A state of art review on internal curing of concrete and its prospect for Bangladesh

Bushra Islam & Md. Shahinoor Rahman
BUET-Japan Institute of Disaster Prevention and Urban Safety, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

Munaz Ahmed Noor
Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

ABSTRACT: In the advancement of concrete technology internal curing is found to be beneficial in terms of enhancing concrete performance as well as economical and environmental friendly. In early periods numerous research works have been performed in this field of study. The current study presents a state of art review on the previous studies and some suggestions on applying this technology in the context of Bangladesh.

1 INTRODUCTION

The concept of curing and recognition of its contribution to obtain desirable properties of concrete is not novel. This technique has been adopted to maintain moisture and temperature conditions in a freshly placed cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop. In earlier stage though it has not received proper attention but nowadays it is found to be one of major concern in the study of concrete performance. However, the concept of internal curing has been developed and now been in practice to eliminate some problems occurred in case of traditional curing. According to the definition provided in America Concrete Institute (ACI) Terminology Guide internal curing is “supplying water throughout a freshly placed cementitious mixture using reservoirs, via pre-wetted lightweight aggregates, that readily release water as needed for hydration or to replace moisture lost through evaporation or self-desiccation (American Concrete Institute, 2010).” From this definition two major objectives of internal curing can be identified as maximizing hydration and minimizing self-desiccation along with its accompanying stresses which may cause early-age cracking. The principal contribution of internal curing results in the reduction of permeability that develops from a significant extension in the time of curing. Internal curing reduces plastic shrinkage cracking and settlement. Also a life-cycle cost reduction was estimated when internally cured high performance concrete (HPC) is used instead of normal concrete. So far different materials have been used for internal curing such as Super Absorbent Polymers (SAP), crushed return concrete aggregates, pre-wetted light weight aggregates (LWA) expanded shale, clays, and slates, recycled waste porous ceramic course aggregate, wooden fiber. In the current study the focus is to have a review on the studies performed on internal curing and study its prospect in Bangladesh perspective.

2 LITERATURE REVIEW

At the beginning, internal curing was made unintentionally in the form of application of lightweight aggregate in producing lightweight concrete. Examples of this type of works can be found in ancient roman structures. However, first recognition of its potential and purpose was made after a number of years (Klieger, 1957, Philleo, 1991). The concept of internal curing is illustrated schematically in figure 1. It is shown that in external curing water is only able to penetrate several mm into low water to cement ratio concrete, whereas internal curing enables the water to be distributed more uniformly across the cross section. Based on this formal development of concept, later studies were made to investigate effect of internal curing through the use of light weight aggregate (Weber and Reinhardt, 1995, van Breugel and de Vries, 1998, Bentur et al., 1999). After those years, other potential materials that could perform as internal water reservoirs, such as superabsorbent polymers (SAP) (Jensen and Hansen, 2001, Jensen and Hansen, 2002) and pre-wetted wood fibers (Mohr et al., 2005) were also investigated. Since now a number of studies have been conducted in the field of internal curing to have a better understanding on its theory, establishing guidance to implement internal curing in practice, material behavior and influence on performance of concrete, present application and future exploration of the concept. Though the process of entering from research area to practical application was not fast but effective introduction of internal curing into concrete technology was made successfully in recent years.

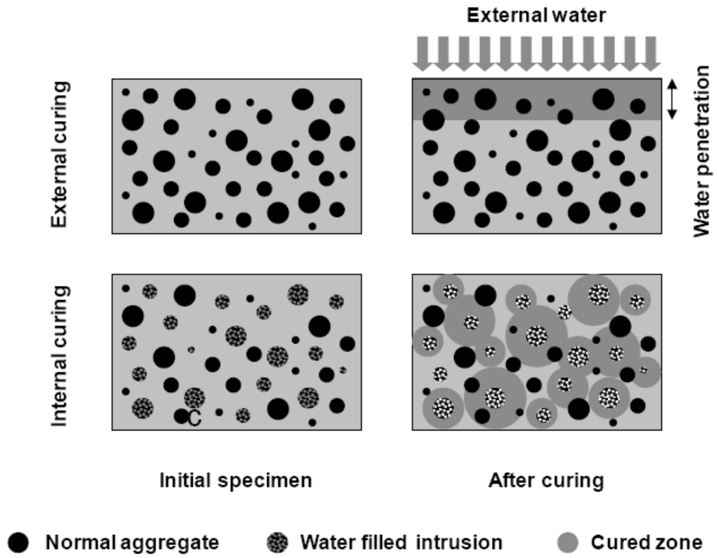

Figure 1. Illustration of the difference between external and internal curing (Castro et al., 2010)

2.1 *Theory*

In cement water reaction, crystalline and gel hydration products form in which incorporated water usually occupies less space than in its bulk form. Hence hydration and pozzolanic reactions are followed by a net chemical shrinkage and before setting is occurred, this chemical shrinkage will result into an equivalent physical shrinkage of the three-dimensional microstructure (Barcelo et al., 1999, Sant et al., 2009). However, after setting is taken place and a finite resistance to deformation is developed, partially filled pores will be created within the microstructure due to this chemical shrinkage. Consequently in the absence of an additional source of water it will produce a self-desiccation (Lura et al., 2009).

The relation between capillary pressure created by pore solution menisci remaining in partially filled pores and surface tension is shown in equation (1) (Alberty and Daniels, 1980).

$$\sigma = (-2\gamma\cos\theta)/r \quad (1)$$

Where, σ = capillary pressure or stress, γ = surface tension of the pore solution, θ = contact angle, r = pore radius. It is observed from the relation that capillary stresses can be reduced either by reducing the surface tension of the pore solution with a shrinkage-reducing admixture (Shah et al.,1998) (Bentz et al., 2001), or by increasing the size of the pores being emptied by providing sacrificial reservoirs of water in larger scale pores within the microstructure, for example with internal curing.

At the same time shrinkage of the microstructure will be produced by this capillary pressure which can be measured by equation (2) (Mackenzie, 1950, Bentz et al., 1998).

$$\varepsilon=(\sigma S/3)[(1/K)-(1/K_s)] \quad (2)$$

Where, ε = measured linear strain, K = bulk modulus of the porous material, Ks = modulus of its solid backbone, S = level of saturation in the pore space (0 to 1). If these autogenous stresses and strains become considerable enough, early-age cracking may occur that will hinder the anticipated design and service life of a concrete structure.

So internal curing can be applied to reduce autogeneous stress and strains which provides a source of readily available additional water and thus keep the hydrating cement paste saturated. This additional water will also aid the process of hydration of the cement and pozzolans in the mixture.

2.2 *Studies on evaluating influence of internal curing on concrete performance*

An experimental study was made on prevention of autogenous deformation of cement pastes and concrete with low water/binder ratios, by internal curing using super-absorbent polymer particles (Igarashi and Watanabe, 2006). Significant amount of reduction in autogeneous shrinkage was achieved though complete reduction was not always possible. The degree of hydration at long ages was slightly increased by introducing SAP while at early age was not increased. It was observed that in case of dense microstructure volume protected by the internal water was reduced. Again integration of SAP adversely reduced the strength of the cement pastes and the concretes. So optimum selection of size and amount of SAP are required for more efficient prevention of autogenous shrinkage is hence important. Another study was performed to observe the effects of internal curing done by super absorbent polymers (SAP) on material properties of self-compacting fibre-reinforced high performance concrete (Mechtcherine et al., 2006). The investigation was made for construction of a thin-walled structure without conventional steel reinforcement. The results of the investigation display that rheological properties of fresh concrete does not change negatively upon adding SAP if extra water is added for the purpose of internal curing. Autogenous shrinkage after setting was strongly reduced by the internal curing, while drying shrinkage increased. A slight decrease in the compressive strength, tensile strength and flexural strength was observed for the investigated HPC due to the addition of SAP and extra water. A study on mitigating autogenous shrinkage in HPC by internal curing using superabsorbent polymers was performed (Pierard et al., 2006). Drying shrinkage and autogenous shrinkage tests were performed from the first hours after casting. The effects of different amounts of SAP on the properties of concrete are presented and discussed. Finally, the effectiveness of this internal curing method to mitigate autogenous shrinkage in HPC is compared to that of more conventional methods using other chemical admixtures, such as an expansive agent and a shrinkage reducing admixture. A study on internal curing of High Performance Blended Cement Mortars in terms of autogenous deformation and compressive strength development was performed (Bentz, 2007). Measured mortar cube compressive strengths for various mixtures cured under sealed conditions for silica fume and fly ash are presented in the paper. The influence of SAP on compressive strength is also dependent on mixture proportions. Hasholt et al. have measured compressive strengths of concretes with different *w/c* and different levels of SAP addition (Hasholt et al., 2010). An extension of this study (Hasholt et al., 2010), considered the elastic moduli of these same mixtures. To better understand the influence of curing conditions on compressive strength, Golias examined four mortar mixtures with *w/c* of 0.3 or 0.5 (Golias, 2010). A reduced elastic modulus can also be related to the reduction in cracking potential (Weiss et al., 1999, Shah and Weiss, 2000, Shin et al., 2011, Raoufi et al., 2011). Reducing the elastic modulus has a beneficial influence on reducing the residual stress due to restraint as a function of time. Raoufi et al. conducted a series of simulations to better understand the influence of reduced stiffness on early age cracking potential (Raoufi et al., 2011).

For new generation high performance and ultra high performance concretes, early age autogenous deformations and self-desiccation are identified as major problems. To overcome the problems, dispersed saturated lightweight aggregates (LWAs) were also studies to use as water reservoirs. The influence of light weight aggregates on internal curing and fracture of concrete was studied (Ackay and Tasdemir, 2006) and experiments have been conducted to determine the effects of volume fractions and the size of saturated LWAs on fracture and mechanical properties of concrete. For this purpose, in concretes prepared with a constant low water to cement ratio, normal aggregates have been replaced by natural LWAs with two different size fractions at three different volume fractions of the total aggregate volume of concrete and the effects of volume fraction and average particle size of LWAs on the load-displacement at mid-span curve are investigated by measuring the fracture energy, the characteristic length, and final displacement. In addition, the nearest surface distribution of LWAs is investigated using the image analysis, and its effects on the autogenous deformation and the fracture properties are determined. The results imply that the inclusion of fine fraction of LWAs in concrete reduces the autogenous deformation significantly compared to that of the coarse fraction. It is also shown that the fracture energy, final displacement at the mid-span curve of the beam, splitting tensile strength and compressive strength of concrete with fine fraction are higher than those of the concrete with coarse fraction. Within the limits of this work, it is demonstrated that the distance between LWAs is more effective than the mean particle size of LWAs on both the autogenous deformation and fracture properties of concretes. Increasing the replacement ratio of LWAs mitigates autogenous deformation, while having an unfavourable effect on fracture and mechanical properties of concrete for both fine and coarse fraction replacements. A study on efficiency of internal curing with water-saturated lightweight aggregates in terms of autogenous shrinkage reduction was conducted (Kovler and Bentur, 2006). Also effects of internal curing on compressive strength were discussed.

Recently, studies have been conducted to compare the plastic shrinkage and cracking tendencies of concretes with and without internal curing (Henkensiefken et al., 2010). In addition, tests were performed to measure the settlement and evaporative weight loss of concrete slabs (Henkensiefken et al., 2010). Also tests were performed to measure the settlement and evaporative weight loss of concrete slabs (Henkensiefken et al., 2010). Probability distribution of crack width occurrences in concrete with different replacement volumes of pre-wetted LWA was investigated (Henkensiefken et al., 2010). A conceptual illustration of the role of water-filled lightweight aggregate at the surface of a concrete exposed to drying immediately after placement was presented in a study (Henkensiefken et al., 2010). A study based on *w/c*=0.30 ordinary portland cement mortars with a constant volume fraction of sand (normal weight and LWA) of 55 %, both with and without internal curing is considered (Raoufi et al., 2011). In this case, internal curing was done by various replacement levels of two different LWAs (LWAK and LWAH). Few studies concerning creep of systems with internal curing have been conducted. Lopez et al. have examined the creep behavior of *w/cm*=0.23 high performance concretes with and without internal curing, contrasting the performance of using pre-wetted vs. dry LWA (with additional water added to the mix to account for the expected absorption by the dry LWA) (Lopez et al., 2008). By maintaining a higher and more uniform RH through the thickness of a concrete member, internal curing may provide the additional benefit of a reduction in curling/warping. Wei and Hansen have observed that during a drying time of 16 d, warping was reduced by 70 % by incorporating internal curing into a *w/c*=0.45 concrete (Wei and Hansen, 2008). Neithalath et al. examined the role of moisture gradients on early-age cracking potential (Neithalath et al., 2005). Influence of internal curing on restrained shrinkage and cracking for mixtures containing a Class C fly ash was studied (Varga et al.). Further influence of internal curing on the residual stress development and reserve stress capacity was also studied. (Schlitter et al., 2011). The temperature change permitted before cracking occurs in mortars with *w/c*=0.3, illustrating a benefit of internal curing was presented in a study (Schlitter et al., 2011). A study was performed on absorption and desorption properties of fine lightweight aggregate for application to internally cured concrete mixtures (Castro et al., 2011). Mixture proportion development for mixtures containing materials used for internal curing requires the specific gravity, water absorption, and water desorption characteristics of the aggregate. This research measured the time-dependent water absorption response for the lightweight aggregate. Different studies on developing methods of internal curing were performed. Replacement of normal weight aggregates (NWAs) by LWAs on a volume basis was studied (Bentz et al., 2005). An estimate for the expected water travel distance can be obtained by equating the projected water flow rate to the value needed to maintain saturation in the surrounding cement paste at its current rate of hydration. A web-based form for performing this estimate, based on extending the analysis first developed by Weber and Reinhardt (Weber and Reinhardt, 1999), is available at the NIST internal curing web site.

A several research works also have been taken place in order to achieve a detail idea on water action or local water distribution during internal curing process. The use of magnetic resonance imaging to analyze internal moist curing in high-performance structural lightweight concrete containing saturated lightweight aggregate was studied (Barrita et al., 2004). The microstructure of high performance blended cement mortars with and without internal curing has been examined using scanning electron microscopy by Bentz and Stutzman (Bentz and Stutzman, 2008). Another investigation on the release of internal curing water from lightweight aggregates in cement paste by neutron and X-ray tomography was performed (Trtik et al., 2011). The results imply that the water for internal curing releases relatively fast and is distributed fairly consistently from the LWA for at least 3 mm within the hydrating cement paste.

2.3 *Practical application*

In recent years internal curing has been applied in a variety of concrete mixtures for diverse applications. This technique has successfully been employed in construction of different structures including bridge decks, pavements, transit yards, and water tanks. In figure 2 and figure 3 two practical cases of using internal curing in practice are shown.

Figure 2. Internally cured concrete being cast at Bartell Road in New York (Wolfe, 2010)

Figure 3. Internally cured concrete bridge deck being cast near Bloomington, IN (Di Bella, Schlitter, & Weiss, 2010)

To present a few effective applications of internal curing, large railway transit yard constructed in Texas, bridges in New York, Ohio, and Indiana and two bridges cast in close proximity in Monroe Co., IN, just outside of Bloomington, in September of 2010 can be mentioned. Moreover the observations made during and after the constructions show an elimination of plastic and drying shrinkage cracking, a reduction in concrete unit weight that may result into reductions in fuel requirements and equipment wear and an increase in concrete strength in few cases. Also form the crack surveys made during the instant no or hardly a very few crack has been noticed.

3. PROSPECT FOR BANGLADESH

The benefits of internal curing are increasingly important in technical point of view when supplementary cementitious materials, (silica fume, fly ash, metokaolin, calcined shales, clays and slates, as well as the fines of lightweight aggregate) are included in the mixture. It is well known that the pozzolanic reaction of finely divided alumina-silicates with calcium hydroxide liberated as cement hydrates is dependent upon the availability of moisture. Additionally, internal curing provided by absorbed water minimizes the plastic shrinkage due to rapid drying of concretes exposed to unfavorable drying conditions.

In Bangladesh perspective internal curing has a wide prospect. Due to the unavailability of modern equipments and unskilled labor, curing process cannot be achieved properly in this country. Now a day the level of ground water table is going down rapidly. If water is to be purchased and carried for construction works, the cost of construction goes much higher. The concreting works done relatively at great heights and in sloped roofs, curing is very difficult. Where thickness of concreting is larger, the percolation of water in the concrete, especially in case of high strength concrete is difficult. Therefore, internal curing can be a desirable solution for removing all these constrains.

The use of lightweight aggregate provides strategies to enhance cement hydration, improve the energy performance of structures, reduce life-cycle costs and reduce costs of material transport and construction. Also lightweight concrete is more fire resistant than ordinary normal weight concrete because of its lower thermal conductivity, lower coefficient of thermal expansion. The use of LWA lowers the thermal conductivity of concrete and provides significantly better insulating qualities for thermally sensitive applications such as cryogenic applications or high temperature petroleum storage structures. Reducing the concrete density increases its thermal resistance.

Traditional curing needs lot of water in dry weather which needs power to pump this amount of water. Bangladesh is facing high power shortage; in addition with that some areas of Bangladesh are facing the problem of water shortage as well. In this point of view again internal curing is advantageous than traditional curing. Another important issue is that the availability of the light weight aggregates in Bangladesh. There is no proper waste material (broken ceramic and wooden fiber) collection system in Bangladesh. This waste may be used as the light weight aggregate as water absorbing agent in internal curing. In this way waste material will get added economic value which will lead the proper collection system of these waste materials and use of these cheap aggregate will reduce the construction cost.

Construction requires transportation. And there is a direct correlation between transportation, weight and environmental impact. Transportation requirements are directly related to weight and demonstrate an economic and environmental advantage when using lightweight aggregate in precast, ready-mix concrete and masonry. Transportation cost savings were seven times greater than the additional cost of lightweight aggregate used to reduce the concrete density (Ries et al., 2010) Fewer trucks in congested cities are not only an environmental necessity but will also generate fewer public complaints.

Considering environmental impact, existing curing practice in Bangladesh, aim of developing high strength or high performance concrete using local aggregate and eliminating significant shrinkage, application of internal curing can be an effective choice in concrete practice. Before applying into practice it is desirable to test concrete strength, shrinkage and durability parameters in case of internal curing.

4. CONCLUDING REMARKS

Internal curing has been discussed as an added advantage in concrete research. It has wider prospect in Bangladesh and it is possible to get benefit from the internal curing instead of traditional external curing. Light weight aggregate are normally used in concrete for the internal curing which are available, cheap and easy to transport in this country. It has a significant contribution in shrinkage reduction, enhancing durability, sustainability and hence improving overall concrete performance. It can aid the construction process economically resulting into effective resource utilization. Also considering environmental impact analysis this technique is found as a desirable one. Additionally introduction of internal curing can open doors for recycling and use of other potential materials. In this regards, internal curing is expected to be beneficial in many fold. So a broad analytical and experimental study can be conducted to explore the prospect of internal curing in Bangladesh.

REFERENCES

Ackay, B., and Tasdemir, M.A. 2010 Effects of Distribution of Lightweight Aggregates on Internal Curing of Concrete, *Cement and Concrete Composites*, 32 (10), 611-616.

Alberty, R., & Daniels, F. (1980). *Physical Chemistry.* New York: John Wiley & Sons.

Barcelo, L., Boivin, S., Rigaud, S., Acker, P., Clavaud, B., & Boulay, C.1999. Linear vs. Volumetric Autogenous Shrinkage Measurement: Material Behaviour or Experimental Artefact? In B. Persson, & G. Fagerlund (Ed.), *Self-Desiccation and Its Importance in Concrete Technology* (pp. 109-125). Lund: Lund University.

Bentur, A., Igarishi, S., and Kovler, K. 1999. Control of Autogenous Shrinkage Stresses and Cracking in High Strength Concretes, Proc. 5th International Symposium of High Strength/High Performance Concrete, Sandefjord, Norway, June 20-24, , 1017-1026.

Bentz, D., & Stutzman, P. 2008. Internal Curing and Microstructure of High Performance Mortars. In D. Bentz, & B. Mohr (Ed.), *ACI SP-256, Internal Curing of High Performance Concretes: Laboratory and Field Experiences* (pp. 81-90). Farmington Hills: American Concrete Institute.

Bentz, D., Garboczi, E., & Quenard, D. 1998. Modelling Drying Shrinkage in Reconstructed Porous Materials: Application to Porous Vycor Glass. *Modelling and Simulation in Materials Science and Engineering , 6*, 211-236.

Bentz, D.P., Geiker, M.R., and Hansen, K.K. 2001. Shrinkage-reducing Admixtures and Early-age Desiccation in Cement Pastes and Mortars, *Cement and Concrete Research*, 31 (7), 1075-1085.

Bentz, D. 2007. Internal Curing of High Performance Blended Cement Mortars. *ACI Materials Journal , 104* (4), 408-414.

Bentz, D., Lura, P., & Roberts, J. 2005. Mixture Proportioning for Internal Curing. *Concrete International , 27* (2), 35-40.

Breugel, K., & de Vries, H. 1998. Mixture Optimization of Low Water/Cement Ratio, High-Strength Concrete in View of Reduction of Autogenous Shrinkage. In P. Aitcin, & Y. Delagrave (Ed.), *Proceedings of the International Symposium on High-Performance and Reactive Powder Concretes*, (pp. 365-382). Sherbrooke.

Castro, J., De la Varga, I., Golias, M., & Weiss, W. 2010. Extending Internal Curing Concepts to Mixtures Containing High Volumes of Fly Ash. *International Bridge Conference.*

Castro, J., Keiser, L., Golias, M., & Weiss, W. 2011. Absorption and Desorption of Fine Lightweight Aggregate for Applications to Internally Cured Concrete Mixtures. *Cement and Concrete Composites.*

Di Bella, C., Schlitter, J., & Weiss, W. 2010. Construction Documentation of Bloomington Bridges.

de la Varga, I., Castro, J., Bentz, D., & Weiss, J. (submitted). Internal Curing Concepts in Mixtures Containing High Volumes of Fly Ash. *Cement and Concrete Composites*.

de Jesus Cano Barrita, F., Bremner, T.W., and Balcom, B.J.2004. Use of Magnetic Resonance Imaging to Study Internal Moist Curing in Concrete Containing Saturated Lightweight Aggregate, ACI SP-218, High-Performance Structural Lightweight Concrete, Eds. J.P. Ries and T.A. Holm, 155-175,

Golias, M. 2010. *The Use of Soy Methyl Ester-Polystyrene Sealants and Internal Curing to Enhance Concrete Durability, M.S. Thesis.* West Lafayette: Purdue University.

Hasholt, M., Seneka Jespersen, M., & Jensen, O. 2010. Mechanical Properties of Concrete with SAP Part I: Development of Compressive Strength. In O. Jensen, M. Hasholt, & S. Laustsen (Ed.), *International RILEM Conference on Use of Superabsorbent Polymers and Other New Additives in Concrete* (p. 10 pp.). Bagneaux: RILEM Publications S.A.R.L.

Hasholt, M., Seneka Jespersen, M., & Jensen, O. 2010a. Mechanical Properties of Concrete with SAP Part II: Modulus of Elasticity. In O. Jensen, M. Hasholt, & S. Laustsen (Ed.). (p. 10 pp.). Bagneaux: RILEM Putlications S.A.R.L.

Henkensiefken, R., Briatka, P., Bentz, D., Nantung, T., and Weiss, J.2010. Plastic Shrinkage Cracking in Internally Cured Mixtures Made with Pre-wetted Lightweight Aggregate, *Concrete International*, 32 (2), 49-54.

Igarashi, S., and Watanabe, A. 2006. Experimental Study on Prevention of Autogenous Deformation by Internal Curing using Super-absorbent Polymer Particles, Proceedings of the International RILEM Conference - Volume Changes of Hardening Concrete: Testing and Mitigation, Eds. O.M. Jensen, P. Lura, and K. Kovler, RILEM Publications S.A.R.L., 77-86.

Jensen, O.M., and Hansen, P.F. 2001. Water-Entrained Cement-Based Materials: I. Principle and Theoretical Background, *Cement and Concrete Research*, 31 (4), 647-654.

Jensen, O.M., and Hansen, P.F., Water-Entrained Cement-Based Materials: II. Experimental Observations, *Cement and Concrete Research*, 32 (6), 973-978, 2002.

Klieger, P. 1957. Early High Strength Concrete for Prestressing, Proceedings World Conference on Prestressed Concrete, San Francisco, CA, A5-1 to A5-14.

Kovler, K., and Bentur, A., 2006. Efficiency of Internal Curing with Water-saturated Lightweight Aggregates in Terms of Autogenous Shrinkage Reduction, Proceedings of the International RILEM Conference - Volume Changes of Hardening Concrete: Testing and Mitigation, Eds. O.M. Jensen, P. Lura, and K. Kovler, RILEM Publications S.A.R.L., 107-115.

Lura, P., Couch, J., Jensen, O., & Weiss, W. 2009. Early-Age Acoustic Emission Measurements in Hydrating Cement Paste: Evidence for Cavitation during Solidification Due to Self Desiccation. *Cement and Concrete Research* , accepted for publication.

Mackenzie, J. 1950. The Elastic Constants of a Solid Containing Spherical Holes. *Proceedings of the Physics Society , 683*, 2-11.

Mechtcherine, V., Dudziak, L., and Schulze, J. 2006. Internal Curing by Super Absorbent Polymers (SAP) - Effects on Material Properties of Self-compacting Fibre-reinforced High Performance Concrete, Proceedings of the International RILEM Conference - Volume Changes of Hardening Concrete: Testing and Mitigation, Eds. O.M. Jensen, P. Lura, and K. Kovler, RILEM Publications S.A.R.L., 87-96.

Mohr, B., Premenko, L., Nanko, H., & Kurtis, K. 2005. Examination of Wood-Derived Powders and Fibers for Internal Curing of Cement-Based Materials. In B. Persson, D. Bentz, & L.-O. Nilsson (Ed.), *Proceedings of the 4th Interntational Seminar: Self-Desiccation and Its Importance in Concrete Technology*, (pp. 229-244). Gaithersburg.

Neithalath, N., Pease, B., Moon, J., Rajabipour, F., Weiss, J., & Attiogbe, E. 2005. Considering Moisture Gradients and Time-Dependent Crack Growth in Restrained Concrete Elements Subjected to Drying. In J. B. al. (Ed.), *NSF Workshop on High Performance Concrete* (pp. 279-290). Westerville: American Ceramic Society .

Pierard, J., Pollet, V., and Cauberg, N. 2006. Mitigating Autogenous Shrinkage in HPC by Internal Curing using Superabsorbent Polymers, Proceedings of the International RILEM Conference - Volume Changes of Hardening Concrete: Testing and Mitigation, Eds. O.M. Jensen, P. Lura, and K. Kovler, RILEM Publications S.A.R.L., 97-106, 2006.

Philleo, R.E. 1991. Concrete Science and Reality, Materials Science of Concrete II, Eds. J. Skalny and S. Mindess, American Ceramic Society, Westerville, OH, 1-8.

Raoufi, K., Schlitter, J., Bentz, D., & Weiss, J. 2011. Parametric Assessment of Stress Development and Cracking in Internally-cured Restrained Mortars Experiencing Autogenous Deformations and Thermal Loading. *Cement and Concrete Composites* . Advances in Civil Engineering, Volume 2011 (2011), Article ID 870128, doi:10.1155/2011/870128

Ries, J. P., Speck, J., Harmon, K.S. 2010. Lightweight Aggregate Optimizes the Sustainability of Concrete, ThroughWeight Reduction, Internal Curing, Extended Service Life, and Lower Carbon Footprint. Concrete Sustainability Conference.

Sant, G., Dehadrai, M., Lura, P., Bentz, D., Ferraris, C., Bullard, J., et al. 2009. Detecting the Fluid-to-Solid Transition in Cement Pastes: Part I - Assessment Techniques. *Concrete Interntional , 31* (6), 53-58.

Schlitter, J., Bentz, D., & Weiss, W. 2011. Quantifying Residual Stress Development and Reserve Strength in Internally Cured Concrete. *ACI Materials Journal.*

Shah, S., Weiss, W., & Yang, W. 1998. Shrinkage Cracking - Can It Be Prevented? *Concrete International , 20* (4), 51-55.

Shah, S., & Weiss, W. 2000. High Strength Concrete: Strength, Permeability, and Cracking. *Proceedings of the PCI/FHWA International Symposium on High Performance Concrete*, (pp. 331-340). Orlando.

Shin, K., Bucher, B., & Weiss, W. 2011. The Role of Low Stiffness Aggregate Particles on the Restrained Shrinkage Cracking Behavior of Mortar. *ASCE Journal of Materials in Civil Engineering.*

Trtik, P., Muench, B., Weiss, W., Kaestner, A., Jerjen, I., Josic, L., et al. 2011. Release of Internal Curing Water from Lightweight Aggregates in Cement Paste Investigated by Neutron and X-ray Tomography. *Nuclear Instruments and Methods in Physics Research, A* , accepted.

Weber, S., and Reinhardt, H. 1995. A Blend of Aggregates to Support Curing of Concrete, Proceedings of the International Symposium on Structural Lightweight Aggregate Concrete, Eds. I. Holand, T.A. Hammer, and F. Fluge, Sandefjord, Norway, 662-671.

Weber, S., & Reinhardt, H.-W. 1999. Manipulating the Water Content and Microstructure of High Performance Concrete Using Autogenous Curing. In R. Dhir, & T. Dyer (Ed.), *Modern Concrete Materials: Binders, Additions, and Admixtures* (pp. 567-577). Thomas Telford.

Weiss, W., Yang, W., & Shah, S. 1999. Factors Influencing Durability and Early-Age Cracking in High Strength Concrete Structures. *SP-189-22 High Performance Concrete: Research to Practice* (pp. 387-409). Farmington Hills: American Concrete Institute.

Wei, Y., & Hansen, W. 2008. Pre-soaked Lightweight Fine Aggregates as Additives for Internal Curing in Concrete. In D. Bentz, & B. Mohr (Ed.), *Internal Curing of High-Performance Concretes: Laboratory and Field Experiences* (pp. 35-44). Farmington Hills: American Concrete Institute.

Wolfe, B. 2010. Personal Communication and Photo.