LUND UNIVERSITY
LUND INSTITUTE OF TECHNOLOGY
Division of Building Materials
Report TVBM-3126

SELF-DESICCATION AND ITS IMPORTANCE IN CONCRETE TECHNOLOGY

Editors: B Persson, D Bentz and L-O Nilsson

Proceedings of the Fourth International Research Seminar, Gaithersburg, Maryland, USA, June, 2005

ISRN LUTVDG/TVBM--05/3126--SE(1-270)
ISSN 0348-7911 TVBM
ISBN 91-631-7102-3

Lund Institute of Technology
Division of Building Materials
Box 118
SE-221 00 Lund, Sweden

Telephone: 46-46-2227415
Telefax: 46-46-2224427
www.byggnadsmaterial.lth.se

PREFACE

This is the fourth Research Semina
Building Materials Division of Lunc
in 1997[1], 1999[2], and 2002.[3] While
National Institute of Standards and
of the participants and the high
characterized the first three seminars

RILEM TC 196-ICC has defined se
humidity of a sealed system whe
chemical shrinkage takes place at th
supportive skeleton, and the che
shrinkage." While self-desiccation
conditions, its effects are quite dep
These pore sizes in turn are depen
particle size distributions of the b
hydration. The continuing trends t
significantly reduced the capillary p
the fresh concrete, and have often re
of self-desiccation are all to visi
minimizing the detrimental effects c
and strains that may lead to earl
providing a "sacrificial" set of
microstructure that will empty first v
will remain saturated. It must be kep
always detrimental, as exemplified
of an earlier RH reduction for floori
damage.

As this volume of proceedings con
different countries, it is obvious that
research on this topic exhibited
understanding of the mechanisms b
scientific foundation, and thus the
basic to an applied phase, from the
researchers to concrete practitioners
strength and durability to this techno

Gaithersburg, MD USA, May 2005

Dale Bentz

[1] Persson, B., Fagerlund, G. (Eds.), Self-Desic
TVBM-3075, Div. Building Materials, Lund I
[2] Persson, B., Fagerlund, G. (Eds.), Self-Desic
TVBM-3085, Div. Building Materials, Lund I
[3] Persson, B., Fagerlund, G. (Eds.), Self-Desic
TVBM-3104, Div. Building Materials, Lund I

t-based Materials I. Principle
.esearch **31**, 647-654 (2001).
Cement-based Materials II.
search **32**, 973-978 (2002).
ortioning for Internal Curing.

t and Concrete Reference
t on Portland Cement
burg, MD, April 2004.
it; Lime; Gypsum, American
en, PA, 2004.
for Measuring Autogenous
Materials and Structures **28**,

on of Cement Hydration and
n Ceramic Society **80** (1), 3-

ır, A., Pumice Aggregates for
Symp. On Concrete Science
LEM Publications S.A.R.L.,
Mindess, and J. Weiss, 137-

e-Reducing Admixtures and
rtars. Cement and Concrete

for Autogenous Shrinkage
77-685 (2004).

CURRENT AND FUTURE TRENDS IN THE APPLICATION OF INTERNAL CURING OF CONCRETE

John W. Roberts
Northeast Solite Corporation, Richmond, Virginia, USA

Abstract

The concept of Internal Curing (IC) has come into the marketplace after 50 years of unobtrusively improving concrete [1, 2] through the use of lightweight aggregate (which was absorbent) in many different applications for purposes other than that of providing absorbed water for the hydration of cement. For instance, lightweight block have sharper edges, and bridges have less cracking through the incorporation of lightweight aggregates in their concrete mixtures.

Observations, as a result of successful and recent tests and research [3-19], have recently put IC in the forefront of breakthroughs of ideas of how to make good concrete better. It improves the results obtained by low water/cement (w/c) ratios, the use of silica fume, the advent of high-performance concrete, and the benefits from certain admixtures.

In the last 100 years [20] there has been placed a certain amount of long-lasting, good performing and economical concrete. However, the deficiencies of much of the concrete have been obvious. In the last 75 years [20] there has been a great amount of knowledge generated of how to make concrete better through the incorporation of specifically engineered ingredients and methods of batching and mixing. There have even been studies of the best means of curing. ACI Committee 308 has studied the subject since Bryant Mather [8, 21, 22] called the industry's attention to "self-curing." It was he who reconstituted and chaired the Committee on Curing. The Guide to Curing Concrete (ACI 308R-01) is being rewritten to recognize the value of internal curing as an adjunct to external curing.

Internal curing can make good concrete better [23]. It can make up for some of the deficiencies brought on by human beings' not following the best practices with external curing. It can even make up for some of the problems brought on by hot or windy weather. For very low w/c (≤ 0.35) concretes, IC may be a necessity [24], but research makes it obvious that there are benefits from IC in many low w/c ratio (≤ 0.43) mixtures. The need for it became obvious with the advent of high performance concrete (HPC). Because of it, more of the cement in a mixture is hydrated in a timely fashion. It results in greater early age strength, much lower autogenous shrinkage and cracking, lower permeability, greater internal relative humidity with elimination of self-desiccation, and other beneficial characteristics. It can benefit many different applications, among which the most obvious are bridges, parking structures, high performance concrete, pavements, precast concrete and high fly-ash concrete. Because its benefits are unique to different applications, other uses will be developed.

In order to use the optimum amount of internal curing agent, a rationale has been developed for mixture proportioning for Internal Curing [25], based on the chemical shrinkage and desorption of readily available water as it migrates to the hydrating cement.

Because of the deficiencies occurring in normal weight concrete, a number of candidates (applications, uses) for internal curing have been identified [26]. These may benefit in accordance with their needs for internal water and in accordance with the amount of IC vehicle used. It is envisioned that in the 21st Century some method of internal curing will be incorporated in all better quality concrete.

1. Introduction and objectives of Internal Curing

1.1 General

What are the purposes of Internal Curing (IC)? What is the present status of internal curing in the market place? The more we delve into how IC improves concrete, the more we have answers to the questions and the more we understand the magnitude of the list of potential applications. Preordained usage is insignificant in 2004, but interest is high and usage will grow because there are many problems involved with concrete that internal curing can resolve.

Internal Curing (Purposes):

A. A means to provide the water to hydrate all the cement [10, 23], accomplishing what the mixing water alone cannot do. In low w/c ratio mixes (under 0.43 and increasingly those below 0.40) absorptive lightweight aggregate, replacing some of the sand, provides water that is desorbed into the mortar fraction (paste) to be used as additional curing water. The cement, not hydrated by the low amount of mixing water, has more water available to it.

B. Provides water to keep the relative humidity (RH) high, keeping self-desiccation from occurring.

C. Largely eliminates autogenous shrinkage [10, 25].

D. Keeps the strength of the mortar and the concrete in the early age (12 to 72 hrs.) above the level where internally induced and externally induced strains can cause cracking [10, 25].

E. Makes up for some of the deficiencies of external curing, both human related (because the most critical time that curing is required is the first 12 to 72 hours) and hydration related (because hydration products clog the passageways needed for the fluid curing water to travel to the cement particles thirsting for water).

Internal curing works, because the thirst for water by the hydrating cement particles is so intense, because the capillary action of the pores in the concrete is so strong, and because the water in the properly distributed particles of lightweight aggregate sand is so fluid [27]. These factors establish the dynamics of water movement to the unhydrated cement particles.

1.2. Internal Curing (present

Although we have inadvertentl
years [1] with lightweight con
carriers) to bring water into th
absorbent lightweight aggregat
characteristics of normal wei
lightweight aggregate in the mi

2. Concrete deficiencies tha

The applications that benefit fr
can provide passageways whic
which low early-age strength i
improved, and even where th
elasticity of the finished pro
considerations. IC can help the
consumed and aid in the GREE
in Energy and Environmental D
construction time (ACTT), pro
maintenance cost and provide g

3. Procedures for optimum

3.1 General

Internal curing results depend c
other ingredients (including cem
used, and how the vehicle is i
mixture with the materials whi
predictably reliable. The materi
uniform in its characteristics.

The material must be able to be
and transported without degrada
water until needed for internal
incorporated should be as eas
material.

The purpose of the whole IC pro

Whether the absorbed water is s
absorptive lightweight aggreg
superabsorbent polymers, it sho
instant the water is needed. Wh
plastic, in its hardening, and in i
the engineer/designer/specifier.
satisfactorily cure the concrete,

1.2. Internal Curing (present status)

Although we have inadvertently cured concrete from the inside for the past fifty (50) years [1] with lightweight concrete, now we must consciously use agents (vehicles, carriers) to bring water into the concrete mixture on purpose by providing it through absorbent lightweight aggregate sand (LWAS) [28]. In doing so we will improve the characteristics of normal weight concrete by using a small amount of absorbent lightweight aggregate in the mixture.

2. Concrete deficiencies that IC can address

The applications that benefit from IC include those in which cracking of the concrete can provide passageways which result in the deterioration of the reinforcing steel, in which low early-age strength is a problem, where permeability or durability must be improved, and even where the rheology of the concrete mixture, the modulus of elasticity of the finished product or the durability of high fly-ash concretes are considerations. IC can help them all. IC can even help reduce the amount of cement consumed and aid in the GREEN effect, such as that promulgated by LEED (Leadership in Energy and Environmental Design). IC can contribute to the elimination of excessive construction time (ACTT), provide quicker turnaround time in precast plants, lower maintenance cost and provide greater performance and predictability.

3. Procedures for optimum Internal Curing

3.1 General

Internal curing results depend on the agent used, the procedure, the methodology, the other ingredients (including cement, aggregates and admixtures), the amount of vehicle used, and how the vehicle is incorporated into the mixture. The key is to design the mixture with the materials which will assist in making the entire process simple and predictably reliable. The material used, itself, needs to be predictable in its effects and uniform in its characteristics.

The material must be able to be batched easily. The concrete must be able to be mixed and transported without degradation of the IC agent. The agent needs to not release its water until needed for internal curing purposes. The concrete with the IC material incorporated should be as easily pumped, placed and finished as without the IC material.

The purpose of the whole IC process is to make good concrete better.

Whether the absorbed water is supplied by the inclusion in normal weight concrete of absorptive lightweight aggregate, (with strong, cubical particle shape) or of superabsorbent polymers, it should have the characteristic of desorbing its water at the instant the water is needed. Whichever is used, the objective is to have concrete in its plastic, in its hardening, and in its service condition with the characteristics desired by the engineer/designer/specifier. To achieve this, it must have sufficient internal water to satisfactorily cure the concrete, reduce autogenous shrinkage to an allowable minimum and retain relative humidity (RH) at a level needed to eliminate self desiccation.

Lightweight aggregate sand (LWAS), as the material providing absorbed water, is in the forefront in 2005 [29]. As more and more projects are designed and constructed, the amount of the LWAS per cubic yard of concrete will be revised to achieve certain purposes. Additionally, other appropriate IC agents or even admixtures might be included, either separately or absorbed into the lightweight sand. Choices will be made for certain uses and others specified for general use. For instance, to further improve the characteristics of the outside millimeter or two, where outside curing might not be sufficient, additional lightweight aggregate sand might provide the additional absorbed water needed to provide the curing necessary near the surface. The relationship of the carrier of water for internal curing with admixtures is important. Admixtures have their own mission; water carriers have theirs. Combined, the absorption of the water and admixtures together can have a salient effect on the final result. Aggregate, silica fume, fly ash, water/binder ratios, and cement/aggregate ratios have their own effects and even limitations. Internal curing can have a beneficial effect on them all. Their relationship with each other, brought about by internal curing, can optimize the influence each has and bring about a synergistic effect on the concrete end product.

3.2 Mixture proportioning for Internal Curing

The paper authored by Bentz, Lura and Roberts in the February issue of Concrete International [25] sets forth the rationale for a methodology for "Mixture Proportioning for Internal Curing." The rationale is based on the chemical shrinkage and the desorption of readily available water as it migrates to the hydrating cement. A formula of Bentz and Snyder [10] is presented for the Internal Curing Water that is required:

3.3. Required Internal Curing water

$$M_{LWA} = \frac{C_f \quad CS \quad \alpha_{max}}{S \quad \Phi_{LWA}}$$

Where

M_{LWA} = mass of (dry) LWA needed per unit of volume of concrete (kg/m^3 or lb/yd^3)

C_f = cement factor (content) for concrete mixture (kg/m^3 or lb/yd^3)

CS = chemical shrinkage of cement (g of water/g of cement or lb/lb)

α_{max} = maximum expected degree of hydration of cement

S = degree of saturation of aggregate (0 to 1) iminate self desiccation.

·oviding absorbed water, is in the
·e designed and constructed, the
ll be revised to achieve certain
or even admixtures might be
·ight sand. Choices will be made
r instance, to further improve the
·re outside curing might not be
provide the additional absorbed
surface. The relationship of the
mportant. Admixtures have their
the absorption of the water and
al result. Aggregate, silica fume,
; have their own effects and even
t on them all. Their relationship
optimize the influence each has
product.

the February issue of Concrete
·logy for "Mixture Proportioning
ie chemical shrinkage and the
the hydrating cement. A formula
uring Water that is required:

me of concrete (kg/m^3 or lb/yd^3)

^{3} or lb/yd^3)

nent or lb/lb)

·nt

Φ_{LWA} = absorption of lightweight aggregate (kg water/kg dry LWA or lb/lb)

The cement factor (C_f) is known, and the chemical shrinkage (CS) of the cement is easily computed from its composition. These two parts of the equation are fixed. The maximum expected degree of hydration of the cement (α max) depends on the water available. The other two factors vary with different lightweight aggregates. A less than optimum lightweight aggregate will desorb water at a lower rate such that the maximum amount of hydration of the cement is not achieved. Certain lightweight aggregates are unable to achieve saturation or desorption quickly enough. The ASTM C128 test for absorption has a time of 24 hours. Since desorption is especially important in the initial and final setting stages, an absorption at 30 minutes [29] has been accepted as a measure of early availability of absorbed water. As far as the absorption of the lightweight aggregate is concerned, each shale, clay or slate out of which the aggregate is made has its own characteristic expansion with resulting void or pore configuration. Some voids are large, some infinitesimally small, some are interconnecting, some are not. The result is that 24 hour absorptions vary from 5% or less to 25% or more. Consequently, the same mass of lightweight aggregate might have widely varying ability to provide water for the hydration of the cement.

The formula is designed for a simple computation. All that is necessary is to know the characteristics of the lightweight aggregate sand through testing. The absorption is ascertained through ASTM C128 and it is suggested that aggregate be tested for 30 minutes, 1, 2, 4 hours, 15 hours (AASHTO) and 24 hours (ASTM) so the desorption rate and effective degree of saturation can be ascertained. Substituting numbers in the equation for a particular lightweight aggregate sand, whose absorption is in the middle of the range of 5 to 25% and a degree of saturation of 95%, we obtain the following for a maximum degree of hydration of 0.94 for 588 pounds (267 kg) of cement per cubic yard of concrete with a water/cement ratio of 0.34.

$$M = \frac{588 \cdot 0.065 \cdot 0.94}{0.95 \cdot 0.15} \quad \text{or} \quad M = \frac{267 \cdot 0.065 \cdot 0.94}{0.95 \cdot 0.15}$$

$$= 252 \text{ lbs. LWAS} \qquad = 114 \text{ kg LWAS}$$

The required lightweight sand that is to be substituted for the natural sand is therefore in this example 252 pounds or 114 kg. The absorbed water that can be desorbed is 37.8 pounds or 17.1 kg. This internal water does not affect the w/c ratio amount, but instead adds to the water which the cement needs for hydration, and is in addition to the mixing water. The internal absorbed and desorbed water has no adverse effect on the permeability, strength or durability but instead has a beneficial effect on all these characteristics.

It is recommended that the practitioner determine the required parameters of all of the ingredients of the concrete mixture, not only of those involved in the formula, but also of the other aggregates and admixtures. For instance, if the stone has an absorption of 1% or more it has been shown that the shrinkage of the concrete made from it is

improved [30]. Absorbent lightweight aggregate is a proven benefit to curing, but there are other materials that also might have an added beneficial effect.
It is important that the absorbed water be distributed throughout the concrete (use sand size rather than coarse), that the LWAS have particle shape, mechanical strength and grading which can improve the characteristics of the mortar rather than detract from them, and that the LWAS be completely saturated (SSD) when incorporated into the mixture [29].

4. Candidates (applications, uses) for IC

4.1 General

We can no longer not address curing of concrete in all its facets. For 100 years we have addressed curing "after the fact," after the concrete is mixed and placed and finished. That is too late.

There are few concrete applications that cannot benefit from IC. Those obvious candidates were addressed in the paper "The 2004 Practice and Potential of Internal Curing of Concrete Using Lightweight Sand" presented at Northwestern University, Evanston, Illinois March 2004 at "Advances in Concrete through Science and Engineering" [26]. Identified in that paper were the following applications that would benefit from IC:

Architectural Concrete	Precast
Bridges	Pavements
Concrete Pipe	Parking Structures
High Performance Concrete	Self Consolidating Concrete
High Fly-ash Concrete	Tilt-up
Mass concrete	Walls

4.2 Benefits and drawbacks of IC

Thinking "outside the box," in order to predict the potential benefits from internal curing, we can review the list of concrete problems and ascertain which of them IC can address. Proper curing, including having the water in the proper place at the proper time, can and does benefit even the best engineered concrete, the best mixture design, and the best and even the less-than-best ingredients. Internal curing enables the practitioner to have the proper amount of water in the proper place at the proper time. Huge benefits result from adding a small amount of saturated surface dry (SSD) lightweight aggregate sand to conventional concrete.

The list of improvements to concrete because of optimum internal curing:

- reduces autogenous cracking,
- largely eliminates autogenous shrinkage,
- reduces permeability,
- protects reinforcing steel,

- increases
- increases
- provides
- higher 3-
- 7 day cor
- lower tur
- improved
- greater ut
- lower ma
- use of hig
- higher m
- through r
- sharper e
- greater cu
- higher pe
- improves
- does not
- does not
- reduces e

Some of these are interrelated
the hydration of the cement not
relative humidity imparted to th

There are potential drawback
However, if the materials have
intended, and if the procedures
can be achieved. The realization

4.3. Applications where IC is

The applications for internal
practiced for the last 100 years
few extra dollars the proven te
Certain uses need certain ben
benefits, but they are especia
addressed. Almost all applicatio
shrinkage, and permeability. Se
day [26].

High performance concrete (HP
IC can make it $H^{+}PC$. The pro
stability, and reduce its autogen

Silica fume has been used in m
should be able to reduce the

- increases mortar strength,
- increases early age strength sufficient to withstand strain,
- provides greater durability,
- higher 3-day flexural strength
- 7 day compressive strength in 3 days,
- lower turnaround time,
- improved rheology
- greater utilization of cement,
- lower maintenance,
- use of higher levels of fly ash,
- higher modulus of elasticity, or
- through mixture designs, lower modulus
- sharper edges,
- greater curing predictability,
- higher performance,
- improves contact zone,
- does not adversely affect finishability,
- does not adversely affect pumpability,
- reduces effect of insufficient external curing.

Some of these are interrelated and have a synergistic effect. All of them occur through the hydration of the cement not hydrated by the mixing water and/or through the higher relative humidity imparted to the concrete by IC.

There are potential drawbacks, as have been pointed out in the research [3-41]. However, if the materials have been chosen wisely for the purposes (uses, applications) intended, and if the procedures outlined have been followed, the characteristics wanted can be achieved. The realization will be to make good concrete better.

4.3. Applications where IC is critically needed

The applications for internal curing are many. We know that external curing, as practiced for the last 100 years and improved for the last decade, is not sufficient. For a few extra dollars the proven technology will pay off. IC is an investment, not a cost. Certain uses need certain benefits. Properly chosen IC agents can provide all the benefits, but they are especially needed for the critical problems that need to be addressed. Almost all applications need IC for its beneficial effect on strength, cracking, shrinkage, and permeability. Seven-day compressive strengths may be achieved in three day [26].

High performance concrete (HPC) is being used in increasingly more applications.

IC can make it H^{+}PC. The proper IC agent will help optimize concrete's dimensional stability, and reduce its autogenous shrinkage.

Silica fume has been used in many instances to densify and provide earlier strength. IC should be able to reduce the amount required per cubic yard, and at the same time impart the desired characteristics.

The 21st Century of Concrete will be the century of curing concrete, inside as well as outside; of not leaving curing to chance, but by incorporating curing in the mixture ingredients, by not leaving it up to the finishing foreman at midnight.

The life cycle of normal weight concrete structures, for instance parking garages, and outside walls, can be lengthened by making the concrete more durable, and durability is linked to low permeability and absence of cracking. IC with structural lightweight aggregate sand is a solution, Table 1.

Society wants the materials used to be ecologically correct, making the cement used be totally effective and not just serve as a filler, and making the structure last longer. Both support the Green effect.

Mass concrete is not cured appreciably by external curing. Internal curing will hydrate the interior cement by providing water when and where it is needed.

Concrete pipe and reinforced structural concrete need low permeability. The hydration of the cement not hydrated by the mixing water fills the pores and reduces the permeability. Desorbed water from LWAS can reduce the permeability 25% [27,29].

In most applications, the mortar is the weakest link in the strength of the concrete. Consequently, it is well to improve the mortar. This can be done through internal curing and can be further accomplished by using an IC agent that improves the rheology and the mortar strength. The choice of the optimum LWAS can assure both of these objectives. The object is to improve rather than detract from the mortar characteristics through the choice of the agent bringing IC water into the concrete mixture. Uses such as bridges, parking structures, pavements, walls and high-performance concrete are candidates for improvement of the mortar.

Table 1 – Applications of Intern

APPLICATIONS ((
USES
ARCHITECTURAL CONCRETE
BRIDGES
CONCRETE BLOCK
CONCRETE PIPE
HIGH PERFORMANCE CONCRI
HIGH FLY-ASH CONCRE'
MASS CONCRETE
PAVEMENTS
PARKING STRUCTURES
PRECAST
PRESTRESSED
SELF-CONSOLIDATING CONCRETE
TILT-UP
WALLS
All 14 uses receive all 1(

curing concrete, inside as well as
orporating curing in the mixture
in at midnight.

for instance parking garages, and
te more durable, and durability is
g. IC with structural lightweight

rrect, making the cement used be
ing the structure last longer. Both

uring. Internal curing will hydrate
e it is needed.

low permeability. The hydration
fills the pores and reduces the
the permeability 25% [27,29].

in the strength of the concrete.
n be done through internal curing
it that improves the rheology and
WAS can assure both of these
ct from the mortar characteristics
the concrete mixture. Uses such
d high-performance concrete are

Table 1 – Applications of Internal Curing.

APPLICATIONS (USES) BENEFITTED BY INTERNAL CURING																
USES	BENEFITS															
	LOW AUTOGENOUS SHRINKAGE	LESS CRACKING	HIGHER EARLY AGE STRENGTH	HIGHER 3-DAY FLEXURAL STRENGTH	7-DAY COMPRESSIVE STRENGTH IN 3 DAYS	LOWER TURNAROUND TIME	LOWER PERMEABILITY	IMPROVED RHEOLOGY	UTILIZATION OF CEMENT	LOWER MAINTENANCE	GREATER DURABILITY	USE OF HIGHER LEVELS OF FLY ASH	HIGHER MODULUS OF ELASTICITY	SHARPER EDGES	GREATER CURING PREDICTABILITY	HIGHER PERFORMANCE
ARCHITECTURAL CONCRETE		*						*		*	*			*	*	
BRIDGES	*	*	*				*	*	*	*	*				*	*
CONCRETE BLOCK		*	*					*	*					*	*	
CONCRETE PIPE				*		*	*									
HIGH PERFORMANCE CONCRETE	*	*	*		*		*	*	*	*	*				*	*
HIGH FLY-ASH CONCRETE					*				*	*	*	*			*	
MASS CONCRETE												*				
PAVEMENTS		*	*	*	*				*		*	*			*	*
PARKING STRUCTURES	*	*	*				*		*	*	*				*	*
PRECAST		*	*	*		*			*						*	*
PRESTRESSED			*				*	*	*						*	
SELF-CONSOLIDATING CONCRETE								*								
TILT-UP			*		*								*			
WALLS		*	*				*	*			*					
All 14 uses receive all 16 benefits. The (*) indicates the most critical.																

5. Summary and conclusions

IC can contribute to accelerated construction technology transfers (ACTT), quicker turnaround times, higher performance, lower maintenance cost and more predictability. There is a pronounced trend away from prescriptive specifications for concrete to performance specifications (P2P). Since curing is an integral part of concrete performance, decision makers will incorporate internal curing in their requirements. Prime applications are concrete pavements. precast concrete operations, parking structures, bridges, Jersey barriers, HPC projects, and architectural concrete.

Concrete, in the 21st century, will be more controlled through the choice of ingredients rather than the uncertainties of construction practices and the weather. Instead of after-the-fact curing of concrete through external applications of water, concrete quality will be engineered through the incorporation of water absorbed within the internal curing agent. In the future, some lightweight aggregate will be incorporated in all better quality concrete.

References

[1] Hoff, G. C., The Use of Lightweight Fines for the Internal Curing of Concrete, Northeast Solite Corporation, Richmond, Va., USA, August 20, 2002, 37 pp., available at www.nesolite.com/reports/solitepaper.pdf (2002).

[2] Hoff, G.C., Internal Curing of Concrete Using Lightweight Aggregates, Theodore Bremner Symposium, Sixth CANMET/ACI, International Conference on Durability, Thessaloniki, Greece, June 1-7 (2003).

[3] Self-Desiccation and its Importance in Concrete Technology, Proceedings, International Research Seminar in Lund, Eds: B. Persson and G. Fagerlund, Report TVBM 3075, June 10, 20 papers, 255 pp. (1997).

[4] Self-Desiccation and its Importance in Concrete Technology, Proceedings, Second International Research Seminar in Lund, Eds: B. Persson and G. Fagerlund, Report TVBM 3085, June 18, 13 papers, 171 pp. (1999).

[5] Philleo, R., Concrete Science and Reality, Materials Science of Concrete II, Eds: J.P. Skalny, Mindess, American Ceramic Society, Westerville, Ohio, 1-8 (1991).

[6] Weber, S., Reinhardt, H.W., A New Generation of High Performance Concrete: Concrete with Autogenous Curing, Advanced Cement Based Materials, Vol. **6**, No. 2, August, 59-68 (1997).

[7] Powers, T.C., Brownyard, T.L., Studies of the Physical Properties of Hardened Portland Cement Paste, Bulletin **22**, Portland Cement Association, Skokie, Illinois, 992 pp. (1948).

[8] Mather, B., Hime, W.G., Amount of Water Required for Complete Hydration of Portland Cement, Concrete International, Vol. **24**, No. 6, June, 56-58 (2002).

[9] Bonneau, O., Aitcin, P-C, Importance of Water Curing to Control the Initial Shrinkage Cracking and Durability of High Performance Concrete (HPC) Structures, Proceedings, Third International Conference on Concrete Under Severe Conditions, CONSEC '01, Eds: N. Banthia, K. Sakai, O.E. Gjorv, University of British Columbia, Vancouver, Canada, 18-20 June, Vol. 2, 1271-1278 (2001).

[10] Bentz, D.P, Snyder, K. A., Protected paste volume in concrete – Extension to

internal curing using satur
Research, Vol. **29**, 1863-1

[11] van Breugel, K., de Vries,
for Reducing Autogenous
Proceedings, 2nd Internati
Concrete, Eds: S. Helland
Norway, 463-472 (2000).

[12] van Breugel, K., Kaptijin,
Autogenous and Drying S
International Symposium
Concrete, Eds: G. Konig,
1488 (2002).

[13] Lura, P., van Breugel, K.,
the Paste on the Early-Ag
International Symposium
Concrete, Eds: G. Konig,
1149-1160 (2002).

[14] van Breugel, K., Lura, P.,
Distribution of Lightweig
Proceedings, 2nd Internati
Concrete, Eds: S. Helland
Norway, pp. 453-462 (20

[15] Tasdemir, M.A., Tasdemi
Fraction in the Fracture o
Proceedings, 6th Internatio
Performance Concrete, Ed
Vol. 2, pp. 1453-1466 (20

[16] Bentur, A., Igarashi, S., K
strength concrete by inter
and Concrete Research, V

[17] Kohno, K., Okamoto, T.,
artificial lightweight aggr
and Concrete Research, V

[18] Roberts, J. W., McWhorte
Corporation, Saugerties, N

[19] Test Report from Professi
Northeast Solite Corporati

[20] ACI, A Century of Progre
Concrete Institute, 123 pp

[21] Mather, Bryant, Self Curi
January pp. 46-47 (2001).

[22] Mather, Bryant, How Mu
pp. 60-62 (2001).

[23] Weber, S., Reinhardt, H.
Concrete Using Lightwei

ology transfers (ACTT), quicker
ance cost and more predictability.
ve specifications for concrete to
s an integral part of concrete
nal curing in their requirements.
st concrete operations, parking
architectural concrete.

through the choice of ingredients
and the weather. Instead of after-
ns of water, concrete quality will
sorbed within the internal curing
e incorporated in all better quality

the Internal Curing of Concrete,
USA, August 20, 2002, 37 pp.,
per.pdf (2002).
Lightweight Aggregates,
ET/ACI, International Conference
2003).
e Technology, Proceedings,
B. Persson and G. Fagerlund,
p. (1997).
e Technology, Proceedings,
d, Eds: B. Persson and G.
apers, 171 pp. (1999).
erials Science of Concrete II, Eds:
ety, Westerville, Ohio, 1-8 (1991).
n of High Performance Concrete:
Cement Based Materials, Vol. **6**,

Physical Properties of Hardened
Cement Association, Skokie,

quired for Complete Hydration of
24, No. 6, June, 56-58 (2002).
Curing to Control the Initial
rformance Concrete (HPC)
onference on Concrete Under
thia, K. Sakai, O.E. Gjorv,
anada, 18-20 June, Vol. 2, 1271-

ume in concrete – Extension to

internal curing using saturated lightweight fine aggregate, Cement and Concrete Research, Vol. **29**, 1863-1867 (1999).

[11] van Breugel, K., de Vries, H., Potential of Mixtures with Blended Aggregates for Reducing Autogenous Deformation in Low Water/Cement Ratio Concrete, Proceedings, 2^{nd} International Symposium on Structural Lightweight Aggregate Concrete, Eds: S. Helland, I. Holand, S. Smeplass, June 18-22, Kristiansand, Norway, 463-472 (2000).

[12] van Breugel, K., Kaptijin, N., de Bruijn, W. A., Effect of Paste Composition on Autogenous and Drying Shrinkage of HSC – Grade B65, Proceedings, 6^{th} International Symposium on Utilization of High Strength/High Performance Concrete, Eds: G. Konig, F. Dehn, T. Faust, Leipzig, Germany, Vol. 2, 1477-1488 (2002).

[13] Lura, P., van Breugel, K., The Influence of the Moisture Flow from the LWA to the Paste on the Early-Age Deformation of LWAC, Proceedings, 6^{th} International Symposium on Utilization of High Strength/High Performance Concrete, Eds: G. Konig, F. Dehn, T. Faust, Leipzig, Germany, Vol. 2, pp. 1149-1160 (2002).

[14] van Breugel, K., Lura, P., Effect of Initial Moisture Content and Particle Size Distribution of Lightweight Aggregates on Autogenous Deformation, Proceedings, 2^{nd} International Symposium on Structural Lightweight Aggregate Concrete, Eds: S. Helland, I. Holand, S. Smeplass, June 18-22, Kristiansand, Norway, pp. 453-462 (2000).

[15] Tasdemir, M.A., Tasdemir, C., Grimm, R., Konig, G., Role of Aggregate Fraction in the Fracture of Semi-Lightweight High Strength Concrete, Proceedings, 6^{th} International Symposium on Utilization of High Strength/High Performance Concrete, Eds: G. Konig, F. Dehn, T. Faust, Leipzig, Germany, Vol. 2, pp. 1453-1466 (2002).

[16] Bentur, A., Igarashi, S., Kovler, K., Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates, Cement and Concrete Research, Vol. **31**, No. 11, November, 1587-1591 (2001).

[17] Kohno, K., Okamoto, T., Isikawa, Y., Sibata, T., Mori, H., Effects of artificial lightweight aggregate on autogenous shrinkage of concrete, Cement and Concrete Research, Vol. **29**, No. 4, April, 611-614 (1999).

[18] Roberts, J. W., McWhorter, Jr., J. F., Internal Curing, Northeast Solite Corporation, Saugerties, New York, 6 pp.

[19] Test Report from Professional Service Industries (PSI), Sterling, Virginia to Northeast Solite Corporation, Saugerties, New York, April 11 (2001).

[20] ACI, A Century of Progress, Supplement to Concrete International, American Concrete Institute, 123 pp. (2004).

[21] Mather, Bryant, Self Curing Concrete, Why Not? Concrete International, January pp. 46-47 (2001).

[22] Mather, Bryant, How Much W in – w/cm? Concrete International, December pp. 60-62 (2001).

[23] Weber, S., Reinhardt, H. W., Modeling the Internal Curing of High Strength Concrete Using Lightweight Aggregates, Theodore Bremner Symposium on

High Performance Lightweight Concrete, Sixth CANMET/ACI, International Conference on Durability, Thessaloniki, Greece, pp. 45 – 64, June 1-7 (2003).
[24] Bentz, D. P., Stutzman, P. E., Effects of Early Age Curing on Long Term Microstructure, April, ACI Spring Convention, New York (2005).
[25] Bentz, D. P., L., Petro, Roberts, J. W., Mixture Proportioning for Internal Curing, Concrete International, February, available at www.nesolite.com/icresearch.pdf (2005).
[26] Roberts, J., The 2004 Practice and Potential of Internal Curing of Concrete Using Lightweight Sand, Advances in Concrete Through Science and Engineering, March 2004, Northwestern University, Evanston, Illinois (2004).
[27] Roberts, J. W., Improving Concrete Pavements Through Internal Curing, Presented at the Open Session, American Concrete Institute Annual Convention, Detroit, Michigan, April 23, 12 pp. (2002).
[28] Bentz, D. P., Jensen, O. M., Mitigation Strategies for Autogenous Shrinkage Cracking, Cement and Concrete Composite, Vol. **26** (6), 677-685 (2004).
[29] Roberts, John, Internal Curing in Pavements, Bridge Decks and Parking Structures, Using Absorptive Aggregates to Provide Water to Hydrate Cement not Hydrated by Mixing Water, Concrete Materials and Placement Techniques Committee, A2E05 of Transportation Research Board, January, available at www.nesolite.com/reports/trb.materials.ic.pdf (2004).
[30] Crawl, D., Sutek, M., A Survey of High Performance Concrete Bridge Decks, Volume IV. District 12, Ohio DOT, 24 pp. (2002).
[31] Hoff, G. C., The Use of Structural Lightweight Aggregates in Offshore Concrete Platforms, Proceedings, International Symposium on Structural Lightweight Aggregate Concrete, Sandefjord, Norway, June 20-24, 349-362 (1995).
[32] Walum, R., Weng, J.K., Hoff, G.C., Nunez, R.A., The Use of High-Strength Modified Density Concrete in Offshore Structures, Proceedings, International Conference on Concrete Under Severe Conditions, Sapporo, Japan, August 1-4, Vol. 2, pp 1368-1377 (1995).
[33] Bentz, D. P., Geiker, M., Jensen, O.M., On the Mitigation of Early Age Cracking, International Seminar on Self-Desiccation and Its Importance in Concrete Technology, Lund, Sweden, 15 June, 195-204 (2002).
[34] Weber, S., Reinhardt, H. W., Manipulating the Water Content and Micro-structure of High Performance Concrete Using Autogenous Curing, Modern Concrete Materials: Binders, Additions and Admixtures, Eds: R.K. Dhir, T.D. Dyer, Thomas Telford, London, 567-577 (1999).
[35] van Breugel, K., de Vries, H., Mixture Optimization of Low Water/Cement Ratio, High-Strength Concretes in View of Reduction of Autogenous Shrinkage, Proceedings, International Symposium on High-Performance and Reactive Powder Concretes, Eds: P. C. Aitcin, Y. Delagrave, University of Sherbrooke, Quebec, Canada, 365-382 (1998).
[36] Bloem, D. L, Gaynor, R.D., Meininger, R.C., Concrete Strength Measurement – Cores vs. Cylinders, ASTM Vol. **65**, pp. 668-696 (1965).
[37] Reinhardt, H.W., Zero-Curing High Performance Concrete, Proceedings, 2nd Concrete and Masonry Symposium, SEI-ASCE, Paper No. T168-5 (1998).
[38] Weber, S., Reinhardt, H. W., A Blend of Aggregates to Support Curing of

Concrete, Proceedings, Int
Aggregate Concrete, Eds:
Sandefjord, Norway, 662-
[39] Lam, Hoa, Effects of Inter
Permeability, University o
[40] ACI 308, Standard Practic
Practice, Part 2, American
[41] ACI 308R, Guide to Curin
Hills, Michigan.

ı CANMET/ACI, International
e, pp. 45 – 64, June 1-7 (2003).
Age Curing on Long Term
, New York (2005).
Proportioning for Internal
able at

Internal Curing of Concrete
ɜ Through Science and
ɹsity, Evanston, Illinois (2004).
Through Internal Curing,
rete Institute Annual Convention,

.es for Autogenous Shrinkage
ɔl. **26** (6), 677-685 (2004).
ridge Decks and Parking
ɔvide Water to Hydrate Cement
rials and Placement Techniques
Board, January, available at
'2004).
nance Concrete Bridge Decks,
)2).
Aggregates in Offshore Concrete
ım on Structural Lightweight
20-24, 349-362 (1995).
\., The Use of High-Strength
res, Proceedings, International
ɔns, Sapporo, Japan, August 1-4,

Mitigation of Early Age
ation and Its Importance in
195-204 (2002).
Water Content and Micro-
Autogenous Curing, Modern
nixtures, Eds: R.K. Dhir, T.D.
).
ation of Low Water/Cement
uction of Autogenous Shrinkage,
-Performance and Reactive
ave, University of Sherbrooke,

oncrete Strength Measurement –
'6 (1965).
:e Concrete, Proceedings, 2nd
, Paper No. T168-5 (1998).
gates to Support Curing of

Concrete, Proceedings, International Symposium on Structural Lightweight Aggregate Concrete, Eds: I. Holand, T. A. Hammer, F. Fluge, 20-24 June, Sandefjord, Norway, 662-671 (1995).

[39] Lam, Hoa, Effects of Internal Curing Methods on Restrained Shrinkage and Permeability, University of Toronto, Thesis, February (2005).

[40] ACI 308, Standard Practice for Curing Concrete, ACI Manual of Concrete Practice, Part 2, American Concrete Institute, Farmington Hills, Michigan, 2002

[41] ACI 308R, Guide to Curing Concrete, American Concrete Institute, Farmington Hills, Michigan.