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Simulation of capillary shrinkage cracking in cement-like materials

V. Slowik *, T. Hübner, M. Schmidt, B. Villmann

Leipzig University of Applied Sciences, PF 301166, 04251 Leipzig, Germany

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ABSTRACT

In drying suspensions, water loss leads to a capillary pressure build-up in the liquid phase. This effect may also be observed in fresh cement-based materials subjected to evaporation at an open surface. If under decreasing water content the near-surface solid particles are no longer covered by a plane water film, menisci develop along with an associated build-up of negative capillary pressure, resulting in shrinkage and possibly in cracking. A 2D model for simulating the described physical process is presented. For arranging the particles in the 2D specimen a stochastic–heuristic algorithm is used. Subsequently, the course of the water front between the particles is calculated by assuming a constant curvature of the water surface. Particle mobility is taken into account by adopting interparticle forces and performing equilibrium iterations. The model allows one to study the influences of the particle size distribution as well as of the properties of the liquid phase on the capillary pressure build-up and on the cracking risk.

1. Introduction

Concrete members may crack already within the first few hours after casting. At this early age, the material has not reached a significant strength yet and it may be regarded as a drying suspension rather than a solid material. The predominant reason for volume changes and cracking at this age are the capillary forces built up in the liquid phase of the material leading to the so-called capillary shrinkage [1,2]. It is also referred to as plastic shrinkage since it is observed when the cement-based material is still in its plastic stage. Resulting damage is usually in the form of cracks that appear in a relatively regular pattern, see Fig. 1. Such early age cracks occur predominantly in concrete floors and slabs where the upper surface is subjected to a high evaporation rate. The cracks shown in Fig. 1 were formed in a concrete slab on grade probably when the material was still in its plastic stage. Capillary shrinkage cracks may have widths of up to 2 mm and depths of up to 10 cm in thick members [2]. In slabs, they may run through the whole depth of the member [3]. Normally, capillary shrinkage cracks are considerably deeper than those formed by drying induced hygral gradients in hardened concrete [4]. During construction work, early age cracks are sometimes superficially covered by using surface smoothing equipment. However, these cracks tend to open observably under tensile stresses occurring during the hardening or at later ages [2,5]. They may influence the durability of the structure [4]. Crack patterns detected during the service life of concrete members are sometimes quite similar to those formed by capillary shrinkage and may only be explained satisfactorily by taking into account the early age material behavior. Although the physical process leading to capillary shrinkage cracking is well known in the concrete research community and has been investigated experimentally [1,3,5–9], its practical consequences are frequently disregarded in concrete technology leading to extra construction expenses for evaluation and repair [10].

Fig. 2 schematically shows the process of capillary pressure build-up in a drying suspension. A more detailed description as well as corresponding experimental observations may be found in a previous paper [7]. In the material considered here, the solid particles may be either cementitious or inert since the physical process explained in the following discussion takes place in both types of materials [1,2,7]. The liquid phase consists mainly of water. When the material is cast into a form, bleeding may occur, i.e. the solid particles settle due to gravitational forces and on the surface a plane water film is formed (Fig. 2A). Evaporation at the upper surface continuously reduces the thickness of the water film and, eventually, the near-surface particles are no longer covered by a plane water surface (Fig. 2B). Adhesive forces and surface tension result in a curved water surface. Menisci are formed between the solid particles and a negative water pressure is built up. The latter depends on the water surface tension γ and on the main radii R of the curved water surface, i.e. maximum R_1 and minimum R_2 of the radius of curvature, as expressed by the Gauss–Laplace equation.

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

* Corresponding author. Tel.: +49 341 3076 6261; fax: +49 341 3076 7045.
E-mail address: slowik@fbb.htwk-leipzig.de (V. Slowik).

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Fig. 1. Early age shrinkage cracks in a concrete slab on grade.

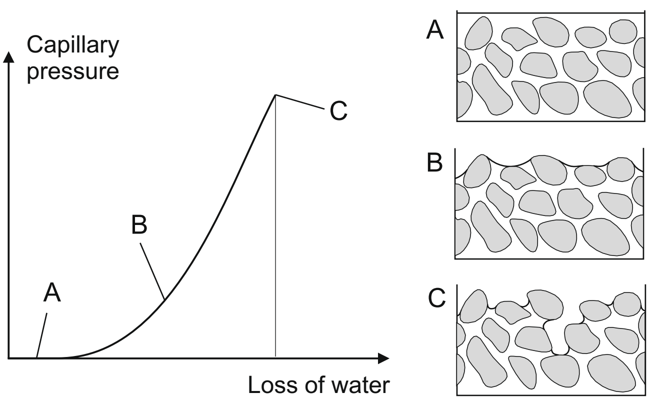

Fig. 2. Capillary pressure build-up in a drying suspension.

In the vicinity of the surface, i.e. up to a depth of at least 10 cm, the water pressure within the interconnected pores is almost uniformly distributed [3]. Fig. 3 shows the capillary pressure measured at several sensor positions. The curves obtained for different distances from the surface follow almost the same path. The maximum absolute pressure values, however, are different. Hydrostatic pressure differences, in this case 0.2 kPa between the sensor positions at depths of 2 cm and 4 cm, respectively, are small when compared to the absolute capillary pressure values.

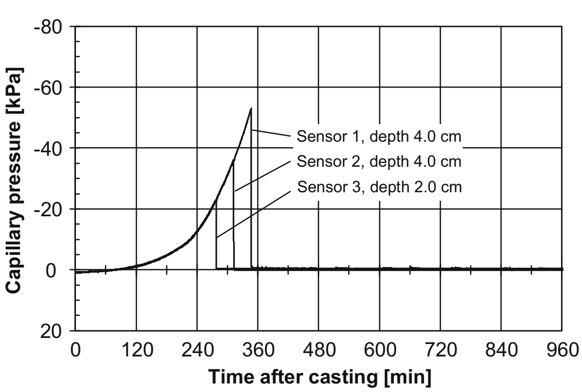

Fig. 3. Capillary pressure at different sensor positions in a concrete specimen with a thickness of 6 cm.

In cementitious materials, the hydration may be an additional cause for the water loss leading to the described capillary pressure build-up [5]. This is of relevance especially for low water–cement ratios.

The negative capillary pressure acts on the particle faces and causes a reduction of the specimen volume. This results first in a settlement or vertical shrinkage strain [2] and later, after the sample is separated from the side faces of the form or cracked, in a horizontal shrinkage strain [7]. The continuing capillary pressure build-up, however, cannot be prevented by the reduction of the interparticle distances. Up to this stage, the specimen volume change is almost equal to the volume of the evaporated water [2,7]. If a certain pressure is reached, the largest gaps between the particles at the surface can no longer be bridged by the menisci and air penetrates locally into the pore system accompanied by a local pressure break-down (Fig. 2C). The pressure value at the first event of air penetration into the pore system is referred to as the air entry value [7,11]. Due to the irregular particle arrangement, the air does not penetrate into all the surface pores simultaneously. The latter are drained successively starting with the larger ones. Therefore, when measuring the capillary pressure at different locations, the corresponding break-down values, i.e. the maximum absolute pressure values, are different and depend on the individual sensor positions. In addition, the capillary pressure might break down locally due to air bubbles reaching the sensor tip [3]. Fig. 4 shows measured pressure versus time curves for different sensor positions at the same depth as well as the corresponding specimen deformations starting from the time of casting. The experimental set-up described in [7] and [10] has been used. It may be seen that the different pressure curves follow the same path as long as the sensor tip is in contact with the pore water. The pressure break-

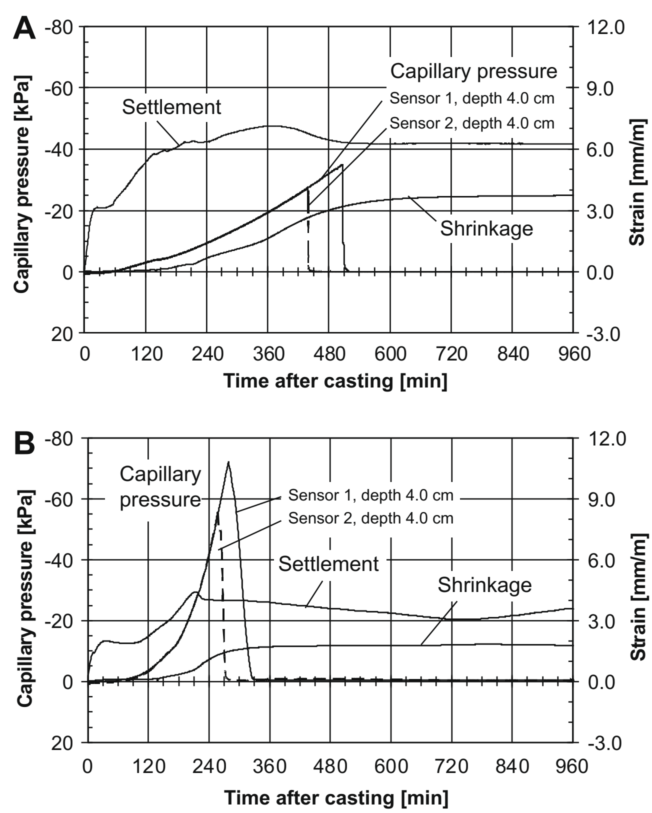

Fig. 4. Capillary pressure, vertical (settlement) and horizontal (shrinkage) strain versus time in a suspension made of fly ash and water (A) and in cement paste (B), specimen thickness 6 cm, identical drying conditions.