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EXPERIMENTAL STUDY ON THE BASIC PHENOMENA OF SHRINKAGE AND CRACKING OF FRESH MORTAR

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ABSTRACT

Evaporation, horizontal shrinkage, settlement, setting and capillary pressure of mortar mixes were measured during first hours with samples which were exposured to wind (velocity 4 m/s, T = 20°C and RH 40%) . The effects of different admixtures (super plasticizer, accelerating, retarding, air-entraining agent and one type of fibre) on the shrinking behaviour of the mortars were studied accordingly. The well-known fact that proper long-term wet curing is vital for the crack-free surfaces of concrete or mortar was confirmed experimentally. The beginning of setting can be regarded as a critical moment. After that the mortar has capacity to resist the capillary forces and thus shrinkage. The mix modified by super plasticizer behaved unexpectedly, and the surface of the sample cracked. This cracking was indicated by zig-zag behaviour in the measured horizontal shrinkage and capillary pressure. Air- entraining agent reduced horizontal shrinkage considerably. Use of fibre reduced shrinkage about 30% when compared to mix without fibre. Based on the results some conclusions are drawn concerning properly timed trowelling on horizontal shrinkage.

INTRODUCTION

Plastic shrinkage induced cracking has become an increasingly recognised problem in concrete technology. The densest, high strength concretes are the most sensitive to such cracking.

The aim of this work was to answer the following questions:

How does evaporation affect shrinkage in the plastic state?
How should concrete be cured?
How do retardation and acceleration affect shrinkage in the plastic state?
What are the roles of fibres and entrained air in plastic shrinkage?

THEORY

Powers (1968) has described water tranferred to the surface of fresh concrete e.g. "bleeding" in great detail. It is due to particle sedimentation and can be measured as settlement of concrete. The concrete surface dries when the amount of evaporating water exceeds that of "bleeding". Plastic horizontal shrinkage (lateral in Power's nomenclature) is caused by capillary forces due to water menisci on the drying surface.

Wittmann (1976) found that plastic shrinkage can be related to capillary pressure in fresh concrete. The pressure drop takes place during the first hours of the "concrete's life" depending on relative humidity, temperature, wind velocity, spaces between solid particles at concrete surface and permeability.

Radocea (1991, 1992 and 1994) developed a method for continuous measurement of evaporation and capillary pressure. He expressed theoretically the pressure drop and the volume change as functions of evaporation. In his experiments shrinkage was not measured in either the horizontal or vertical directions.

Our approach to early volume changes in concrete is illustrated in Figs. 1 and 2. The scope of the study was to analyse phenomena leading to both vertical and horizontal volume changes. The initial volume is that after placing, and the final volume is that after the capillary pressure drop. The final volume is the initial volume reduced by the volume change due to settlement and horizontal shrinkage. All vertical volume changes, e.g. particle sedimentation and volume change due to capillary pressure drop, were included in the settlement. Both were measured with the same displacement transducer and therefore could not be accurately separated. The volume fractions in the final state depend upon the magnitude of evaporation and contraction due to hydration. In the final state the fraction Δ comprises the air volume created by different mechanisms during measurement. Volume fractions in the final state, settlement, horizontal shrinkage, evaporation and contraction due to hydration were determined. A typical measured volume and capillary pressure behaviour of base mix in the plastic state is given in Fig. 2.

In practical concrete technology horizontal shrinkage takes usually place under restrained conditions and therefore shrinkage causes undesired plastic cracking. Whether the concrete shrinks horizontally and consequently cracks or whether it remains undamaged during the pressure drop depends on its capacity/strength to withstand forces at the time of the pressure drop. The later the pressure drop takes place the stronger is the concrete and the more probably the pressure drop causes air penetration into pores instead of horizontal shrinkage or cracking.

EXPERIMENTAL

The capillary pressure drop was systematically delayed with water curing (by adding fixed amounts of water onto the surfaces of the samples). The setting of fresh mortar was both accelerated and retarded to test the effect of setting time on plastic behaviour. The experimental programme is presented in Table 1.

The experiments comprised continuous measurement of evaporation, settlement, horizontal shrinkage, capillary pressure and setting. Capillary pressure, plastic shrinkage and settlement were measured from samples cast in an oiled ply-wood mould with polished steel bottom (270 by 270 by 100 mm). Evaporation

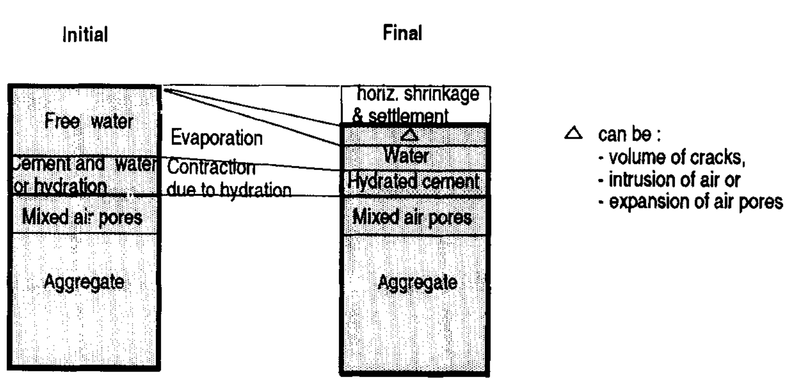

Fig. 1. Early state volume changes of concrete.

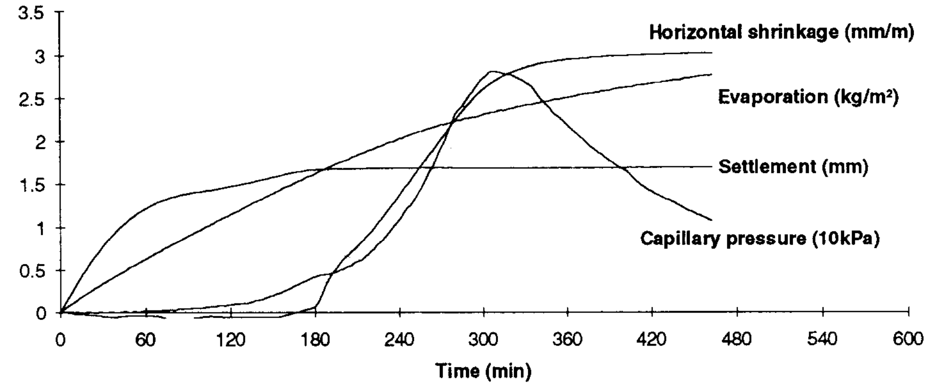

Fig. 2. Measured volume and capillary pressure drop behaviour in the plastic state. Evaporation and settlement begins immediately after placing. Settlement during the first 120 min is only due to particle sedimentation. During this time the surface is covered by a water film. After 120 min the volume of evaporation exceeds that of the settlement, indicating drying of the surface. At this time the capillary pressure drop develops due to water menisci inducing further settlement (e.g. vertical shrinkage) and horizontal shrinkage.

and setting were measured in separate moulds. Measurements were started 30 minutes after mixing and were carried out at 20 ± 2°C and RH 40 ± 5%. The surfaces of the test samples were exposed to wind of 4 m/s induced by a fan.

Evaporation was measured in terms of weight loss of a sample 100 mm high. The setting time was measured by an automatic penetration test (Penetrometro automatico recistratore, Luigi Giazzi, Milano) found suitable for our experimental set up. The setting time is indicated by rapidly increasing penetration resistance. To avoid the undesired effect of dry skin formation the penetration tests were carried out with water cured samples. A water film covered the surface throughout the penetration test. The thickness of the sample in the penetration test was 30 mm.

The test arrangement and experimental instrumentation are illustrated in Fig. 3. The methodology and instrumentation for the capillary pressure drop measurement is based on the work of Radocea (Radocea 1991 p. 48 - 62), and that for the volume change measurement on the work of Nykänen (1994).

With one exception all mixes tested were standard mortars used for quality control of cements of composition 1:3:0.5 (cement:sand:water). The plasticized mix D had a water-cement ratio of 0.4 instead of 0.5 to the others. The composition and properties of fresh mortar are given in Table 2. The basic properties of the cement were as follows: Fineness (Blaine) 447 m^2/kg, compressive strength 2 d 39.3 MPa, 28 d 57.8 MPa.

Table 1. Experimental program.

Amount of water added to the surface	Mix A Base mix	Mix B Accelerated	Mix C Retarded	Mix D Plasticied	Mix E Air-entrained	Mix F Fibres	Mix G Curing compound
0 kg/m^2	A0	B0	C0	D0	E0	F0	G0 and GN 1)
1 kg/m^2	A1	B1					
2 kg/m^2	A2	B2					
3 kg/m^2	A3		C3				
4 kg/m^2			C4				

1) Wind velocity 0 m/s in GN. In all other experiments 4 m/s.

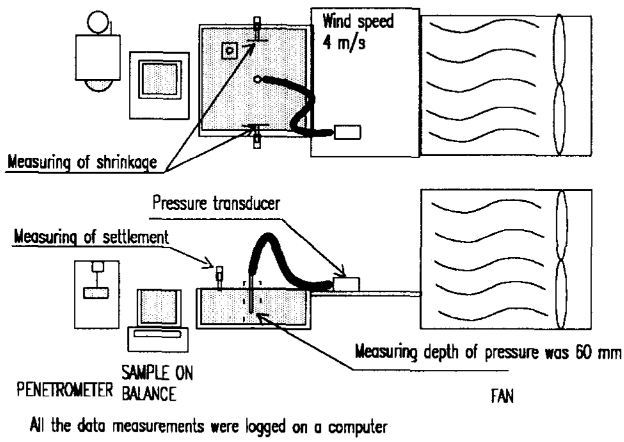

Fig. 3. Test arrangement.

Table 2. Composition and properties of the fresh mortar.

Property	Mix A and G Base mix	Mix B Accelerated	Mix C Retarded	Mix D Plasticized	Mix E Air-entrained	Mix F Fibres
Composition PC:Sand:Water	1:3:0.5	1:3:0.5	1:3:0.5	1:3:0.4	1:3:0.5	1:3:0.5
Admixture	-	accelerator 2.0% of PC	retarding plasticizer 0.5% of PC	super-plasticizer 2.0% of PC	airentraining agent 0.02% of PC	polypropylene fibre 1.0 vol. % of mix
Air porosity (vol. %)	3.5 - 5.8	6.4 -6.5	4.7 - 5.4	9.7 - 10.5	16	4.4 - 4.6
Workability / cm (flow table, DIN 18555)	16 - 18.5	17.5 - 19	20 - 20.5	17.5 - 19	18	11.5 -12
Start of setting (min)	270	180	375	330	360	270

Mix A was a base mix without admixtures. Mix G was the same as the base mix A except that a curing compound was sprayed on its surface after placing. All other mixes were modifications of base mix A. Mix B was accelerated with a sodium tiocyanate based agent at a dose of 2.0 weight-%. Mix C was modified with 0.5 weight-% lignosulphonate based retarding plasticizer. Mix D was plasticized with 2.0 weight-% naphthalene formaldehyde based super plasticizer. Air-entrained mix E contained 0.02 weight-% polyglycol ether sulphonate based agent. Mortar mix F contained 1.0 vol.-% (relative to the total mortar volume) polypropylene fibre (Krenit Fine Special 12, length 12 mm). Hydration contraction (autogenous shrinkage) of mixes A, B and D was measured as described by Radocea (1992). Density, air porosity and workability were measured to characterise the basic properties of fresh mortars. Workability tests were carried out with a Haegermann flow table (DIN18555).

RESULTS AND EXAMINATION OF RESULTS

Effect of water curing on horizontal shrinkage

The settlement period for specimens cured with water or with curing compound lasted only for about 1 hour and the amount of vertical settlement varied from 0.5 to 1.3 vol. %. As the surface was not allowed to dry, the settlement was due to particle sedimentation only. In tests without curing the mortar surface was allowed to dry. In these cases the capillary pressure action extended the settling period roughly by 2 hours and the settlement was roughly 40 - 100 % greater. The so called "skin" formation (dried cement paste layer on the surface) took place during this capillary pressure extended period. The maximum values of capillary pressure drop for all mixes varied widely from 5 to 30 kPa. It is important to note that a large pressure drop did not necessarily cause great shrinkage and that on the other hand even a small pressure drop may have led to considerable shrinking.

The greater the amount of water used in curing, the later both the pressure drop and shrinkage took place. The results for mix A are shown in Fig. 4. The later the pressure drop started, the more set was the mortar at the time of the pressure drop. Hydration reactions even at this very early age increased the mortar strength to withstand forces during the pressure drop. This early strength limits the shrinkage to lower values.

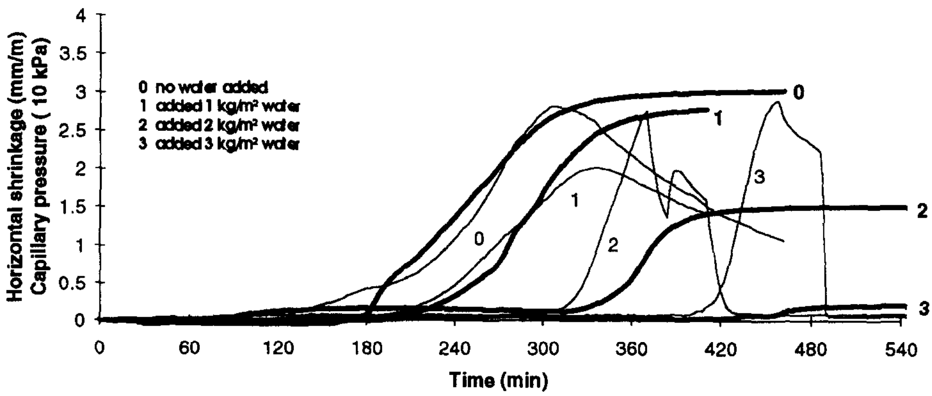

Fig. 4. Capillary pressure and horizontal shrinkage development of base mix A. Water curing (water added to the surface in kg/m²) delayed pressure development and had clear effect on final horizontal shrinkage (indicated with thicker lines), whereas the maximum capillary pressure was unaffected.

Acceleration (mix B) and retardation (mix C) shortened and extended respectively the period needed to gain enough capacity/strength to limit shrinkage (Fig 5). The strength at this early age was too low to be measured, so setting time determination was used to describe the beginning of strength development. The later the mortar set the more curing water was needed to limit shrinkage.

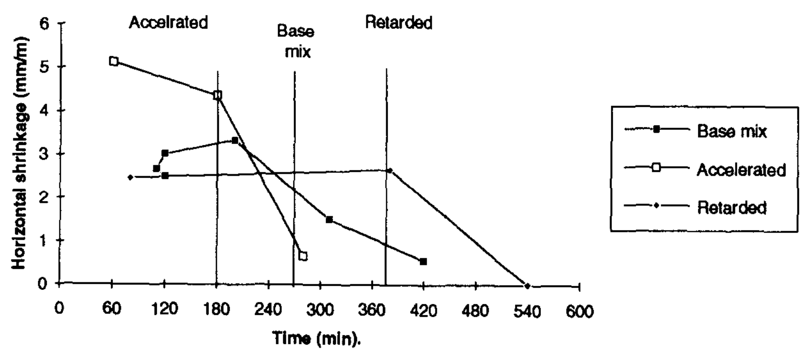

Fig. 5. Maximum values of horizontal shrinkage versus initial time of capillary pressure drop. When mortar was water cured to delay capillary pressure drop until strength development begins, practically no horizontal shrinkage occured. Measured setting of mixes is indicated with vertical lines.

Role of fibres, entrained air, curing compound and plasticizer in plastic shrinkage

In test samples with fibres, the capillary pressure vanished somewhat earlier than that of the base mix. Therefore shrinking also ceased earlier, remaining at a 30% lower level.

In the air-entrained sample the capillary pressure developed more slowly than that of the base mix. In fact the maximum pressure drop occurred after the mix had set. The total shrinkage value remained at a relatively low level, below 1 mm/m (Fig. 6).

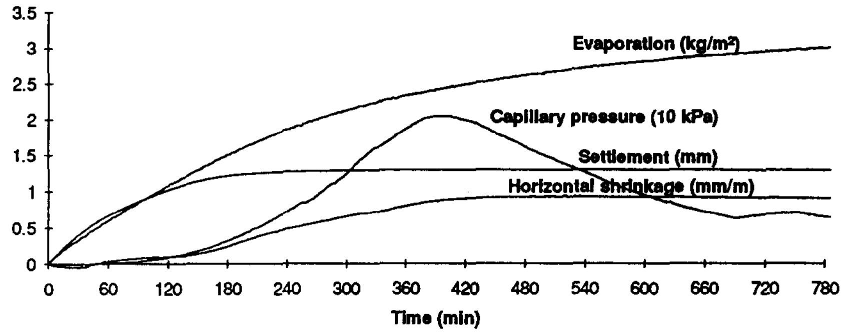

Fig. 6. Behaviour of air-entrained specimen. Capillary pressure developed slowly and the maximum was reached after setting of the mortar. This is probably the reason for the small final shrinkage.

The curing compound delayed evaporation considerably (Fig. 7). In wind (velocity 4 m/s) the curing agent evidently evaporated in 4.5 h, as indicated by the sharp acceleration of water evaporation at that age. In this case the curing compound did not delay the capillary pressure drop enough to prevent shrinking. Treatment with a curing compound should therefore be repeated in windy conditions. Without wind the curing compound delayed the pressure drop adequately to prevent shrinking.

Without a curing compound the evaporation rate during the first hour was nearly the same for different mortars (0.6 kg/m^2/h) (Fig. 7). After the first hour evaporation was clearly slowest for plasticized mix. These evaporation rates were measured from specimens without water curing.

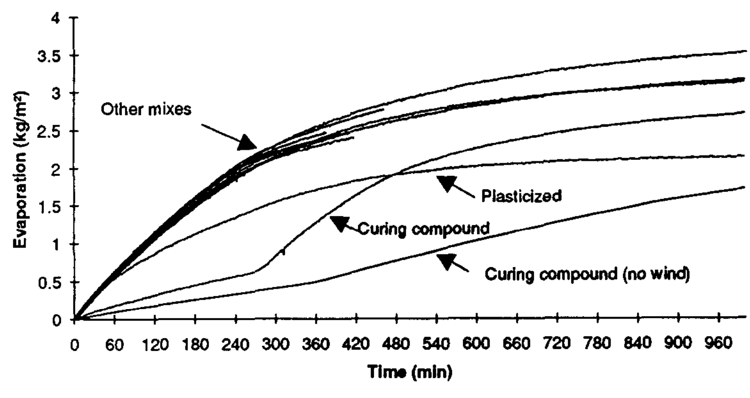

Fig. 7. Evaporation without water curing. At wind velocity of 4 m/s the rate of evaporation was initially about 0.6 kg/m^{2}h. In plasticized mixes the water-cement ratio was lower and the rate of evaporation was after 1 hour lower than with other mixes. A curing compound delayed evaporation from 5 to 6 hours.

The behaviour of the plasticized mix deviated strongly from that of the other mixes. Both the measured shrinkage and capillary pressure behaved almost randomly. The typical zig-zag behaviour of horizontal shrinkage is shown in Fig 8. This behaviour can be attributed to cracking of the specimen. After the test the surfaces of the hardened specimens were polished and the cracks inspected visually with a fluorescing agent. A very fine net-like cracking pattern was observed with a mesh size of roughly 3 cm. Under optical microscopy the crack width was found to be 5 - 10 µm and depth 2 - 5 mm.

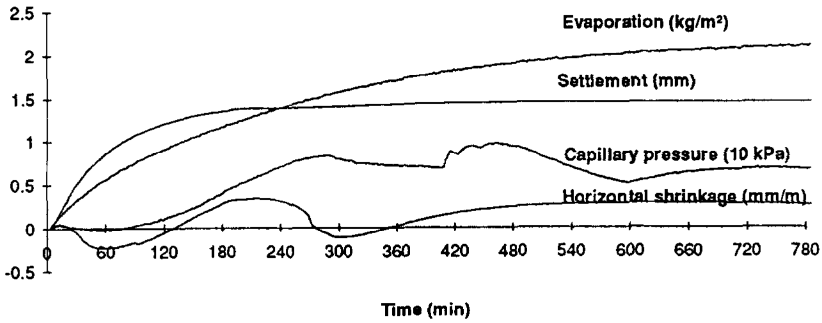

Fig. 8. The shrinkage behaviour of the plasticized mix was peculiar, showing a "zig zag" expansion indicating cracking. Capillary pressure did not develop continuously and no clear "breaktrough" behaviour was observed.

SUMMARY AND CONCLUSIONS

Based on the test results the following conclusions were drawn:

In our experiments, were ambient conditions were RH 40%, temperature 20° C and wind 4 m/s, the capillary pressure drop started in nonplasticized base mortar at the age of roughly 2 hours, inducing plastic horizontal shrinkage, which would cause cracking in practice.

A very low capillary pressure may induce significant shrinkage.

If the capillary pressure drop development is delayed enough, plastic horizontal shrinkage can be avoided almost entirely.

The delay needed in pressure drop to avoid horizontal shrinkage depends on the hardening rate of the mix. The later the hardening starts, the greater the needed delay.

Curing with water or curing with compound were found to be adequate ways to delay the pressure drop. The amount of water or agent needed depends on drying conditions and strength development. In our experiments the amount of curing water needed for the accelerated mix was 1 kg/m^2, for the base mix 2 - 3 kg/m^2 and for the retarded mix 3 kg/m^2.

Horizontal shrinkage of fibre and air-entrained mixes was smaller. This result offer some basis for speculation. The results indicate that air intrudes into the polypropylene fibre concrete with lower capillary pressure due to the hydrophobic nature of the fibres, thus shortening the shrinkage period. As to the air-entrained mix, air pores may expand due to the capillary pressure. However, the measurements of settlement and shrinkage were not accurate enough to demonstrate this quantitatively. The results show, that in all concretes the volume fraction Δ described in Fig. 1 increased continuously with time. This increase, being up to 10 ml/l, was far too large to be attributed to systematic error in measurement.

DISCUSSION

Though water curing or prohibiting evaporation by curing compound are known for years to be the critical steps for when avoiding plastic shrinkage and cracking, there is still some phenomena involved in cracking behaviour, which are not fully understood. In practice is vitally important to notice that with some concrete mixtures the curing shall be started immediately after placing and continue it for a sufficiently long period.

It is often believed that trowelling heals cracking. It is important to keep in mind that concrete is equally sensitive to cracking before and after trowelling if it has not set well enough before or during it. Therefore, to be sure to avoid cracking it is necessary to continue curing immediately after trowelling. "Skin" formation as a result of drying should not be confused with setting. "Skin" causes cracking, setting prevents it.

In our experiment the shrinkage measured was free shrinkage. In practice, shrinkage is more or less restrained and the strain capacity of mortar or concrete has a profound role in the cracking process. According to Manns (1993), horizontal shrinkage < 1 mm/m in normal concrete is not likely to cause plastic cracking. Thus without fibres free horizontal shrinkage > 1 mm/m could be regarded as equal to cracking in the restrained case. Fibres may increase the strain capacity of concrete, and therefore their ability to prevent plastic cracking may be better in practice than in our experiments.

While these experiments were being performed, close collaboration with The Concrete Floor Association of Finland provided us with some important practical aspect. The following issues related to our results came up in the discussions:

> The probability of evaporation cracking increases if concrete setting is delayed. The delay may be caused by slow binder type, retarding admixtures or low temperature. Strong "skin" formation is typical in such cases.
>
> On site workers often experience a feature called "suction". In concrete it is sensed with different tools and makes timing of trowelling difficult. This may be related to the capillary pressure drop. With plasticized water reduced mixes, suction starts almost immediately after placing.

ACKNOWLEDGEMENTS

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LITERATURE

Manns, W. 1993. Rissvermeidung bei der Betonherstellung. Ben 10/93, pp. 504 - 510.

Nykänen, E. 1994. Nuoren betonin ominaisuudet (Properties of young concrete) VTT Research notes 1580. VTT Offset paino. Espoo. Finland. 41 p. ISBN 951-38-4674-1. ISSN 1235-0605.

Powers, T. C. 1968. Properties of Fresh Concrete. John Wiley & Sons, Inc. 664 p.

Radocea, A. 1991. Pore water pressure in fresh and young cement paste: method of testing, preliminary models and parameter studies. Licentiate thesis. Chalmers University of Technology. Gothenburg. (Division of Building Materials, CTH - Publ. P-91:5). 139 p. ISSN 0280-7262.

Radocea, A. 1992. A study on the mechanism of plastic shrinkage of cement-based materials. Doctor Thesis. Chalmers University of Technology. Gothenburg. (Division of Building Materials, CTH - Publ. P-92:9). 125 p. ISSN 0280-7262, ISBN 91-7032-760-2.

Radocea, A. 1994. A model of plastic shrinkage. Magazine of Concrete Research, 1994, 46, No. 167, June.

Wittmann, F.H. 1976 On the action of capillary pressure in fresh concrete. Cement and concrete research, Vol. 6, No. 1, pp 49 - 56.