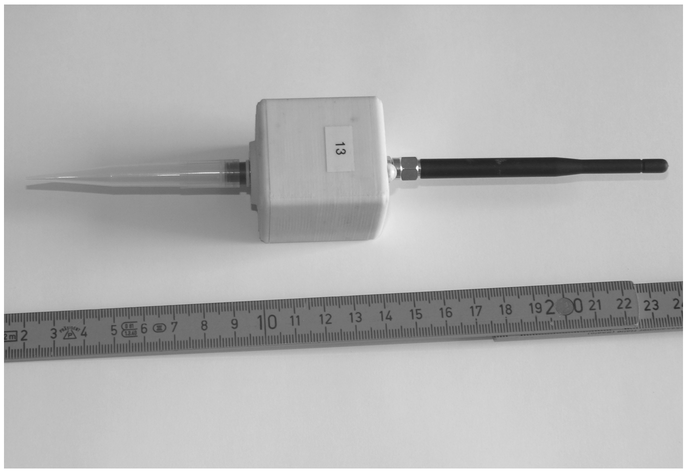

Figure 7. Wireless capillary pressure sensor.

For the on-site capillary pressure measurement, a wireless sensor has been developed, see Figure 7. The intension was to avoid cable connections which usually cause problems on construction sites. The sensor consists of a robust light-weight case, a replaceable conic tip and an antenna. The case contains a 2.4 GHz radio module and a battery which may be contactless recharged. Under typical site conditions, the range of radio transmission amounts to 50 m. The conic tip allows the sensor to be plunged into the compacted concrete and carries the sensor's weight. It needs to be filled with outgased water in order to provide a hydraulic connection between the pore water of the material and the sensor element. After the measurement, the sensor may easily be extracted from the concrete surface.

Figure 8 shows the complete measuring system. It consists of up to eight wireless sensors, a radio receiver box and the contactless battery charger. A mobile computer is used for recording and visualization of the measured capillary pressure values.

Figure 8. Measuring system consisting of the receiver box on a tripod, a mobile computer and the transport cases.

Especially in concrete road construction, see Figure 9, the on-site capillary pressure measurement appears to be a useful method for the estimation of the cracking risk, for the optimization of curing measures in the very early age and for the technical documentation of the construction process.

Figure 9. Wireless capillary pressure sensors on a road construction site.

5 INFLUENCE OF CAPILLARY SHRINKAGE CRACKS ON THE CRACKING BEHAVIOR OF HARDENED CONCRETE STRUCTURES

Cracks formed already in the plastic stage of the concrete may have an influence on the crack pattern appearing in the hardened material. Even if the capillary shrinkage cracks have been closed superficially during surface finishing, they promote damage localization under the loads the structure is subjected to in the young age or during the service life. In addition to external forces, thermal and hygral gradients may cause damage processes which, possibly, are influenced by preexisting early age cracks. In numerical simulations of cracking due to thermal gradients in young concrete, it was found that existing early age cracks may lead to significantly larger crack widths and depths.

In the following, results of 2D numerical simulations of drying shrinkage cracking in hardened concrete are presented. It was necessary to use mesolevel models for these simulations in order to realistically reproduce the damage localization within the heterogeneous material. The aggregate particles of the largest grain size fraction were modeled in a discrete manner and embedded in a homogeneous mortar matrix. Figure 10 shows a mesolevel model which was used in some of these simulations. It represents a cutout of a 200 mm thick concrete slab on grade. The bottom face was fixed in the mechanical analyses, whereas no boundary conditions were applied to the top face representing the open surface of the concrete slab. At the two side faces, symmetry boundary conditions were applied.

Fracture was simulated by using the smeared crack approach. In some of the mesolevel models, an initial crack has been created prior to the actual drying shrinkage simulation. This crack was supposed to represent a preexisting capillary shrinkage crack. An uniform shrinkage strain has been imposed on the mortar matrix and, as a result, a single localized crack was formed normal to the surface with a length of more than one half of the model height, see Figure 10. The crack opening at the surface was adjusted to approximately 0.1 mm by altering the magnitude of the applied shrinkage strain. The objective of this pre-analysis was not to simulate capillary shrinkage cracking by solid fracture mechanics, but to generate realistic initial conditions for the subsequent simulation of drying shrinkage cracking in a predamaged hardened concrete structure.

The one-dimensional water transport to the upper surface of the hardened specimen was simulated on the basis of the non-linear diffusion theory and under the assumption of a homogeneous material. In this way, the time-dependent moisture distribution in the specimen was obtained and the shrinkage strains could be calculated and assigned to the mortar matrix in the mesolevel model. The resulting stresses led to the formation of vertical cracks originating from the upper face; i.e., from the open surface of the concrete slab.

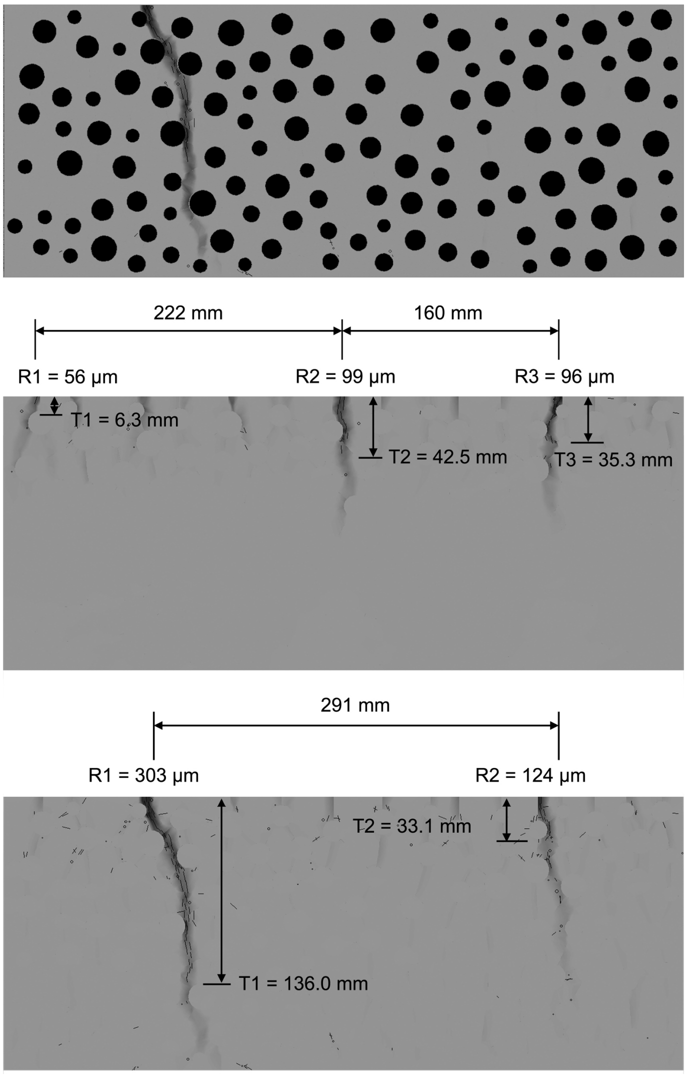

Figure 10. Simulation of drying shrinkage cracking in a concrete slab on grade, thickness 0.2 m, drying from the upper surface; at the top: mesolevel model with a maximum aggregate size of 20 mm and a simulated capillary shrinkage crack; in the middle: crack pattern after 200 days of drying; at the bottom: crack pattern after 200 days of drying with the preexisting capillary shrinkage crack.

In parametric studies, particular attention has been paid to the influence of simulated preexisting capillary shrinkage cracks on the cracking behavior of the hardened concrete. Figure 10 shows the crack patterns obtained after 200 days of drying for both without and with preexisting crack. The initial relative air humidity amounted to 80%. During drying, above the upper surface 50% has been assumed. Both analyses were performed with the Finite Element program ATENA, Červenka Consulting Prague, for the mesolevel model also shown in Figure 10. Stress relaxation has not been taken into account. In Figure 10, cracks with widths of at least 50 µm are shown as black lines. The dark shade indicates regions of high total horizontal strain and the assigned numbers correspond to crack spacing, depth and width at the surface. It was generally observed that drying shrinkage leads to a further opening of the preexisting cracks. Crack widths of more than 0.2 mm at the surface were obtained in numerous simulations under realistic boundary conditions. Such cracks increase the concrete permeability and may degrade the structural durability. Despite the distinct damage localization caused by a preexisting crack, see Figure 10 at the bottom, new drying shrinkage cracks are formed. Preexisting cracks lead to stress relief only in their vicinity.

6 CONCLUDING REMARK

The capillary pressure build-up in plastic concrete within the first few hours after casting may lead to cracks which strongly affect the durability and the serviceability of the structures. This type of damage may be avoided by appropriate curing measures. It seems to be reasonable to base the curing concept on the actually developing capillary pressure which may be measured in situ.

ACKNOWLEDGMENT

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