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IN SITU MEASUREMENT OF THE CAPILLARY PRESSURE IN CONCRETE ROAD CONSTRUCTION

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ABSTRACT

Concrete pavements are vulnerable to cracking already in the plastic material stage, i.e., before the concrete has reached a significant strength. Due to the evaporation of water at fresh concrete surfaces, a capillary pressure is built up in the pore system of the material. This underpressure leads to the so-called capillary or plastic shrinkage and possibly to cracking. Since the capillary pressure provides direct information on the response of the concrete to the water loss by evaporation, it may be used to estimate the cracking risk in situ and to control curing procedures. At the examples of an on-site measurement, the applicability of capillary pressure sensors is demonstrated and discussed.

KEY WORDS

CONCRETE ROADS / PLASTIC SHRINKAGE / EVAPORATION / CURING / CAPILLARY PRESSURE

1. MOTIVATION

Concrete roads and other planar concrete structures like airfields or industrial floors are especially prone to capillary shrinkage since their comparatively large surface is exposed to the environment and without curing even unprotected. Immediate curing is necessary in order to prevent early age cracking. In road construction, usually curing agents are applied to the surface. If curing starts too late or if its effect is insufficient, the durability of the structure may significantly be reduced. If reactive aggregates are used, pre-existing damage originating from the early age may enhance the damaging effects of the alkali-silica reaction (Breitenbücher 2006).

It is assumed that cracks which are initiated already in the plastic stage of the material will have an influence on the crack pattern formed in the hardened concrete. Even if these early age cracks are not visible or if they have been closed superficially, they may promote damage localisation under different load cases during the service life of the structure. Sometimes, crack patterns observed in hardened concrete members are quite similar to those formed in the plastic stage and may only be explained by considering the early age material behaviour. In addition to external forces, thermal and hygral gradients may cause damage processes which, possibly, are influenced by existing early age cracks.

In numerical simulations of cracking due to hygral gradients in hardened unreinforced concrete, it was found that existing early age cracks may lead at a later age to significantly larger crack widths and depths (Slowik et al. 2008b, Slowik et al. 2010). Figure 1 shows the crack patterns obtained after 200 days of simulated drying without and with pre-existing early age crack, respectively. The latter was located about 100 mm apart from the left side of the specimen. The two simulations the results of which are presented in Figure 1 have been performed with the same mesolevel model, i.e., with the same arrangement of aggregate particles. Drying was possible at the upper surface only. The time-dependent moisture profiles were obtained by nonlinear diffusion theory and for the damage simulation a smeared crack model was used. The obtained crack widths are printed at the crack mouths in Figure 1.

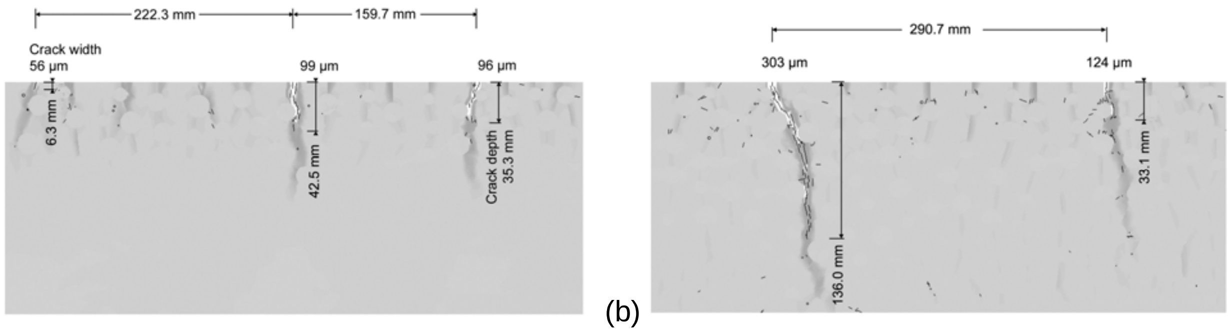


Figure 1 – Simulation of drying shrinkage cracking in a concrete slab on grade, thickness 0.2 m, drying from the upper surface; (a) Crack pattern after 200 days of drying; (b) Crack pattern after 200 days of drying with a pre-existing capillary shrinkage crack (after Slowik et al. 2010)

Pre-existing cracks lead to a stronger damage localisation, i.e., fewer, but wider and deeper cracks are being formed during drying shrinkage of the hardened concrete. In view of the structural durability, this is an unfavourable effect. It may be noted, that despite the distinct damage localisation caused by a pre-existing crack, see Figure 1 (b), new drying shrinkage cracks are being formed. Pre-existing cracks lead to stress relief only in their vicinity. In real pavements, the crack pattern is also influenced by contraction joints which are cut into the surface. The simulation results obtained at the 0.5 m wide models demonstrate, however, that damage localisation at pre-existing cracks may occur between the construction joints, see crack spacing in Figure 1 (b).

It is concluded that capillary shrinkage cracks formed in the plastic material stage should not be tolerated in concrete construction. Their width and depth may exceed those of the cracks formed in hardened concrete under mechanical loading and hygral gradients.

2. DAMAGE MECHANISM

Shrinkage in plastic concrete is mainly caused by the build-up of a negative pore water pressure as a result of the evaporation of water from fresh concrete surfaces (Wittmann 1976, Radocea 1992, Slowik et al. 2008a). Due to adhesive forces and due to the surface tension γ, water menisci are formed between the solid particles at the surface when these particles can no longer be covered by a plane film of water. If axi-symmetric pores are assumed, the capillary pressure difference Δp between the atmosphere and the pore water can be calculated in a simplified way by using the Young-Laplace equation, Eq. (1).

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

In simplifying discussions, typically full wetting, i.e., a wetting angle $\beta \approx 0°$, is assumed. According to Eq. (1), the pressure difference Δp is inversely proportional to the radius R of the meniscus.

Figure 2 (a) shows schematically the formation of a water meniscus between two particles. The formation of the menisci starts when there is no longer a plane (bleeding) water film on the surface and the evaporation rate exceeds the bleeding rate. The more water evaporates, the smaller the radii of the menisci will become. It has to be taken into account that horizontal and vertical particle movements, e.g. due to settlement or capillary forces, are not considered in Figure 2 (a). The particle mobility appears to be important for the development of the capillary pressure. Since the latter acts on the solid particles, the system is compacted and, consequently, the pore system becomes narrower and water is transported to the surface where it delays the capillary pressure development.

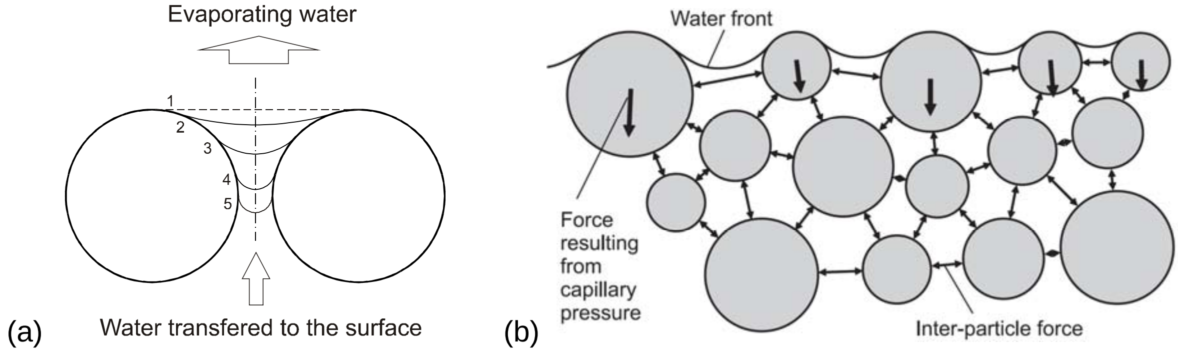


Figure 2 – Decreasing radius of a meniscus between two particles due to evaporation (a); Inter-particle forces between solid particles and forces resulting from capillary pressure (Slowik et al. 2011) (b)

The forces resulting from capillary pressure, gravitational and uplift forces, and inter-particle forces form system in equilibrium, see Figure 2 (b), which reacts on water loss due to evaporation. If the radius of a meniscus becomes equal to the minimum radius of a pore, see Figure 2 (a), a state of instability is reached. Under continuing water loss the meniscus can no longer bridge the distance between the particles and the pressure “breaks through” (Wittmann 1976). This break-through will start at the largest pores. Depending on the pressure and on the pore size distribution, it may affect multiple particle layers up to a depth of a few centimetres. It stops when a new state of equilibrium of the static forces is reached. The pressure value at which a significant air penetration into the pores takes place is in soil physics referred to as air entry value (Fredlund et al. 1993). At this pressure level, the cracking risk is high because the re-orientation of the forces resulting from capillary pressure leads to a strain localisation. In other words, due to air entry into a pore the attracting force between the neighbouring particles vanishes and the respective pore is widened under the action of the capillary pressure (Slowik et al. 2011). This damage mechanism is referred to as capillary shrinkage cracking.

3. CAPILLARY PRESSURE SENSORS

The capillary pressure in drying suspensions may be measured with appropriate sensors (Wittmann 1976). Such sensors consist of a pressure transducer which allows measuring a negative pressure and an attached sensor tip filled with a liquid. The liquid in the tip, usually water, connects the pressure transducer to the pore water and transmits the capillary pressure in this way.

In cementitious materials, normally tube-like sensor tips with an open end are used whereby the diameters of the opening are ranging from about 0.5 mm to a few millimetres. The tips may be flexible plastic tubes (Wittmann 1976), syringe needles (Scott et al. 1997), or small metal tubes (Radocea 1992, Hammer et al. 2006, Slowik et al. 2008a). For the capillary pressure sensors shown in Figure 3 (a), brass tubes with an inner diameter of 3 mm are used.

Experience from on-site measurements has shown that cable connections limit the usability of the capillary pressure sensors. Furthermore, in large planar concrete structures, especially in road construction, it appears to be difficult to monitor the capillary pressure development at different locations. In order to resolve these problems, capillary pressure sensors with an integrated radio module have been developed (Slowik et al. 2010, Schmidt et al. 2013a). A conic tip made of transparent plastic is used as measurement tip. The transparent plastic allows to check the tip for correct bubble-fee water filling. The conic shape and the stiffness of the measurement tip allow to plunge the sensor into the plastic concrete after casting and compaction. Furthermore, it supports the sensor’s weight. Figure 3 (b) shows a wired and a wireless capillary pressure sensor for on-site applications, both equipped with the aforementioned conic measurement tip.

(a) (b)

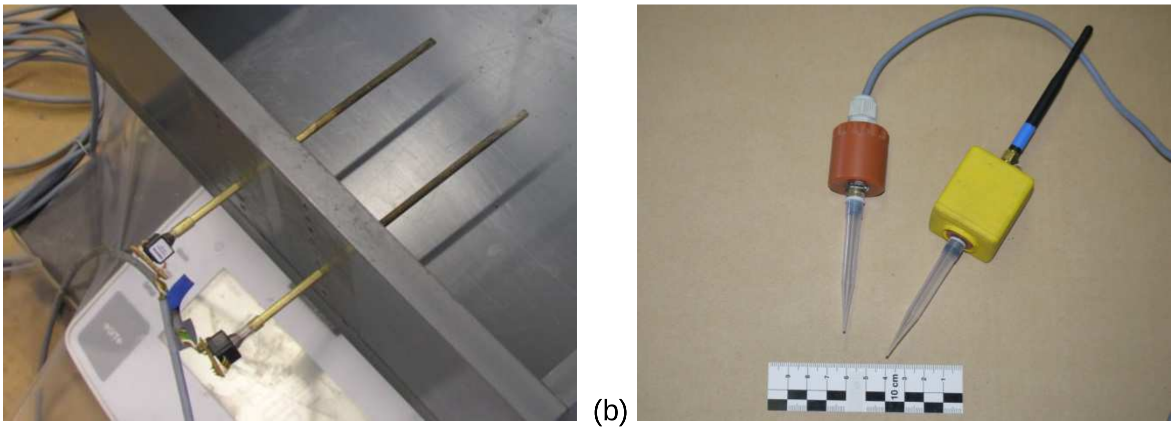


Figure 3 – Capillary pressure sensors: Pressure transducers with connected brass tubes (a); Wired and wireless capillary pressure sensors with conic measurement tip for on-site applications (b)

4. CONCRETE CURING AND CAPILLARY PRESSURE MEASUREMENT IN CONCRETE ROAD CONSTRUCTION

In road construction, the bleeding rate of the normally used concrete is comparatively low. Since the concrete is placed in most cases by using slip-form pavers, it needs to have a stiff consistency. Such concrete compositions may be very vulnerable to plastic shrinkage. According to the following empirical equation, Eq. (2), a nearly linear relationship between the bleeding rate and the water-binder ratio w/cm is assumed (Poole 2005).

$$B = (0{,}051 \cdot w/cm - 0{,}015) \cdot h \qquad (2)$$

This equation allows to estimate an average bleeding rate B in kg/(m²·h) for a pavement of thickness h in cm (Poole 2005). Typical concrete compositions used for pavements in road construction have a water-binder value between 0.38 and 0.50 (Poole 2005, TL-Beton StB 07). With a thickness of 30 cm, an average bleeding rate between 0.13 kg/(m²·h) and 0.32 kg/(m²·h) is obtained. Evaporation rates of this order of magnitude may occur even under moderate drying conditions. Taking into account the often considered critical evaporation rates between 0.5 kg/(m²·h) and 1.0 kg/(m²·h) (Dao et al. 2010), it may be concluded that concrete used in road construction has to be protected against drying as soon as possible after the placing.

Curing in traffic route construction is usually conducted by the application of curing compounds. Depending on the construction method, the compound is sprayed on the surface when it appears as pale damp. In recent years, the usage of exposed aggregate concrete has become the standard road construction method in Germany. According to this method, a special agent being a combination of a curing compound and a retarder is sprayed on the concrete surface immediately after placing.

A disadvantage of most curing methods is that there is no "feedback" from the concrete, i.e., no real-time information on the efficiency of the curing. It was pointed out before that the capillary pressure being built up in plastic concrete is the driving force for cracking in this age. Consequently, the capillary pressure may be used as an indicator for the cracking risk and for the demand for curing in the early age. The capillary pressure provides direct information on the response of the concrete to the water loss due to evaporation. It captures the influences of the environmental conditions, of the material composition, and of the height of the concrete member.

In on-site measurements on a road construction site (Schmidt et al. 2013a) and during the reconstruction of a parking structure (Schmidt et al. 2013b) it was shown, in which way the applied curing measure delays the capillary pressure development in comparison to the one in uncured reference specimens.

In the following, a capillary pressure measurement undertaken at the concrete pavement of a highway is discussed. This particular pavement is 12.50 m wide and 0.32 m thick. Due to a slight rainfall during casting, this example demonstrates the sensitivity of the capillary pressure and its immediate response to environmental influences. The concrete was placed by a concrete paver in two layers on a gravel subgrade. A special cement for pavements, CEM I 32.5 R (st), and an air entraining agent were used. The w/c ratio amounted to 0.45. For surface finishing, a fabric made of jute has been dragged over the surface. The paver was followed by a curing machine in a distance of about 50 m and a membrane forming curing compound was sprayed on the surface (175 to 200 g/m² about 40 minutes after placement) in order to reduce the water evaporation rate, see Figure 4 (a).

(a) 

(b) 

Figure 4 – Road construction site: Spraying of the curing agent (a);
Application of wired capillary pressure sensors (b)

For the capillary pressure measurement, sensors with cable connections were used, see Figure 4 (b). Therefore, the sensors could not be applied before the curing machine had passed the intended sensor position and before the curing agent was applied. About 60 minutes elapsed between the placement of the concrete and the start of the measurement. Since no capillary pressure build-up had taken place within this time period, the delay did not have an effect on the results of the capillary pressure measurement.

The evaporation rate for the unprotected concrete was measured by using a Curing Meter (Jensen 2006). The latter appears to be a small sensor which allows to measure the amount of water evaporating from an exposed reference surface. The evaporation rate estimated in this way amounts to about 0.3 kg/(m²·h). According to the empirical Eq. 2, the bleeding rate of the concrete is approximately 0.25 kg/(m²·h), i.e., it is slightly smaller than the evaporation rate. Hence, without curing a capillary pressure is expected to build up soon after the placement of the concrete.

The capillary pressure versus time is presented in Figure 6. Obviously, the curing agent could not completely prevent the capillary pressure build-up. The absolute pressure value starts to rise about two hours after the placement of the concrete. About 100 minutes later, a gentle rain started and continued for about 10 minutes. The comparatively small amount of rainwater added to the surface led to a noticeable decrease of the absolute capillary pressure value, despite the membrane forming curing agent. Water transport through this membrane appears to be possible. After the rainfall, the absolute capillary pressure value continued to rise. The slope of the curve, however, was slightly steeper after this “rewetting” of the surface. This may be attributed to the already reduced particle mobility. Hydration processes had probably started already. The cement used here starts to set normally after about 175 minutes.

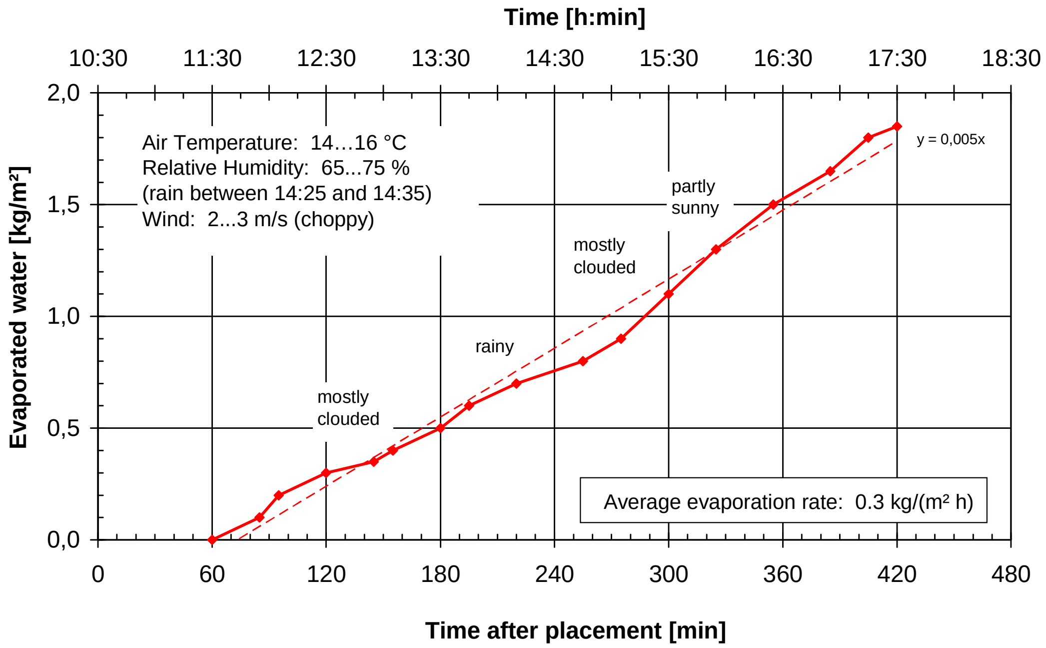


Figure 5 – Estimating the evaporation rate by using a Curing Meter

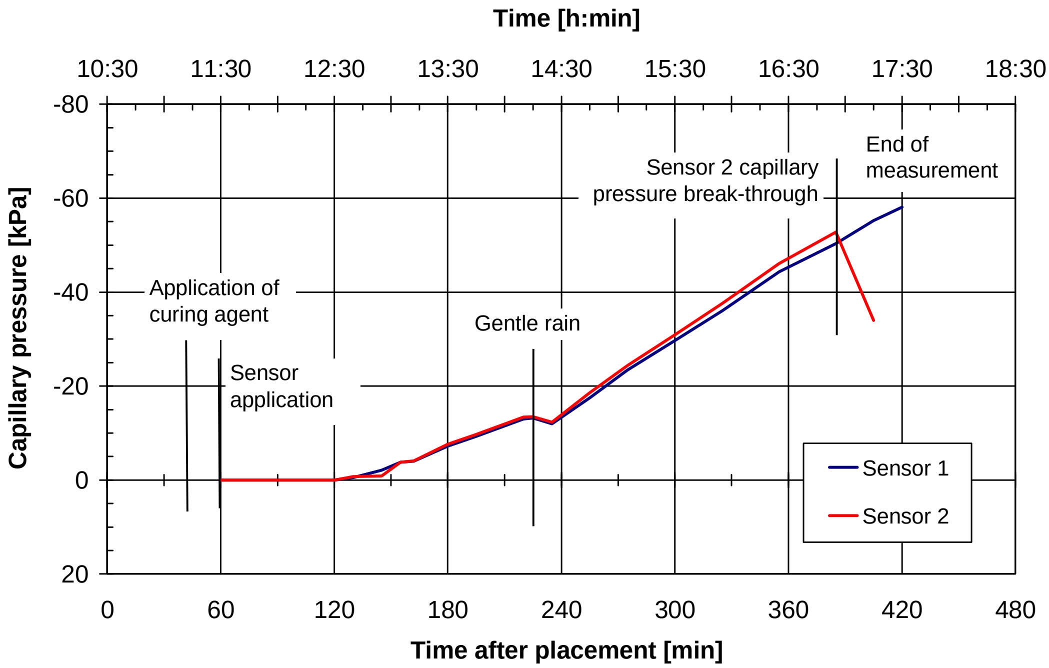


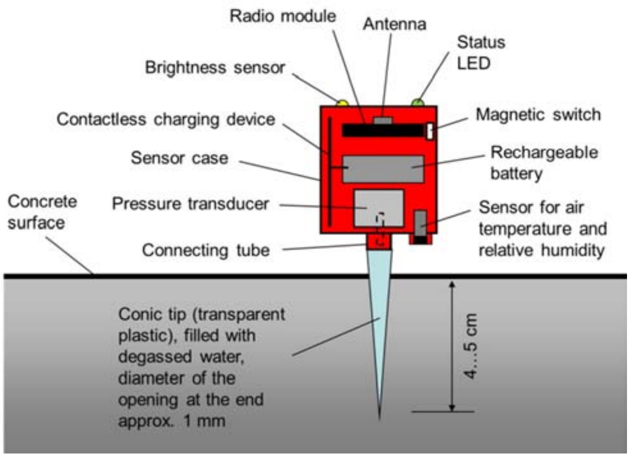
Figure 6 – Capillary pressure measured in a concrete pavement (highway construction)

This example has shown that rewetting of fresh concrete surfaces has a significant and immediate effect on the capillary pressure development. In other on-site measurements (Schmidt et al. 2013a), it has been observed that the decrease of the evaporation rate, normally due to the application of a curing compound, leads to a deceleration of the capillary pressure build-up. Consequently, the cracking risk is reduced since the concrete is gaining strength in time and the resistance to capillary shrinkage cracking increases.

5. PRESENT SENSOR DEVELOPMENT

Since the capillary pressure build-up depends to a large extent on the environmental conditions, the newest prototype sensors will not only monitor the capillary pressure, but also air temperature and relative humidity above the concrete surface. An integrated brightness transducer serves for estimating the magnitude of solar radiation. Furthermore, the sensor system includes additional transducers for measuring the concretes temperature. Figure 7 shows a schematic view and a picture of the new capillary pressure sensor. It is recommended to also measure the wind speed. This may be accomplished by using commercially available devices.

(a)



(b)

Figure 7 – Prototypes of an enhanced wireless capillary pressure sensor:
Schematic view of an applied sensor (a); Capillary pressure sensors on charging station (charging by electromagnetic induction) (b)

On the basis of the measured environmental data, it would be possible to estimate the evaporation rate. Knowing the bleeding rate of the concrete, the start of the capillary pressure build-up may then be predicted. In case a curing compound is used, its sealing coefficient has to be considered. The recording of the climatic conditions, of the evaporation rate as well as of the capillary pressure development as influenced by the curing will allow for a complete documentation of the concrete placing conditions and may help to correlate them to the long term durability of the concrete road.

6. CONCLUDING REMAKS

In planar concrete structures like concrete roads, the capillary pressure build-up within the first few hours after casting may lead to cracks in the plastic material. It is possible to measure the capillary pressure on site and to use it as an indicator for the cracking risk. On the basis of the measured capillary pressure, it is also possible to evaluate and document the efficiency of curing measures. For these evaluations, capillary pressure reference curves are required which may be determined under laboratory conditions.

The developed wireless capillary pressure sensors could be tested successfully under site conditions in concrete road construction.

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REFERENCES

Breitenbücher, R. (2006) “Potentielle Ursachen der Rissbildung in Betonfahrbahndecken“. In: Proceedings 16. Internationale Baustofftagung IBAUSIL, September 20-23, 2006, Weimar, Band 1, 1239–1254.

Dao, V.T.N., Dux, P.F., Morris, P.H., O’Moore, L. (2010) “Plastic shrinkage of concrete”. Australian Journal of Structural Engineering Online: 35-42.

Fredlund, D.G., Rahardjo, H. (1993) “Soil mechanics for unsaturated soils”. New York, Chichester, Brisbane, Toronto, Singapore: John Wiley and Sons Inc.

Hammer, T.A. (2006) “The use of pore water pressure to follow the evolution from fresh to hardened concrete”. In: Proceedings of the 2nd International Symposium on Advances in Concrete through Science and Engineering, 11-13 September 2006, Quebec City, Canada RILEM Publications SARL.

Jensen, O.M. (2006) “The Curing Meter”. In: Proceedings of Advanced testing of fresh cementitious materials, August 3-4, 2006, Stuttgart, Germany, 139-146.

Poole, T.S. (2005) “Guide for curing of Portland cement concrete pavements”. Research report No. FHWA-RD-02-099, USAE Research and Development Center (ERDC), Vicksburg, USA.

Radocea, A. (1992) “A Study on the Mechanism of Plastic Shrinkage of Cement-Based Materials”. PhD thesis, Chalmers University of Technology, Göteborg, Sweden.

Schmidt, M., Slowik, V. (2013a) “Capillary pressure-controlled concrete curing in pavement construction”. In: Proceedings of the 2013 Airfield and Highway Pavement Conference, June 9–12, 2013, Los Angeles, California, USA, American Society of Civil Engineers, 2013, 295-306.

Schmidt, M., Slowik, V. (2013b) “Instrumentation for optimizing concrete curing”. Concrete International 35(8), 60-64.

Scott, M.L., Lane, D.S., Weyers, R.E. (1997) “Preliminary investigation of the relationship between capillary pore pressure and early shrinkage cracking of concrete”. Research report, Virginia Transportation Research Council.

Slowik, V., Schmidt, M., Fritzsch, R. (2008a) “Capillary pressure in fresh cement-based materials and identification of the air entry value”. Cement & Concrete Composites 30(7): 557-565.

Slowik, V., Schmidt, M., Neumann, A., Dorow, J. (2008b) „Early age cracking and its influence on the durability of concrete structures”. In: Proceedings of the 8th International Conference on Creep, Shrinkage and Durability of Concrete and Concrete Structures - CONCREEP 8, September 30 - October 2, 2008, Ise-Shima, Japan, Taylor & Francis Group, London, Vol. 1, 471-477.

Slowik, V. Schmidt, M. (2010) “Kapillare Schwindrissbildung in Beton“. Bauwerk Verlag, Berlin.

Slowik, V., Ju, J.W. (2011) “Discrete modeling of plastic cement paste subjected to drying”. Cement and Concrete Composites 33(9): 925–935.

Wittmann, F.H. (1976) “On the action of capillary pressure in fresh concrete”. Cement and Concrete Research 6: 49-56.

TL Beton-StB 07 (2007) „Technische Lieferbedingungen für Baustoffe und Baustoffgemische für Tragschichten mit hydraulischen Bindemitteln und Fahrbahndecken aus Beton“. FGSV Verlag, Köln.