

Moisture Warping in Jointed Plain Concrete Pavements

Will Hansen¹, Ya Wei², and Erik Schlangen³

Abstract

It is generally believed that slab warping uplift in Jointed Plain Concrete Pavements (JPCP) is caused by drying shrinkage moisture gradients that develop within the top region of a slab cross section. Field experience has shown that excessive moisture warping uplift of joints can develop if a slab on grade is exposed simultaneously to drying at the top and moisture at the bottom surface. The results from this study show that internal self-desiccation causes a uniform reduction in humidity within a cross section for a sealed curing condition. This renders the cross section prone to moisture warping if either the top or bottom surface is exposed to water. Thus, drying at the top and wetting at the bottom create a moisture gradient that causes increased moisture warping uplift. This was verified from beam uplift tests.

Introduction

Jointed Plain Concrete Pavements will develop some degree of moisture warping uplift dependent on the stiffness of grade at the joints and especially the corners. This is generally attributed to the non-uniform moisture gradient and associated moisture deformation. Floor slabs exposed to in-door moisture conditions have been found to develop permanent joint corner uplift due to the moisture loss from drying (Ytterberg 1987, Suprenant 2002, Nasvik 2002). Observations and experiences tell us that when a floor slab or a highway pavement is exposed to water at the slab bottom while the top dries and shrinks, excessive warping deformation (5-6 mm at joint corner) can develop within months after construction (Hveem 1951, Leonards and Harr 1959). How can this phenomenon be explained? It is well-known from work by Powers and Brownyard (1946) that self-desiccation of pores in the hydrating cement paste develops due to the chemical reactions and that this property is especially pronounced for water-cement ratios below 0.40.

The major objective of this work is to determine: (1) The influence of exposure to wetting at the slab bottom on the joint uplift of a JPCP with a 4.57 m (15 ft) joint spacing,

¹ Professor, 2340 G. G. Brown, University of Michigan, Ann Arbor, MI 48109, whansen@umich.edu

² Graduate Student Research Assistant, University of Michigan

³ Associate professor, Delft University of Technology, The Netherlands

and (2) the cause for this uplift.

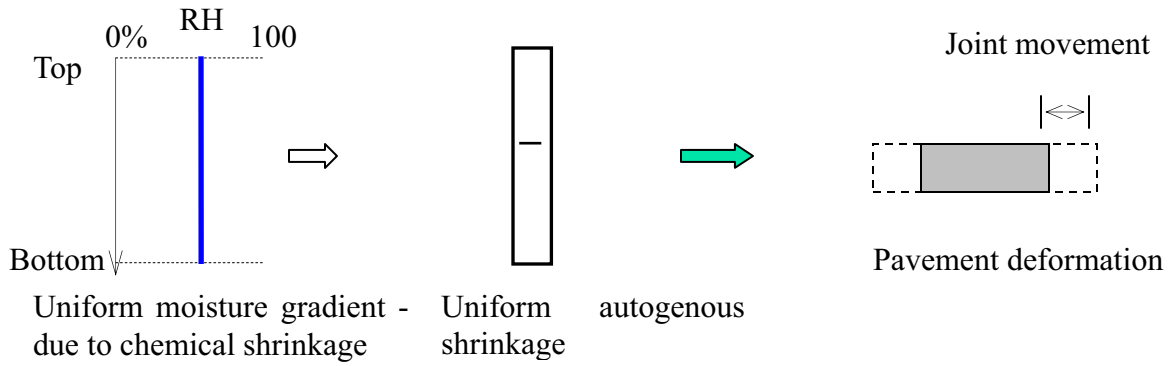
Research Significance

It is commonly believed that moisture warping uplift of joints is a drying shrinkage phenomenon. Work presented here shows that exposing the slab bottom surface to wetting is a key factor as well. This condition can develop if the sub-surface drainage system is ineffective, leading to a saturated base/subbase condition and water contact with the slab bottom.

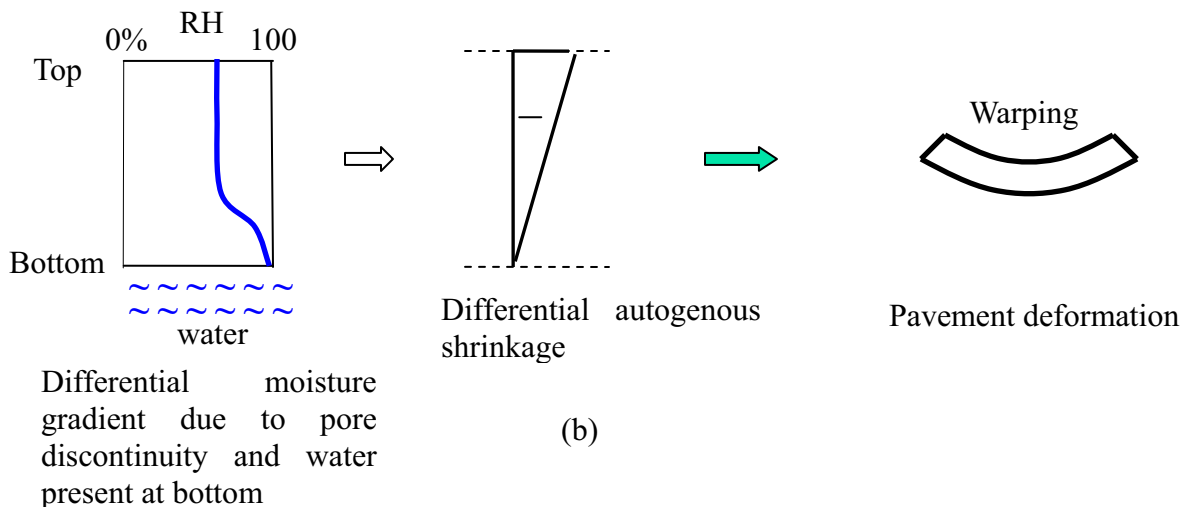
Moisture Transport

Moisture transport in concrete due to capillary suction and diffusion varies and depends on the moisture content, the thickness of the member and the duration of the exposure. The majority of moisture transport is limited to a surface region of less than about 80 mm (Beddoe and Springenschmid 1999). Consequently, concrete pavements and floors which are subject to drying shrinkage at the top and wetting at bottom develop significant upward warping (Springenschmid and Plannerer 2001).

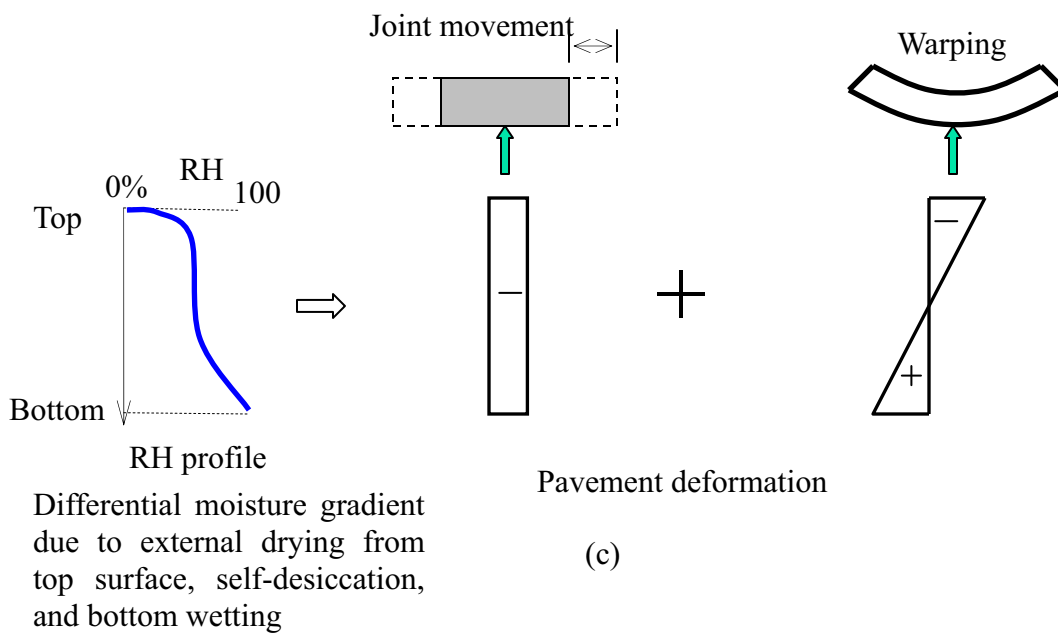
The added warping from continued exposure to moisture at the bottom surface is likely a result of differential autogenous moisture gradient. During the hydration of cement a volumetric reduction occurs in cement paste, which is proportional to the degree of cement hydration. This phenomenon is known as autogenous shrinkage. As long as the concrete surfaces are sealed during hydration, autogenous shrinkage is uniform and thus no warping develops. Capillary discontinuity is another fundamental factor associated with hydration (Powers et al. 1959). The curing time for reaching this condition is water-cement ratio dependent. Once capillary discontinuity has developed, any slab thicker than about 80 mm is subject to nonlinear moisture gradient if one of the free surfaces is exposed to moisture. This is what causes a differential autogenous shrinkage strain. Thus, warping can be the result of drying shrinkage and differential autogenous deformation. Figure 1 illustrates both phenomena.



(a)



(b)



(c)

Figure 1. Sketch of slab deformations under different moisture gradients

Experimental

Self-desiccation

The linear self-desiccation shrinkage also known as autogenous shrinkage was measured on sealed Portland cement paste specimens with a cross-section of 60 mm by 100 mm and length of 1000 mm (Schleibinger 1999). To control bleeding after placement, the 0.45 w/c ratio paste was allowed to hydrate for a few hours and then re-mixed and placed in the molds. Drying was prevented by sealing the specimens using a plastic wrap. External restraint was overcome by placing a soft, flexible, 2 mm-thick foam rubber between the mold and the sealed specimen. The curing temperature was maintained at 23 °C by circulating constant-temperature water through the channels built-into the sides and the bottom of the mold. One end of the specimen was fixed to the mold and the other end was free to move horizontally. The free end had an LVDT attached for measuring linear autogenous deformation. This measurement was initiated after final set. Two replicate specimens were tested.

Autogenous shrinkage increases substantially with decreasing w/c ratio as shown in Figure 2. The results show that a significant autogenous shrinkage can develop within a highway concrete with a w/c ratio in the 0.40 to 0.45 range during the first 28 days, if cured in a sealed moisture condition (i.e. no moisture exchange with the surroundings). This agrees with the findings by Baroghel-Bouny (1996) and Toma et al. (1999).

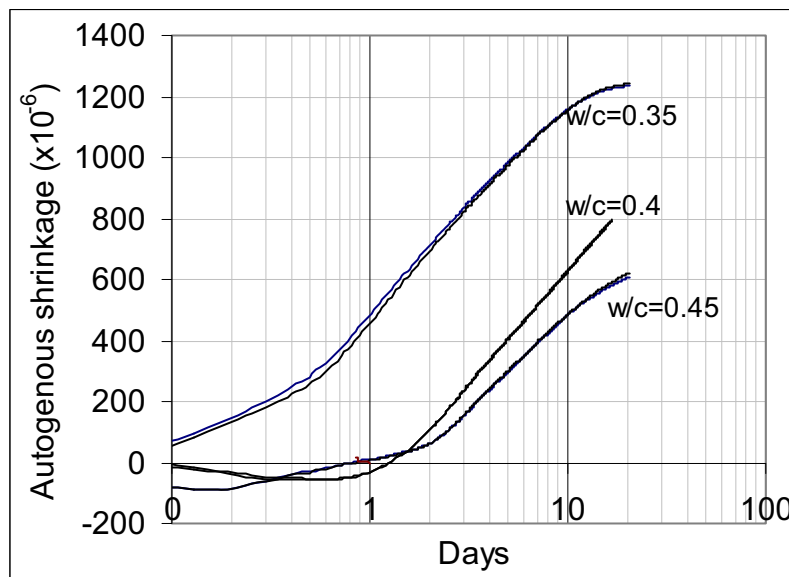


Figure 2. Measured self-desiccation shrinkage of Portland cement paste

Beam tests were undertaken in order to better understand the extent of moisture warping from drying shrinkage only, and warping from combined effects of drying

shrinkage at the top and wetting at the bottom surface. The beam uplift test set up is modified based on the work by Springenschmid and Plannerer (2001), which allows for exposing the beam to simultaneous drying from the top surface and water uptake at the bottom. In this case, beam length was 2.3 m which is half of the JPCP slab length. The beam cross section is 0.2 m in height and 0.15 m in width. One end of the beam is fixed. A dial-gauge was installed at the free end to record the magnitude of the moisture warping over time. The beam was seated on spacers to facilitate contact with water at the bottom surface. For drying shrinkage tests all surfaces except the top were sealed using a water-proof paint. The entire set up was placed in an environmental chamber with a relative humidity of 50 percent and constant temperature (23°C). The test was initiated after 7 days of sealed curing.

Beam warping development is shown in Figure 3. These results show that excessive moisture warping uplift develops at the free end due to the combined effects of drying shrinkage at the top and water exposure at the bottom. Within 30 days of exposure a moisture warping uplift of 2 mm has developed and is still increasing.

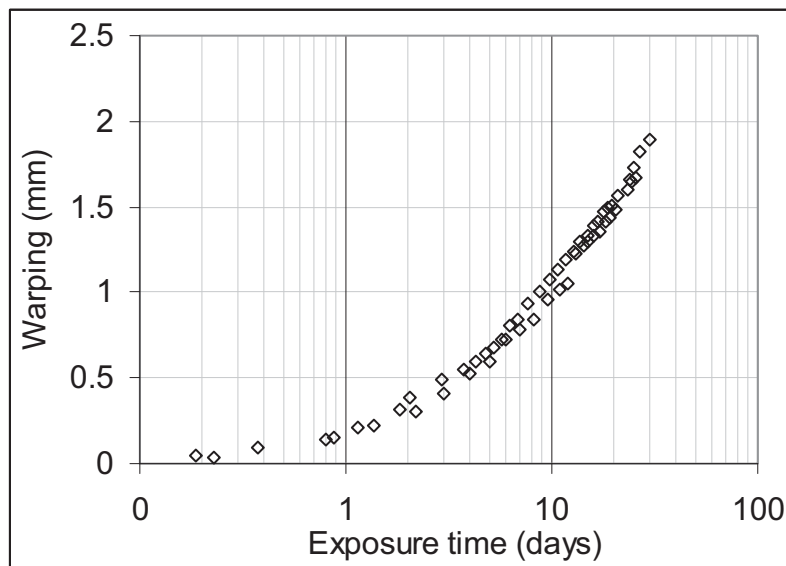


Figure 3. Beam warping uplift.

Finite Element Modeling of Moisture Warping

MLS Model

MLS (MLS 2003) is a 2-D finite element software capable of computing the physical and mechanical behavior of hardening concrete and taking varying environmental conditions into account. The physical and mechanical models that are used in this study include: moisture transport properties, concrete maturity, heat of hydration, and viscoelasticity.

A field JPCP slab (4.6m in length, 3.7m in width and 250mm in thickness) was modelled in MLS. As shown in Figure 4, the slab was resting on an unbound base which was modelled as a series of linear compression springs with a total stiffness of 0.054MPa/mm. Since MLS is a 2-D FE program, the predicted warping is corresponding to the uplift located at the center of the transverse joint.

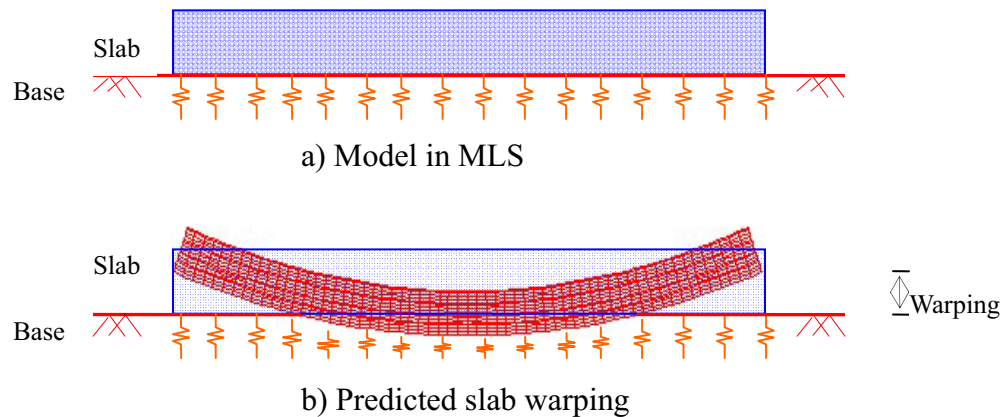


Figure 4. Slab model in MLS

Hygral Properties

Modeling of moisture transport in porous materials such as concrete is rather complex because water transport is highly nonlinear and dependent not only on the environments but also on the internal pore relative humidity. Bazant's model is used to obtain the transport coefficient for the changing pore humidity (Bazant and Najjar 1972). The diffusivity C_1 of $5 \times 10^{-6} m^2/h$ is used. Considering the environmental effects, the moisture transfer coefficients of the boundaries are chosen as $f_{top} = 5 \times 10^{-5} m/s$ and $f_{bottom} = 5 \times 10^{-3} m/s$ for the top and bottom surface, respectively.

The self-desiccation related pore humidity is determined from the evaporable water content which is coupled via the desorption curves. The desorption curves which are an input in the model are a function of degree of hydration and of temperature. While the hydration process develops the internal moisture content decreases, which results in a decrease in the moisture potential.

Results

MLS humidity profile predictions are shown in Figure 5 for different curing times. They are uniform and thus cause no warping in sealed curing conditions. Superimposed surface drying, results in a steep gradient. A much larger moisture gradient develops for simultaneous drying at the top (50% RH) and water uptake at the bottom as seen from

Figure 6. Without self-desiccation water transport from the bottom and up would be insignificant.

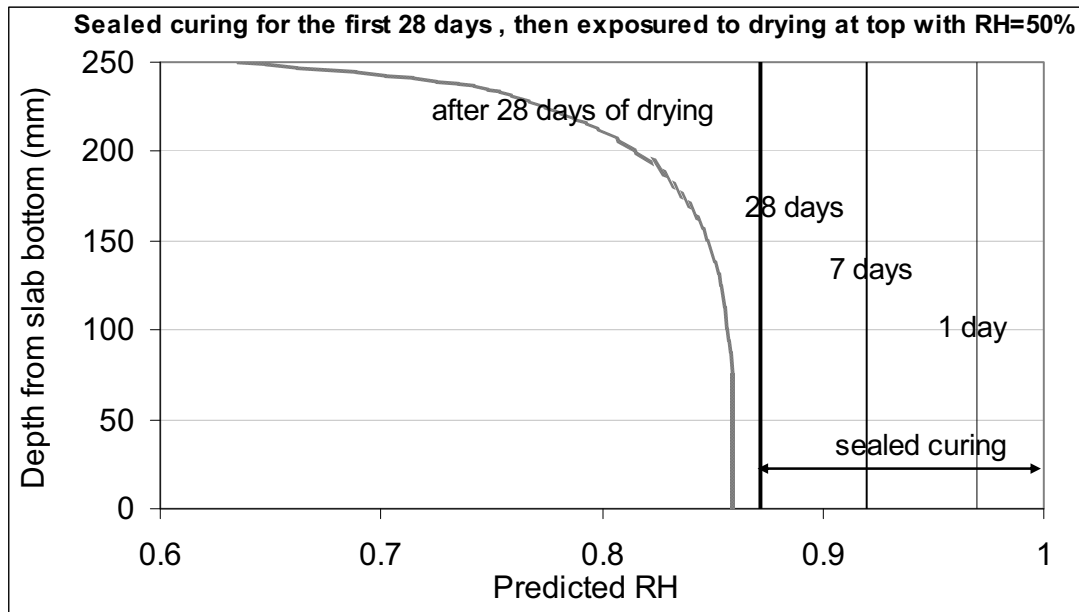


Figure 5. Predicted humidity profiles from 28-day sealed curing followed by drying at the top, $w/c=0.45$.

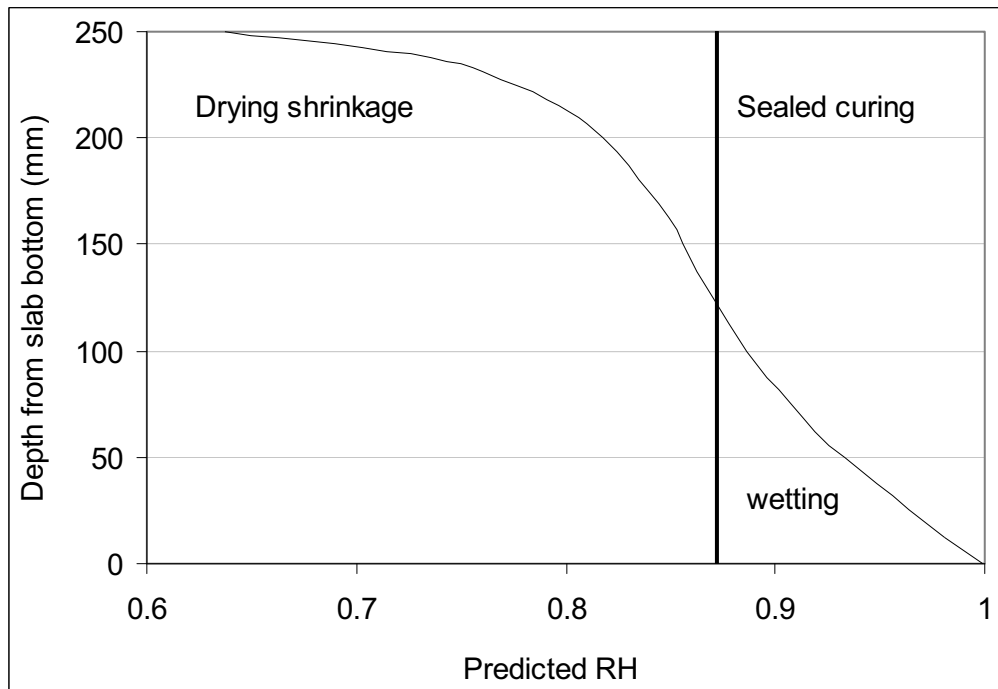


Figure 6. Predicted humidity profiles from 28-day sealed curing followed by combined drying at the top and exposure to water at the bottom for 28 days, $w/c=0.45$.

Conclusions

A permanent and excessive moisture warping uplift is predicted in concrete slabs on grade from combined drying at the top surface and wetting exposure at the bottom surface. This condition creates two moisture gradients that combine to increase slab joint corner uplift.

Acknowledgment

We acknowledge the support of the National Science Foundation under grant No. CMMI-0510854 and a grant from the Michigan Department of Transportation, No. 2006-0412, authorization No. 1. The contents of this work reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the views or policies of the National Science Foundation or the Michigan Department of Transportation or the Federal Highway Administration. This work does not constitute a standard, specification, or regulation.

References

- Baroghel-Bouny V., (1996), "Texture and moisture properties of ordinary and high-performance cementitious materials", Proceedings of Séminaire RILEM.
- Bazant, Z.P., Najjar, L.J., (1972), "Nonlinear water diffusion in nonsaturated concrete", *Mater. Struct.*, 5, 1-18.
- Beddoe, R., and Springenschmid, R., (1999), "Moisture transport through concrete structural components", (In German), *Beton-und Stahlbetonbau*, 94 (4), 158-166.
- Hveem, F.N., (1951), "Slab warping affects pavement joint performance," *Journal of the American Concrete Institute*, June, 797-809.
- Leonards, G.A., and Harr, M.E., (1959), "Analysis of concrete slabs on ground," *Journal of the Soil Mechanics and Foundation Division*, Proceedings of the American Society of Civil Engineers, June, 35-58.
- MLS, (2003), "Computer program for the analysis of the thermal and mechanical behavior of hardening concrete", User Manual.

Nasvik J., (2002) “Reducing curling of concrete floor and slabs”, *Concrete Construction*, September, 21-25.

Powers, T.C., and Brownyard, T.L., (1946), “Studies of the physical properties of hardened Portland cement paste”, *Journal of the American Concrete Institute*, Vol. 43.

Powers, T.C., Copeland, L. E., and Mann, H.M, (1959), “Capillary continuity or discontinuity in cement paste”, *PCA Bull.*, 10, 2–12.

Schleibinger, (1999), “Manual of autogenous shrinkage deformation measurements”.

Springenschmid, R., Plannerer, M, (2001), “Experimental research on the test methods for surface cracking of concrete”, *Institute for Building Materials*, Technical University Munich, Germany.

Suprenant, B. A., (2002), “Why slabs curl-Part II: Factors affecting the amount of curling”, *Concrete International*, American Concrete Institute, April.

Toma, G., Pigeon M., Marchand J., Bissonnette B. and Barcelo L., (1999), “Early age restrained shrinkage: stress build up and relaxation”, International research seminar: Self-desiccation and Its Importance in Concrete Technology, Lund, Sweden, June 18, 61-71.

Ytterberg, R. F., (1987) “Shrinkage and curling of slabs on grade Part III-Additional suggestions”, *Concrete International*, June, vol. 9, 72-81.