SINTEF REPORT

SINTEF Building and Infrastructure
COIN – Concrete Innovation Centre

Address: NO-7465 Trondheim
NORWAY
Location: Richard Birkelands vei 3
Telephone: +47 73 59 52 24
Fax: +47 73 59 71 36

Enterprise No.: NO 948 007 029 MVA

TITLE

COIN P1 Advanced cementing materials
SP 1.3 F Reduced cracking

Reduced cracking by internal curing of Concrete

State of the art

AUTHOR(S)

Harald Justnes

CLIENT(S)

Aker Kværner Engineering and Technology, Borregaard LignoTech, maxitGroup, Norcem A.S, Norwegian Public Roads Administration, Rescon Mapei AS, Spenncon AS, Unicon AS, Veidekke ASA and

REPORT NO. SBF BK A07028	CLASSIFICATION Unrestricted	CLIENTS REF. Terje F. Rønning	
CLASS. THIS PAGE Unrestricted	ISBN 978-82-536-0992-8	PROJECT NO. 3D006030	NO. OF PAGES/APPENDICES 35
ELECTRONIC FILE CODE		PROJECT MANAGER (NAME, SIGN.) Harald Justnes	CHECKED BY (NAME, SIGN.) Hedda Vikan
FILE CODE	DATE 2007-12-20	APPROVED BY (NAME, POSITION, SIGN.) Tor Arne Hammer, Centre Manager	

ABSTRACT

The literature on mitigation of autogenous shrinkage cracking by internal curing (i.e. internal supply of water NOT belonging to the mix water) of concrete has been reviewed.

The use of saturated, surface dry (SSD) lightweight aggregate (LWA) is extensively investigated and proven to work as internal curing agent relieving stresses in concrete. It is now also used in practice in USA to combat shrinkage cracking in pavement and slabs.

There seems to be a size effect, so SSD LWA as internal curing agent function better in practice with large objects than in laboratory investigations on small specimens.

However, the potential of saturating the LWA with solutions of admixtures (e.g. shrinkage reducing admixture) that otherwise would interfere with the initial setting and hardening has not yet been fully exploited and is recommended for pursuit in COIN.

Very limited investigations have been performed on water saturated derivatives of wood; from wood powder, through cellulose fibres to cellulose derivatives, as agents for internal curing. Such materials are also recommended for studies within COIN.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Materials technology	Materialteknologi
GROUP 2	Concrete	Betong
SELECTED BY AUTHOR	Shrinkage cracking mitigation	Svinnriss kompensasjon
	Self-desiccation	Selvuttørking
	Internal curing	Indre herding

Foreword

COIN - Concrete Innovation Centre - is one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfill this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %). The present industrial partners are:

Aker Kværner Engineering and Technology, Borregaard LignoTech, maxitGroup, Norcem A.S, Norwegian Public Roads Administration, Rescon Mapei AS, Spenncon AS, Unicon AS and Veidekke ASA.

For more information, see www.sintef.no/coin

TABLE OF CONTENTS

1 INTRODUCTION

Early-age cracking of concrete is a well known phenomenon that may seriously affect the service life of structures. High-performance concrete (HPC), in particular on horizontal surfaces such as bridge decks, is prone to cracking even less than 12 hours after placing in spite of efforts to avoid drying (Sellevold et al., 1994). Kompen (1994) has summarized field experience in early-age cracking of HPC. Thus, the importance of autogenous shrinkage as a driving force may have been under-estimated in the past, but it is now widely accepted that autogenous shrinkage is an important cause for crack formation in HPC with w/(c+s) < 0.40 and fine supplementary cementing materials (SCMs). Autogenous shrinkage was in fact refered to as the "Achilles' heel" of HPC by Kovler and Jensen (2005).

This state-of-the-art report (STAR) is an effort to summarize the research on mitigation of autogenous shrinkage by internal curing (i.e. water supply by concrete incredianets other than the mixing water). Other mechanisms leading to early cracking, like drying shrinkage (i.e., water evaporation) and thermal deformations due to heat of hydration, are omitted. Since the review focuses on paste and concrete matrix measurements, it is important to note that autogenous shrinkage of concrete and mortar will normally be less than predicted from their volume of paste due to restraint caused by the embedded aggregate and the release of absorbed water from the aggregate.

This STAR does not intend to encompass all factors of internal curing, but merely the principles, materials for use and examples of applications. This was choosen since RILEM TC 196-ICC recently issued a thorough STAR of 140 pages on the subject of internal curing of concrete.

2 OBJECTIVE

The overall objective of the activity in COIN where this report belongs is to make concrete with crack free surfaces, or at least make them invisible by distribution. The specific objective of this report is to elucidate how internal curing may be used to mitigate shrinkage cracks and to review the state of the art of this topic.

3 DEFINITIONS AND MECHANISMS

RILEM Technical Committee 181-EAS (2002) issued a comprehensive report on early-age cracking in cementitious systems, where some terminology has been agreed upon:

Chemical shrinkage is the internal-microscopic volume reduction which is the result of the fact that the absolute volume of hydration products is smaller than that of the reacting constituents (cement and water). It is roughly proportional to the degree of hydration beyond the very early stage.

Autogenous shrinkage is the external-macroscopic (bulk) dimensional reduction of the cementitious system which occurs under isothermal conditions without exchange of moisture or any other substance with the surroundings (i.e., sealed curing). Autogenous shrinkage is usually driven by chemical shrinkage and the magnitudes of the two are roughly equal as long as the paste matrix is fluid-like. The autogenous shrinkage becomes smaller than the chemical shrinkage when the paste matrix has developed a self-supporting skeleton and the difference between them is manifested as internal *contraction pores* (roughly at the time of setting as shown by Justnes et al. (2000a) and reproduced in Fig. 1). Factors influencing autogenous shrinkage of cementitious systems have been reviewed by Justnes (2004).

Self-desiccation is the reduction of internal relative humidity in a sealed system when empty contraction pores are generated.

Chemical shrinkage is sometimes denoted as *total chemical shrinkage*, while autogenous shrinkage is denoted as *external chemical shrinkage* in line with the above definitions (e.g. Justnes et al. (1994)).

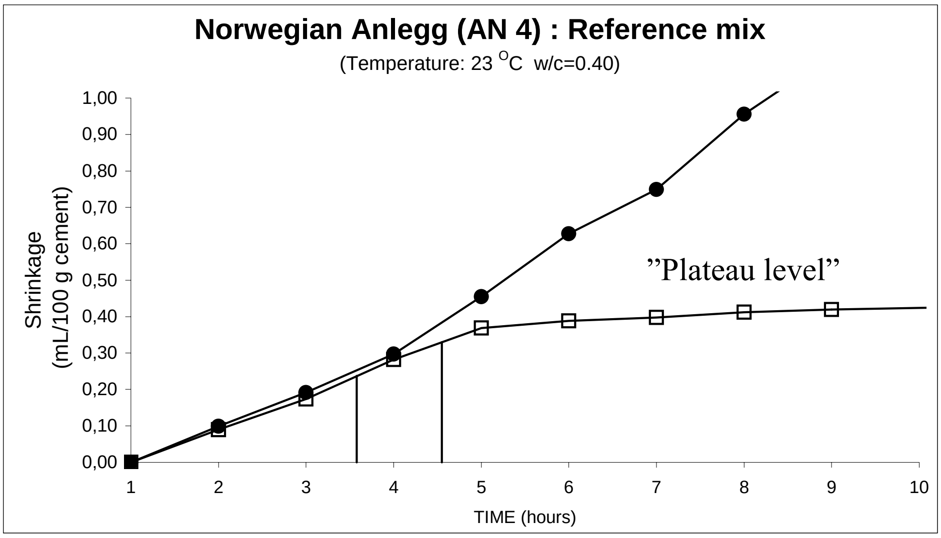


Fig 1 Chemical (●) and autogenous (□) shrinkage of cement paste (w/c = 0.40) compared with initial (left vertical line) and final (right vertical line) setting time by Vicat Needle. The gap between the two curves corresponds to the volume of contraction pores. (Justnes et al., 1994).

Chemical shrinkage is simply the difference in volume between hydration products and reactants. This is exemplified for the two phases with dominating reactivity during the first day (Justnes et al., 1998a); Tricalcium aluminate together with gypsum in Eq. 1 and alite (C_3S) in Eq. 2. Knowing the density, ρ (g/ml), of reactants and products of a chemical reaction, it is possible from the molar weight, M (g/mol), of the involved compounds to calculate the volume change, ΔV (ml), pr mass, m (g), reactant remembering the basic relations $n = m \cdot M$ (mol) and $\rho = m/V$.

The shrinkage of the initial ettringite formation will then be;

$$C_3A \quad + \quad 3\,C\bar{S}H_2 \quad + \quad 26\,H \quad = \quad C_6A\bar{S}_3H_{32} \qquad [1]$$

m = 1.00 g	1.91	1.73	4.64
M =270.20 g/mol	172.17	18.02	1255.26
n = 3.70 mmol	11.10	96.20	3.70
ρ = 3.03 g/ml	2.32	0.998	1.78
V = 0.330 ml	0.823	1.733	2.607

$\Delta V = 2.607 - (0.330+0.823+1.733) = -0.273$ ml/g C_3A, while the chemical bound water is 1.73 g/g reacted C_3A, meaning that the chemical shrinkage is about 16 % of the chemically bound water.

The shrinkage of the alite reaction can be estimated in a similar manner, but the magnitude is strongly dependent of the composition and density of the CSH-gel formed. Justnes and Kjellsen (2003) estimated the density of a 28 days CSH gel of composition $C_{4.7}S_{3.1}H_{5.9}$ to 2.49 g/ml, which leads to the chemical shrinkage of this balanced reaction;

$$C_3S \quad + \quad 3.39\ H \quad = \quad 0.325\ C_{4.7}S_{3.1}H_{5.9} \quad + \quad 1.48\ CH \qquad [2]$$

m = 1.00 g	0.268	0.786	0.480
M = 228.32 g/mol	18.02	552.3	74.09
n = 4.38 mmol	14.84	1.42	6.48
ρ = 3.15 g/ml	0.998	2.49	2.24
V = 0.317 ml	0.268	0.316	0.214

$\Delta V = (0.316+0.214) - (0.317+0.268) = -0.055$ ml/g C_3S, while the chemical bound water is 0.27 g/g C_3S, meaning that the chemical shrinkage is about 8 % of the chemical bound water. It is important to note that the chemical shrinkage of the C_3A reaction is much higher (≈ 5 times) than the reaction of C_3S.

The chemical shrinkage of Portland cement being a mixture of a number of minerals, is in general considered to be about 0.06 ml/g cement (or about 25 % of the chemical bound water of 0.23 g/ g cement reacted according to Copeland and Hayes, 1953).

The total porosity of a cement paste based on 1 g cement of density 3.15 g/ml and water-to-cement ratio (w/c) of 0.40 can then be calculated as follows assuming a degree of hydration $\alpha = 0.30$ (30 %) for the first day;
Chemical bound water = $0.23 \cdot 0.30 = 0.069$ g/g cement
Physically bound water = $0.17 \cdot 0.30 = 0.051$ g/g cement
Liquid water with density 1.0 g/ml = capillary porosity = $0.40-(0.069+0.051) = 0.28$ ml/g cement
Empty contraction pores (i.e. vacuum) = $0.25 \cdot 0.069 = 0.017$ ml/g cement
Total porosity is then $(0.280+0.017)$ ml·100 vol%/$(1/3.15 + 0.4/1)$ ml = 41.4 vol%

The total porosity after 1 day hydration is distributed between 39.0 vol% water filled capillaries and 2.4 vol% empty capillary pores. The vacuum in the empty pores can be relieved by either shrinking the concrete in its plastic stage or by sucking air from the surface. Nevertheless, water menisci will be created in the pores and tension induced that potentially will lead to shrinkage cracks.

The basic mechanisms of autogenous shrinkage were recently evaluated by Lura et al. (2003). Other contributions to understanding the mechanisms have been given by Wittmann (2001), Mitani et al. (2001), and Thomas and Jennings (2001). The basic mechanisms are actually more or less outlined in the preceding definitions of chemical shrinkage, autogenous shrinkage, and self-desiccation.

Before setting, when chemical shrinkage and autogenous shrinkage are equal, the external volume change will be followed by a stretched, elastic rubber membrane if used. See Justnes et al. (1994) for detailed experimental set-up. In a uni-axial, horizontal dilatometry set-up, this external volume reduction would be manifested as subsidence and usually not recorded, or the measurement starts after setting and demolding.

After setting there will be a formation of empty contraction pores that initially are empty and that are forming an under-pressure. At this stage, the pore connectivity is quite high, so the water will re-distribute so the coarsest pores will empty first. Koenders and de Rooji (2003) discussed internal moisture flow by microstructural contraction. They concluded that the empty pores will have a minimum pressure equal to the partial pressure of water in equilibrium with the pore water and some dissolved air going into the gas phase when the pressure is reduced (i.e., solubility of gas is proportional to the pressure). The magnitude of this under-pressure is governed by the amount of solute in the water according to Raoult's law;

$P/P_0 = X$ (= relative humidity in case of water) [3]

where P = is partial pressure over the solution, P_0 = the pressure over pure solvent, and X is the molar fraction of free solvent in the solution. Note that in the case of water, water molecules coordinating around the ions also have to be subtracted in calculations. Water in fresh paste contains in general about 0.1 M alkali hydroxides and some sulphates that will ion-exchange to hydroxides rather quickly. Lura et al. (2003) measured an initial RH of 0.98 (i.e. P/P_0 in Eq. 3) due to this effect, while Page and Vennesland (1983) measured 0.967 for the composition of the pore solution extracted from a w/c = 0.45 paste after 2 months. However, the effect of Raoult's law will first become an important factor when solutions are getting concentrated (achievable for w/c < 0.4) where RH on the order of 0.4 may be obtained easily. This is the same principle used to obtain constant humidity by saturated salt solutions. Concentrated KOH gives, for instance, 9 % RH at 20°C.

However, at the stage of concentrated salt solutions, the pore refinement has progressed for a while. Before that, the equilibrium pressure of water over the meniscus in the coarsest pore filled with water (i.e., assuming that water will redistribute easily) will dominate in accordance with the Kelvin equation for cylindrical pores;

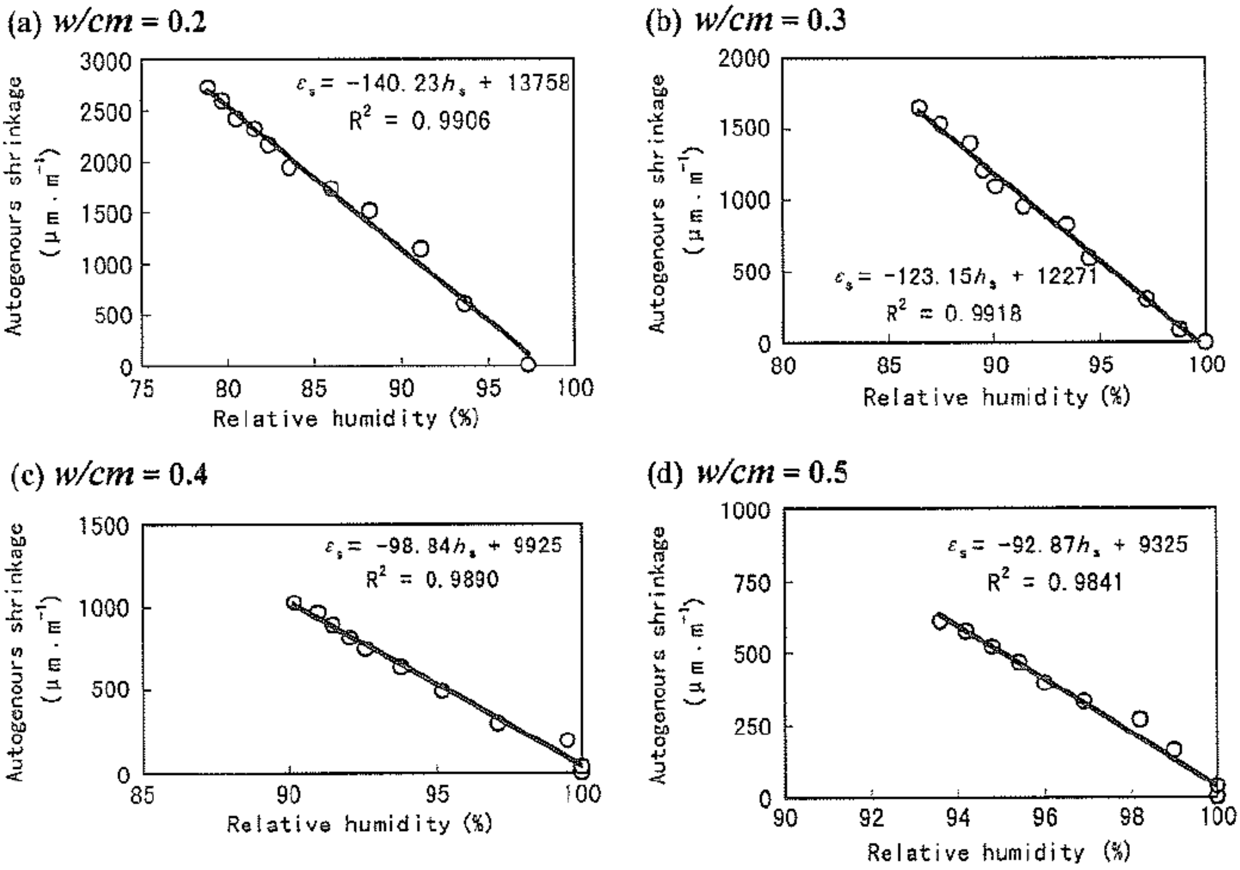
$$\ln\left(\frac{P}{P_0}\right) = \frac{-2\cdot\gamma\cdot M\cdot\cos\theta}{\rho\cdot r\cdot R\cdot T} \qquad [4]$$

where γ = surface tension of water (0.073 N/m in pure water and 0.055 N/m for a pore fluid according to Jensen (1993)), M = molar mass of water (18.02 g/mol), θ = the contact angle between water and solids (close to 0°), ρ = density of water (approx. 1,000 kg/m^3), r = the radius of the meniscus (m), R = the ideal gas constant (8.314 J/mol·K), and T = the absolute temperature (K).

If the effect on relative humidity by dissolved salts according to Raoult's law in Eq. 3 could be isolated from the effect of the water meniscii according to the Kelvin equation (Eq. 4), the radius, r, of the coarsest pore filled with water could be calculated from simple RH measurements. This could be used to calculate the tensile stress in the pore fluid according to the La Place law for cylindrical pores;

$\sigma_{Cap} = 2\cdot\gamma/r$ [5]

This tension stress of capillary water, σ_{Cap}, is generally thought to be the major driving force of autogenous shrinkage. Jensen (1993) claimed that the measured relative humidity could be approximated by the product of the contributions from Eqs. 3 and 4. This was also used by Lura et al. (2003) who also claimed that the contribution of dissolved salts in accordance with Raoult's law (Eq. 1) was constant to 2 % RH reduction throughout hydration. The present author will argue that these assumptions are not correct, and the fit between observed and calculated linear shrinkage by Lura et al. (2003) showed a large deviation when RH caused by meniscus formation fell below 97 %. Jiang et al. (2005) demonstrated a linear relation ship between autogeneous strain and RH for pastes with different w/c as reproduced in Fig. 2.


(a) *w/cm* = 0.2

(b) *w/cm* = 0.3

(c) *w/cm* = 0.4

(d) *w/cm* = 0.5

Fig. 2 Autogenous shrinkage as a function of relative humidity of pastes with different w/c as reproduced from Jiang et al. (2005).

There will be an under-pressure in the empty pores, which for a sealed case without air bubbles and dissolved air can not exceed the pressure of water vapour above free water (23 torr at 25 °C), but will be much less due to the effects described by Eqs. 3 and 4.

The pressure drop in the paste can also be measured directly by a method developed by Radochea (1992), using a water filled tube attached to a pressure transducer. The tension recorded in the water in the tube is believed to reflect the tensile stress of the pore water (σ_{cap} in Eq. 5), which in turn is transferred to the pore walls creating shrinkage. Examples of pressure drop in pastes of cements of different fineness are shown by Sellevold et al. (1994) and the Radochea (1992) device was later used by Hammer (2001). Generally at first, in the experiment with the water filled tube immersed into the paste ,the pressure equals the hydrostatic pressure of the suspended paste (i.e. a column of cement paste) according to

$$P = \rho \cdot g \cdot h \qquad [6]$$

where ρ = the density of the paste (kg/m^3), g = gravitational constant and h = depth of measurement below surface (m).

The pressure drops slowly as a function of time to a level corresponding to a column of same height of water percolating through the network of selfsupporting particles (i.e., only ρ changes from about 1,900 to 1,000 kg/m^3 in this “segregation” process of hydrating particles). Thereafter, there is a plateau until the first water menisci and vapour filled pores are formed roughly at the point of setting, followed by a gradually capillary water tension increase at first, which is rapidly accelerating. As seen in Fig. 3, the time from setting to achieve a pore water tension of 100 mm “hanging” (i.e., negative) water column is in the order of 1 hour, and from there it may take only half an hour to increase the pore water tension further to a 500 mm negative water column, and even less. Note that at such a low tension, the water vapour pressure is not affected much, so water may evaporate from coarser pores, be transported as vapour, and condensate in smaller pores. For comparison, it will take a pore water tension build up corresponding to a 10^6 mm water column (i.e., 1 km water column or 100 atm) before the relative humidity is reduced to 93 % (according to Eqs. 4 and 5).

Charron et al. (2001) compared autgenous shrinkage by a volumetric method with that of a linear dilatometric method for mortars. They found, like many others, that there is a large discrepancy between the two methods, where the dilatometry method gives an order of magnitude less shrinkage after setting, even when the results are made comparable by multiplying the linear measurements by a factor of 3 to take into account all principal directions. The authors did not find any good arguments for this observation.

According to the present author, one cannot rule out that the samples for linear measurements are not sealed properly, even when they are covered by wraps to avoid evaporation (with the exception of the corregated tubes used by Jensen (1993)). The pressure in the pores will then soon approach atmospheric by air being sucked in to them. The vacuum contribution to shrinkage will then be removed. The capillary tension due to menisci will, however, still be in place. The capillary tension can be lowered due to capillary condensation if evaporation is hindered by placing the sample in a chamber of high humidity. This could be an important contribution to explaining the discrepancy between volumetric and linear shrinkage measurements.

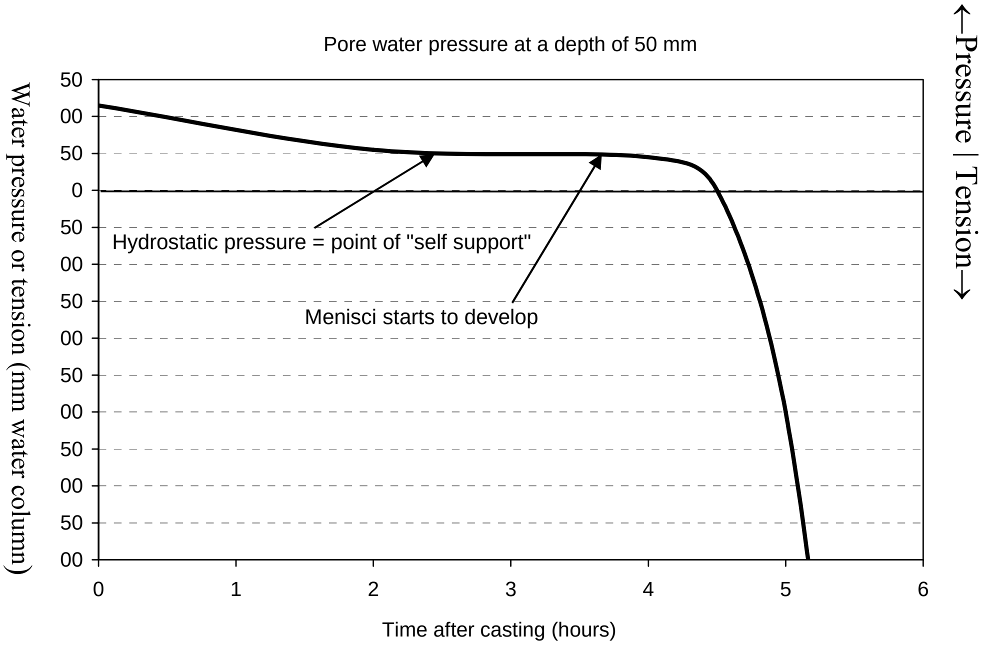


Fig. 3 Principle for interpretation of the development of pore water pressure and tension in cement paste with the measuring tube at 50 mm depth, after Hammer (2001).

The smaller autogenous shrinkage observed by linear methods relative to volumetric methods was discussed in detail by Hammer et al. (2001). They mentioned factors like 1) friction between sample and substrate, 2) bleeding and re-suction of bleed water creating expansion and 3) thermal expansion effects as the three important factores. In particular the 3rd effect, since temperature rise due to heat of hydration in non-submersed samples is difficult to avoid, and it may reach as much as 10°C above ambient temperature. This effect may actually be the reason for the difference (factor of 10) observed by Charron et al. (2001) since they compared the residual shrinkage after the thermal expansion peak for the sample in the linear experiment with that of the autogenous volumetric autogenous shrinkage of a submersed specimen. Since hydration rate is roughly increased by a factor of 2 per 10°C increase, the sample for the linear measurement would have been more mature at the point of comparison.

Since autogeneous shrinkage cracking is most prone for HPC and the characteristics of HPC are low w/c, use of supplementary cementing materials (SCMs) and use of plasticizers, a few pages should be spent on these three items.

Justnes et al. (1996) measured the effect of w/c on chemical and autogenous shrinkage of two different cement pastes. Chemical shrinkage (water saturated curing) was largely independent of w/c over the investigated w/c range (0.3 to 0.50) and time (0 to 48 h). Autogenous shrinkage (sealed curing) against time curves matched the chemical shrinkage crurves until a plateau level, was reached (see Fig. 1). This level was largely independent of w/c when shrinkage was expressed as mL/100 g cement, meaning that the volumetric autogenous shrinkage increases with decreasing w/c (since there is more cement per unit volume). There was also a tendency towards a more rapid fluid to solid skeleton transition at higher w/c and a slower more gradual transition at lower w/c.

Justnes et al. (2000b) investigated the effect of w/c in addition to the effect of admixtures on autogenous shrinkage. It was confirmed that the magnitude of autogenous shrinkage was only marginally (within 0.1 mL/100 g cement) influenced by w/c (0.3, 0.4 and 0.5) when measured as mL/100 g cement. A similar conclusion was drawn from an independent study by Justnes et al. (2000a).

Baroghel Bouny (1996) measured linear atogenous deformation (AD) on paste as a function of w/c (see Fig. 4), while Charron et al. (2001) measured the same on mortar with w/c = 0.45 and 0.35 and Toma (1999) measured linear AD on concrete with w/c 0.25, 0.35 and 0.45 (see Fig. 5). They all found larger shrinkage for the lower w/c simply because a lower w/c in this case means a larger cement content in a specimen of same size, and hence more AD. Thus there is no contradiction to the finding of Justnes et al. (2000a,b) who found volumetric AD to be largely independent of w/c when expressed as per unit cement content. The lower permeability of specimen with lower w/c may also hamper suction of air relieving the under-pressure and thus enhance the increased AD by decreased w/c in the linear type experimental set-up. However, one could argue that this experimental set-up is more in line with practice than volumetric measurements.

Another w/c-series on concrete have been reported by Tazawa and Miyazawa (1999) and some results are shown in Fig. 6 where autogenous deformation (AD) was measured on prismatic 100· 100·400 mm samples from the time of initial set. The tests were performed at 20°C with a minor temperature increase (below 5°C) due to hydration heat which has been compensated for by assuming that the thermal dilatation coefficient (TDC) had a constant value of $10 \cdot 10^{-6}$/°C. The w/c-ratio was reduced by keeping a more or less constant water content (160-170 l) while adding more cement/reducing the amount of aggregate meaning that the paste volume varies considerably: The paste volume increases from 33% at w/c = 0.50 to the very high value of 47% at w/c = 0.20. This means that the strong effect of reducing the w/c-ratio on AD shown in

Fig. Fig. 5 is strongly intensified by the increased paste volume, although reduced w/c *per se* gives increased AD of the binder. The same w/c decrease also involved an increase of the SP-dosage. Hence, the addition of SP may also have influenced the development of AD. These "design parameters" are, however, quite relevant in practical concreting, and the results may therefore give some indications on the AD - w/c relationship during realistic mix design. It is noticeable that w/c = 0.40 and 0.50 have nearly zero AD within the first 4 days. But for those below w/c = 0.40, AD becomes very high during the first day - in which most of the differences in AD is generated.

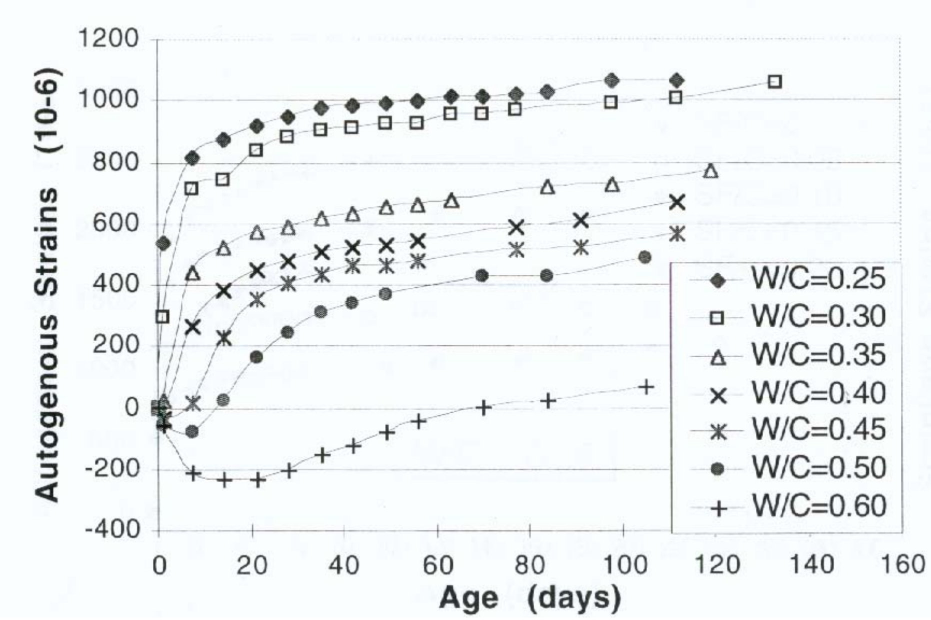


Fig. 4 Linear autogenous deformation of paste as a function of w/c and time as reproduced from Baroghel Bouny (1996). Specimens were cylindrical Ø20·140 mm and rotated until initial set (to minimize segregation and bleeding) after which the measurement was started.

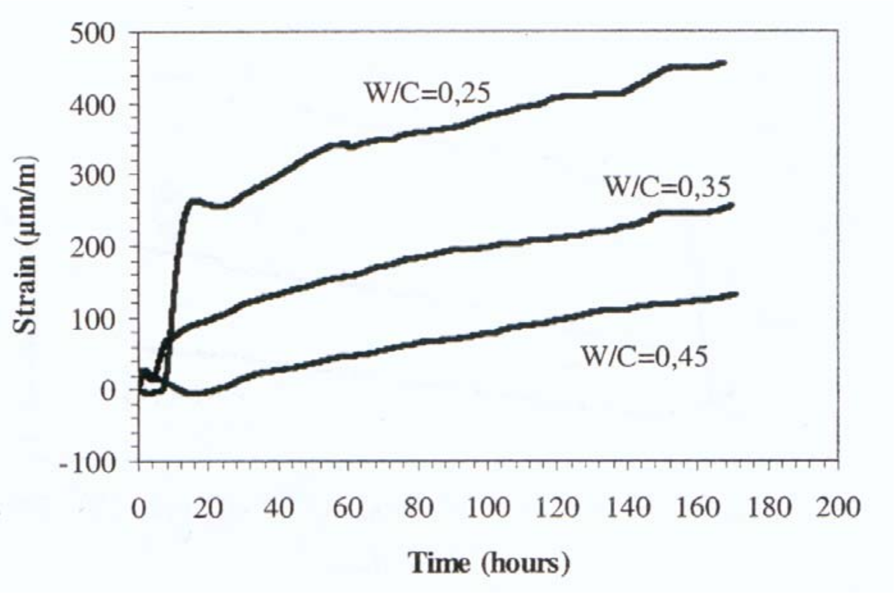


Fig. 5 Linear deformation of concrete as a function of w/c and time (Toma et al., 1999). The strain was measured on prismatic 50·50·1000 mm samples from the time of casting.

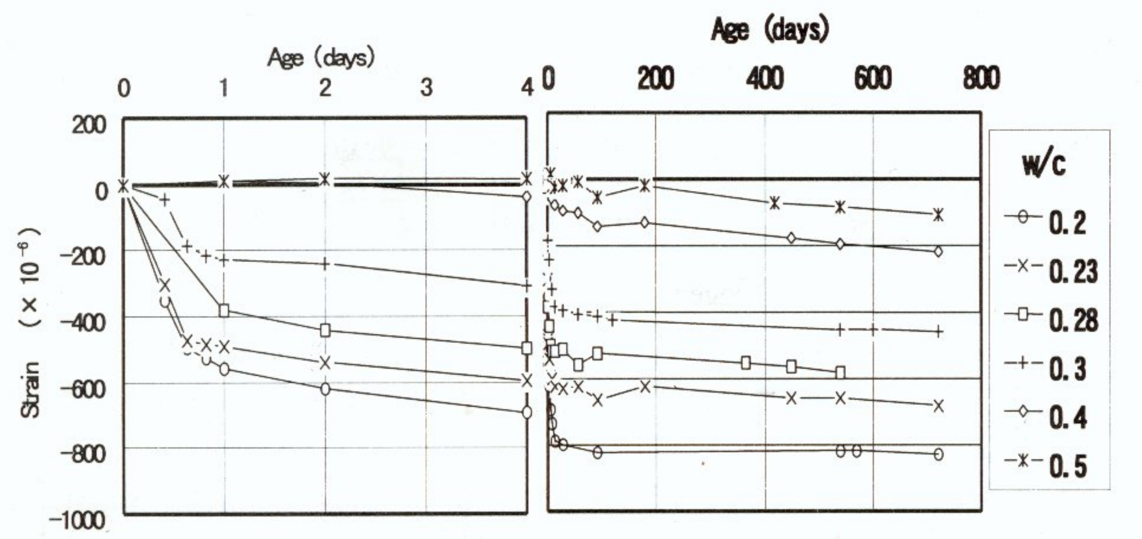


Fig. 6 Effect of w/c-ratio on AD in OPC-concrete during 20°C isothermal tests, Tazawa and Miyazawa **Error! Reference source not found.**(1999). Measurements are done from initial set. Reduced w/c-ratios means higher paste volumes in addition to increased AD of the binder due to reduced w/c.

Justnes et al. (1999) tested the effect of 10 % precipitated calcium carbonate and silica fume on the chemical and autogenous shrinkage of pastes with different cements. The influence of the mineral additives on chemical shrinkage rate was dependent on cement type; sometimes accelerating and sometimes equal to the reference. The effect of mineral additives on autogenous shrinkage was also depending on the cement type; sometimes increasing the plateau level and sometimes leaving it equal relative to the reference. A higher plateau level for pastes with fine mineral additives can be explained by pore refinement and menisci formed by initial contraction pores leading to stronger forces. Thus, more hydration is required to create stronger network to resist them.

Justnes et al. (1998) tested the effect of silica fume (SF) replacing cement at dosages of 0.0, 2.6, 5.3, 11, 20 and 25 % on chemical and autogenous shrinkage up to 7 days. Deformation was reported as mL/100 g cement, which means that a lower, equal or higher value correspond to a pozzolanic reaction that expands, has no volume change, or shrinks, respectively. Chemical shrinkage increased with increasing SF dosage, showing that the pozzolanic reaction leads to shrinkage, as expected. The autogenous shrinkage showed (see Fig. 7) equal plateau levels for SF replacements up to 11 %, while 20 and 25 % SF successively increased the autogenous shrinkage. This observation was explained by the particle packing of the system; up to 11 % SF replacement of cement (about 0.15 μm size) fills in the gaps formed between the irregular cement grains (average size 15 μm), maintaing close contact between individual cement grains. About the same amount of hydration is then required to form a hydrate network strong enough to resist the contracting forces. With greater SF replacements, cement grains are dispersed in excess silica fume and a higher degree of hydration is required to form such a network.

Justnes et al. (1998) investigated the chemical shrinkage of the pozzolanic reaction between lime and silica fume and between lime and class F fly ash without cement. The effects of lime/silica ratio, pH, and water content of these pastes were investigated. The rate of chemical shrinkage decreased with increasing pH of SF with lime, in spite of the catalytic necessity of alkalis for rapid pozzolanic reaction. This was explained by the fact that increasing pH (12.5, 13.0, and 13.5) decreases the solubility of calcium hydroxide (CH) due to the common ion effect assuming dissolution of CH is followed by the precipitation of CSH as the rate limiting step. The chemical shrinkage was relatively unaffected by mass ratios *w/c+s* in the range 0.8 to 1.2 and by molar C/S ratios in the range 0.7 to 1.5. On the other hand, the rate of chemical shrinkage increased with increasing pH for the lime-fly ash mixture indicating that the dissolution of the glassy aluminosilicate phase by alkalis is rate determining for this pozzolanic reaction. The chemical shrinkage of the pozzolanic reactions was crudely estimated to be 8.8 mL/100 g of reacted SF and 10.0 mL/ 100 g of reacted fly ash, as compared to 6.3 mL/100 g for hydrated cement. However, taking into account density differences (2,200 kg/m^3 for silica fume and 3,150 kg/m^3 for cement), the chemical shrinkage was roughly equal when expressed per unit volume of cementing material.

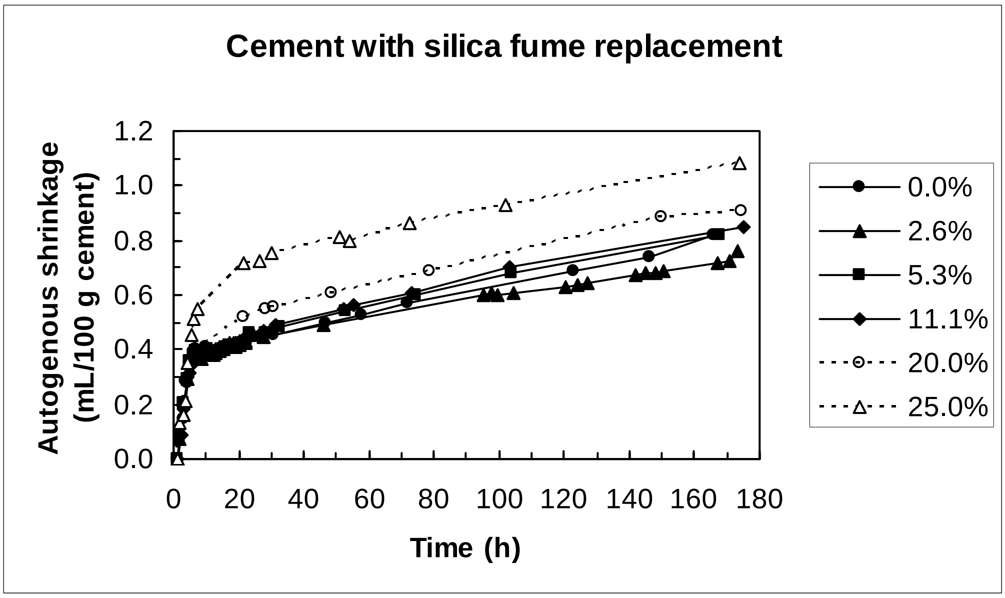


Fig. 7 Autogenous shrinkage of cement pastes as a function of silica fume replacement (after Justnes (1998)).

Jensen and Hansen (1996) studied the influence of SF on linear autogenous shrinkage of cementitious paste (w/c = 0.30) in horizontal corrugated plastic tubes for two different cement types and 0, 5, 10, and 20 % SF addition. Note that with addition, rather than replacement, *w/c+s* is reduced from 0.30 to 0.25 for 20 % SF addition. The effect of silica fume was increased linear autogenous deformation with increasing addition rate. Particularly surprising was the large increase in autogenous shrinkage from 0 to 5 % SF addition, while the effect from 10 to 20 % was minor. Note that any minor bleeding by the reference paste would hamper the results, since suction of bleed water will counteract shrinkage and even may lead to swelling. However, both the effective lowering of *w/cm* and refinement of the pores by improved particle packing will lead to earlier meniscus formation in finer pores and thereby create higher tensile stresses. Reduced tensile strain capacity of the paste with SF relative to the magnitude of the tensile stress build-up may explain the results.

Justnes et al. (2000c) investigated the effect of the three types of plasticizers (lignosulphonate, naphtalene sulphonate-formaldehyde condensate and sulphonated melamine-formaldehyde condensate) in 3 different dosages on chemical and autogenous shrinkage of cement paste made from 5 types of portland cement. They concluded that the plateau level of autogenous shrinkage was independent of admixture type, and was the same as for the reference paste without admixtures, as long as the specimens were rotated (i.e., undisturbed by bleeding). Furthermore, the admixtures did not directly influence the chemical shrinkage in a way that should indicate a higher risk of cracking. However, the retardation of early hydration and setting of cement by lignosulphonate could allow a longer period of evaporation of water from floors and bridge decks in practice. For this reason mixtures with lignosulphonates might be more prone to form drying shrinkage cracks. These conclusions were confirmed by Justnes et al. (2000b).

Another aspect is the influence of self-desiccation on degree of hydration and how internal curing may improve the degree of hydration. Sellevold and Justnes (1992) measured the amount of non-evaporable water content for sealed cured and water cured cement pastes with water to binder ratios 0.2, 0.3 and 0.4 with 0, 8, and 16 % silica fume. The non-evaporable water content accurately represents the degree of hydration, as shown by relating the non-evaporable water to nuclear magnetic resonance data on both cement components and silica fume consumption during hydration (Justnes et al., 1992). The samples were 27 mm cylinders (moulded in glass tubes). At the age of 150 and 800 days samples were broken in pieces (about 20 gram each) and dried at 105°C to find the evaporable water content and then ignited at 1000°C to determine the non-evaporable water content. The results are consistent regarding the influence of water curing: The amount of non-evaporable water is always between 0.01 and 0.022 g/g_{cem} lower in the self-desiccated specimens (see Fig 8). The differences correspond to approximately 6 % in degree of hydration of the cement pastes without silica fume at 150 days. Still, the hydration continues in all the sealed cured pastes as seen from the results at 800 days of age. Thus, the results show that self-desiccation significantly slows down the hydration, which opens for internal curing to achieve the potential degree of hydration.

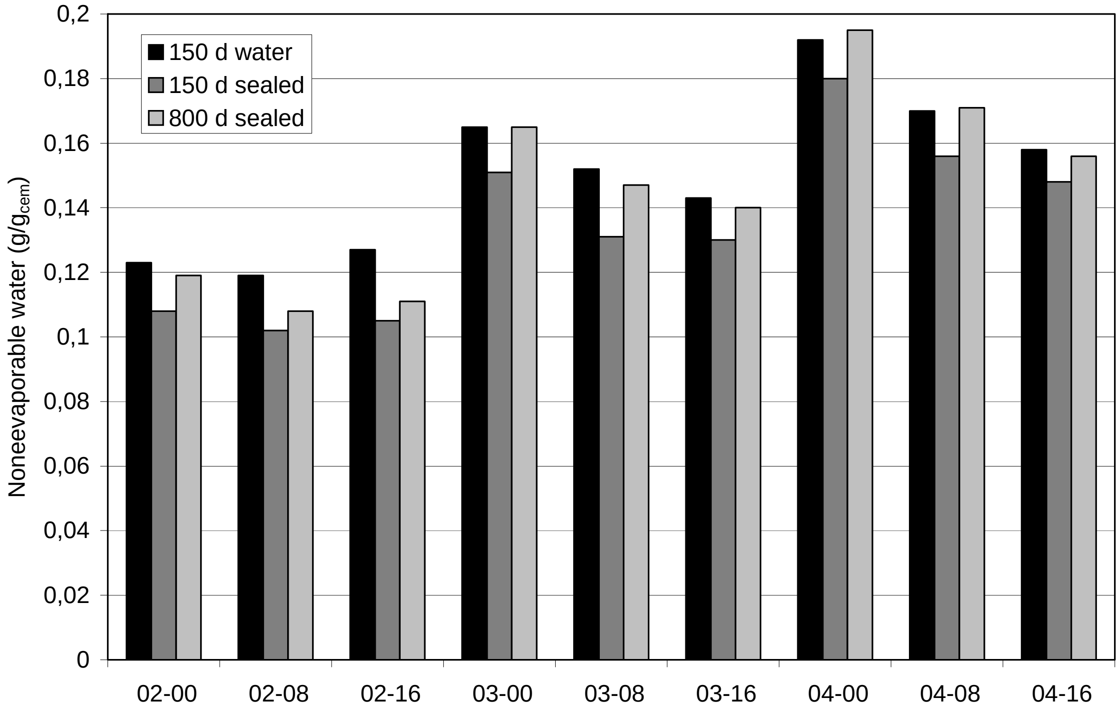


Fig.8 Non-evaporable water in water-cured and sealed-cured cement pastes with w/b = 0.2, 0.3 and 0.4, with 0, 8 and 16 % silica fume (1992).

4 AMOUNT OF INTERNAL WATER DEFICIT

The reasoning in this chapter is taken from Hammer et al. (2004). The amount of water needed for internal curing depends on concrete composition (mainly amount of cement), and, of course, on whether the concrete is exposed to drying to the surroundings. The most demanding case is for concrete with rather high permeability used in a thin section and exposed to very dry conditions from an early age. Such a case may give a water loss of the order of 50 liters/m^3 in a few weeks.

The minimum amount of required water is for *sealed* curing conditions, i.e. no exchange of water with the surroundings. This minimum amount is the volume needed to fill the empty space resulting from chemical shrinkage (CS) associated with cement hydration. After a sufficiently rigid skeleton has formed in the binder (roughly the time of final set), chemical shrinkage results in empty pore space (self-desiccation) and the development of capillary tension in the pore water, which again produces external volume contraction, i.e. autogenous shrinkage (AS) as discussed in the previous chapter. The capillary tension (and hence AS) increases with decreasing pore size (e.g. with decreasing w/b and increasing dosage of silica fume). Since AS is very small compared to CS we assume that the volume of self-desiccation pores, V_{sd}, equals the chemical shrinkage volume, V_{cs}. According to the original work by Powers and Brownyard (1948) V_{cs} corresponds to 25 % of the reacted volume of water, a value that also works for today's cement. Furthermore, we assume that 1 part of cement binds 0.24 parts of water at full hydration, and obtain:

$$V_{sd} = V_{cs} = 0.25 \cdot 0.24 \cdot \alpha \cdot c = 0.06 \cdot \alpha \cdot c \qquad [7]$$

where c is cement content (kg/m^3) and α is degree of hydration. Note that the value of 0.24 is chosen partly for convenience; different cements differ in their ability to bind water - values are commonly reported in the range 0.23 - 0.26. The precise value is not vital to our present concerns.

Fig. 9 shows the volume of self-desiccation pores. For a typical high performance concrete with a cement content of 400 kg/m^3 and $\alpha = 0.60$ this means a "water demand" of about 14 litres per m^3 concrete. This is a small amount of water and may even be available as absorbed water in normal weight aggregates. For light weight aggregates, even put into the concrete in a dry condition, just the water absorbed before setting is probably well above this amount. Consequently, to provide the needed amount of water is easy, the question is how to make it available so that the cement paste maintains full saturation throughout its volume during hydration.

The three main points to consider are (with aggregate particles as examples of water sources):

1) The amount of water in the aggregates. Obviously, it must be at least as much as the volume of self-desiccation pores, $V_{sd.}$

2) Aggregate spacing, i.e. the distance between the aggregate particles, or more properly the longest distance from a unit paste volume to the nearest particle (water source), must be short enough to allow water flow to fill the empty pores as they are created.

3) The pore structure of the particle relative to that of the paste. There is a competition between the two for water, the phase with the finest pore structure wins, since the smallest pore produces smallest capillary meniscus radius and the greatest tension in the water. Thus, the aggregate porosity must be as coarse as possible. In addition the volume decrease associated with CS will create under-pressure and a suction effect that helps the cement paste.

It should be noted that $V_{sd} = V_{cs}$ as assumed above for sealed conditions is an upper limit. Up to setting, AS is identical to the CS, since the paste is liquid and “collapses” as hydration and CS proceeds – no empty pores form. Empty pores form from about $\alpha > 10\%$ (see Fig. 1), i.e. the needed amount of water to maintain saturation can safely be reduced by 10%, implying $V_{sd} < (0.90 \cdot V_{cs})$ in practice.

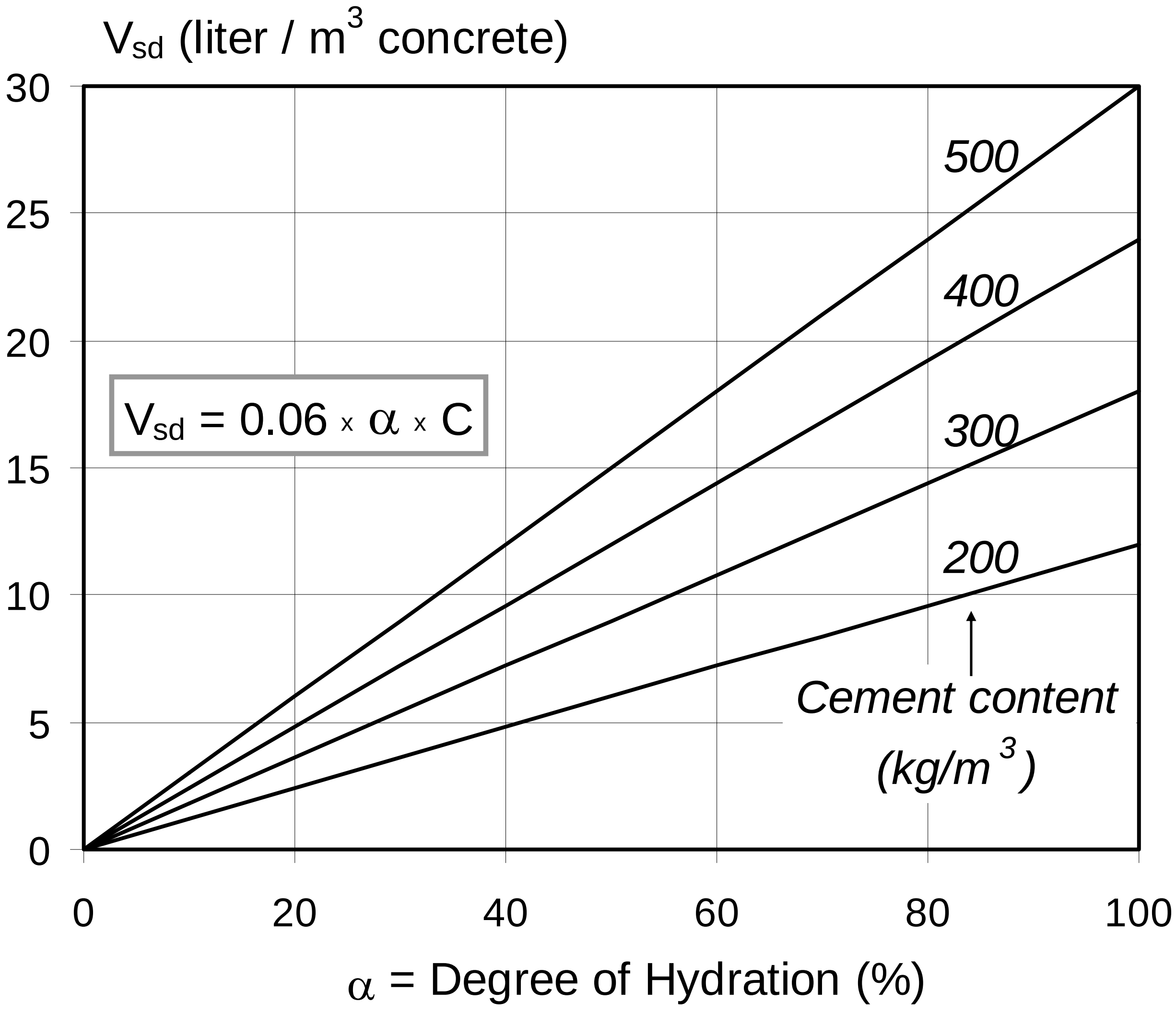


Fig. 9 Volume of self-desiccation pores, V_{sd}, pr. m^3 concrete as a function of cement content and degree of hydration.

Note also that elimination of AS does not imply that the paste has been kept saturated. In fact, water curing leads to slight expansion of paste and concrete. Consequently, zero AS probably indicates a state where a paste layer surrounding the water source is saturated and slightly expanding, while the remaining paste is less than saturated and slightly contracting - the net result being zero.

The volume of empty pore space created by the chemical shrinkage is easy to calculate just knowing the amount of cement and the relevant degree of hydration (Fig. 9). To assess the consequences of this self-desiccation for the concrete it is useful to relate the empty pores to the total paste porosity (gel + capillary pores) according to Powers model. Using 1 g of cement (density 3.12 g/cm^3) as basis, and Eq. 7, the volume porosity of the paste (ε_p) becomes:

$$\varepsilon_p = \frac{\frac{w}{c} - (1-0.25)\cdot 0.24\cdot\alpha}{\frac{w}{c} + \frac{1}{3.12}} = \frac{\frac{w}{c} - 0.18\alpha}{\frac{w}{c} + 0.32} \qquad [8]$$

The empty part (ε_{sd}) becomes:

$$\varepsilon_{sd} = \frac{0.06\alpha}{\frac{w}{c} + 0.32} \qquad [9]$$

Then the degree of saturation (DCS) may be calculated as:

$$DCS = \frac{\varepsilon_p - \varepsilon_{sd}}{\varepsilon_p} = \frac{\frac{w}{c} - 0.24\alpha}{\frac{w}{c} - 0.18\alpha} \qquad [10]$$

The term DCS (degree of capillary saturation) is often used in Scandinavia to emphasize that Eq. 10 only concerns the fundamental porosity of the binder phase in concrete (gel + capillary pores), and not the air/macro-porosity.

Fig. 10 shows the DCS as a function of the degree of hydration for w/c-ratios from 0.30 to 0.60. The fraction of empty pores increases strongly (i.e. DCS decreases strongly) as w/c-ratio decreases and degree of hydration increases. For field concrete several years old with w/c-ratios around 0.50 the degree of hydration is expected to be 70-80 % and then according to Fig. 10 the DCS to be in the range 80 - 90%. This has been found to be true for several Norwegian coastal bridges for concrete samples taken more than a few cm away from the surface (Relling, 1999, and Sellevold, 1997). The implication is that little moisture exchange takes place between the bulk concrete away from the surface and the environment, and that its moisture state is determined largely by the self-desiccation during hydration. As we move to better concrete qualities (lower w/c) clearly the bulk of field concretes can be expected to be dryer according to Fig. 10. Thus any strategy to supply water internally during hydration will lead to wetter moisture states in the field.

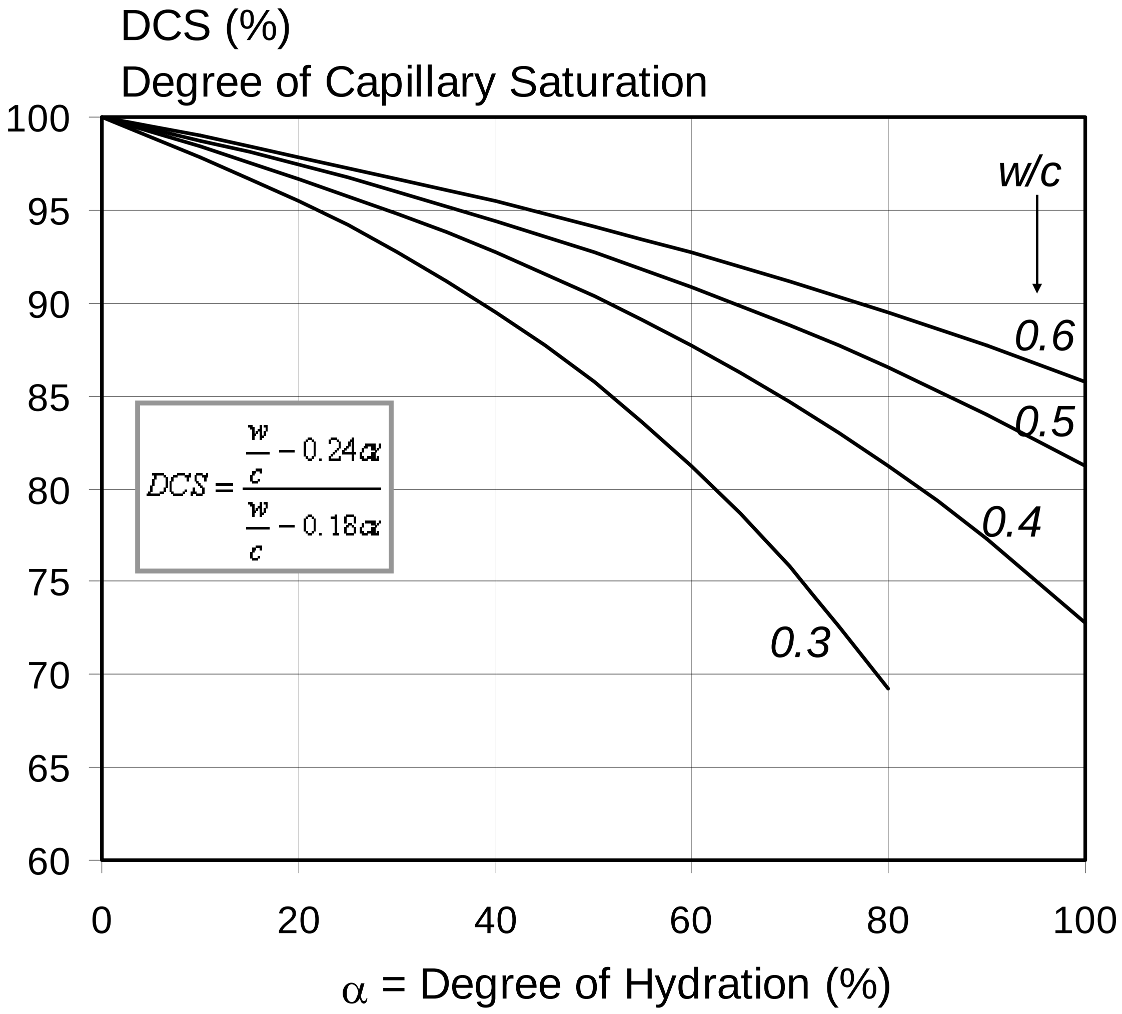


Fig. 10 Degree of Capillary Saturation after sealed curing to different degrees of hydration

5 MITIGATING AUTOGENOUS SHRINKAGE BY INTERNAL CURING

5.1 General

Internal curing of concrete was regarded as so an important topic at the ACI fall convention 2007 that two sessions were devoted to this, and it was also an important part of the plenary paper by Benz (2007) on early age properties of cement-based materials at the latest congress on the chemistry of cement.

There are two principle measures for mitigating autogenous shrinkage in accordance to its mechanisms. One is to supply the cement paste with water from internal sources when it self-dessicates. The second is to modify the surface tension of the pore water to reduce the stresses formed by menisci in partially emptied capillary pores. Bentz and Jensen (2004) summarized the different mitigation strategies based on these principles. Jensen and Lura (2003) reviewed techniques for so called internal water curing of concrete, ranging from inclusion of super-absorbant polymers (SAP) to water filled porosity in lightweight aggregate (LWA). Berke and Li (2003) evaluated the effect of a shrinkage-reducing admixture (SRA) based on glycol-ether and found that it reduced the autogenous as well as drying shrinkage. SRAs are however treated in another STAR in COIN.

5.2 Availability of internal water

5.2.1 Desorption experiments

A practical and theoretically sound way to characterize the ability of aggregate to release water is to measure the desorption isotherm; for internal (sealed) curing this means from saturation to about 70 % RH (the lowest level achieved by self-desiccation). Desorption behavior of concrete with LWA may also yield some information, and one such experiment where two different LWA were used is referred below. Smeplass (1998) used "Leca" LWA (expanded clay) known to have a rather coarse continuous pore system and "Stalite" LWA (expanded slate), known to have a finer and less continuous pore system. The water content of “Leca” was 7.0 % (initially dry, the water was absorbed from the mix water) and 29.0 % (pre-saturation for 1 day at 50 atm.), and corresponding values of 3.0 % and 10.6 % for “Stalite”. The concretes contained 0-8 mm natural sand. The 4-12 mm LWA, 4 - 12 mm constituted approximately 45 % of the concrete volume. The effective water to binder ratio was 0.40 for all mixes (i.e. extra mix water was added to compensate mix water absorption of the initially dry LWA), using a low alkali pure Portland cement and 5 % silica fume (of cement weight). Fig. 11 shows the desorption isotherms for the two concretes and the two initial moisture states of LWA. Note that the specimens were 10 mm discs sawn from 150 mm diameter cylinders. A large part of the aggregate particles were therefore sawn through and directly exposed to drying, i.e. the water loss was controlled by the particle pore structure. The saturated “Leca” concrete looses some of its moisture content at 97.4 % to almost join the pre-dried “Leca” concrete curve, indicating that most of the “Leca” pores are greater than the Kelvin meniscus radius of 0.04 μm corresponding to 97.4 % RH. On further desorption the two initial moisture conditions produce the same curve. The “Stalite” concretes behave differently. Both initial moisture conditions result in some loss from saturation to 97.4 % RH, but the pre-saturated one maintains higher concrete moisture content down to at least 70 %. This indicates a very fine pore structure indeed, and implies that “Stalite” is a less efficient light weight aggregate than “Leca” from an internal curing point of view.

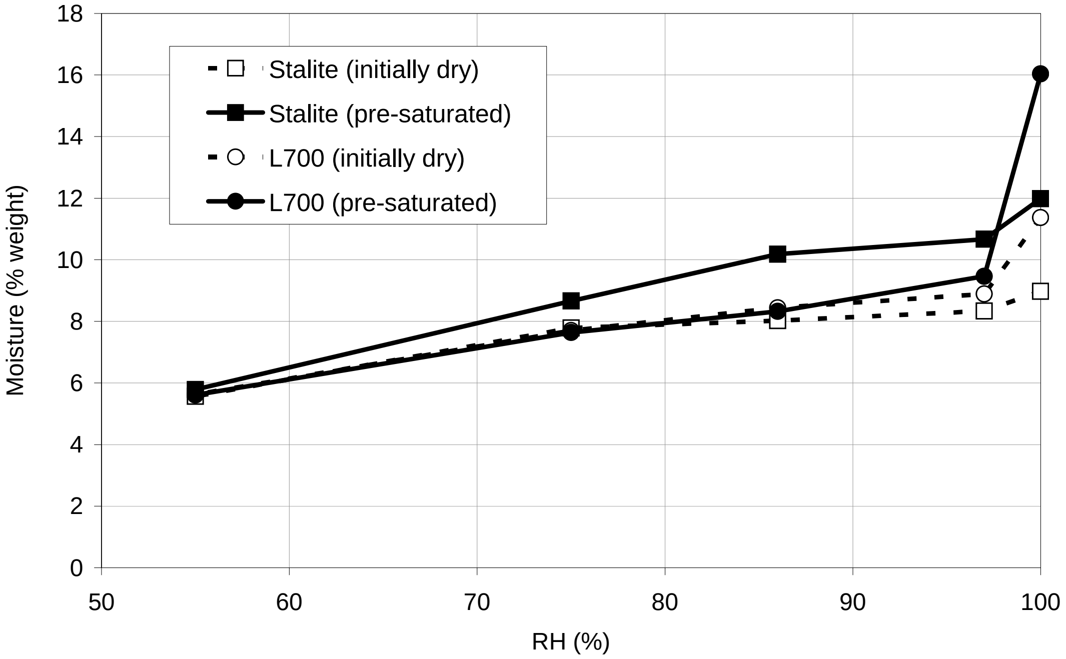


Fig. 11 Desorption isotherms for concretes with 4-12 mm Leca 700 (L700) and Stalite aggregates, respectively (w/b = 0.40, 5 % silica fume) after Smeplass (1998).

5.2.2 Importance of spacing factor

Assuming that the amount of water needed and its availability is sufficient, the situation for the paste in concrete with respect to water supply in LWA is equivalent to that of paste in Erlenmeyer flask with water on top, which is the common experimental set-up for chemical shrinkage testing. Geiker (1983) has shown that if the maximum effective thickness of the sample in Erlenmeyer flask is less than about 5 mm, where the self-desiccation pores are being filled even in dense pastes (i.e. with w/c of 0.3) within one week of age. This is in line with the fact that even 4-8 mm LWA, indicating spacing of some millimetres, are effective at least the first week of age. Bentz and Snyder (1999) have developed simple equations to estimate the replacement level of pre-wetted LWA needed to ensure sufficient water supply for complete curing of concrete. They consider LWA distributions corresponding to maximum spacing factors of 0.2 mm were needed to keep the paste saturated, which appears to be in contradiction to Geiker's (1983) results.

5.3 Normal density aggregate

Bjøntegaard (1999) has tested the autogenous deformation (AD) at 20 °C of a concrete and of the equivalent paste with w/b = 0.40 with 5 % silica fume (see Fig. 12). The paste did not contain any plasticisers, while the concrete contained both plasticizer with a retarding effect, and superplasticizer. As seen from Fig. 12, the developments in the first week are significantly different: The expansion of the concrete at the beginning is typical for concrete and is mainly related to re-absorption of bleed water (Bjøntegaard, 1999, and Hammer, 1999). The paste did not show any significant bleeding. The slower development of AD for the concrete in the first week may be partly due to absorption of water from the aggregates (absorbed water corresponds to approximately 12 liter/m^3), and partly due to a restraining effect of the aggregates. However, from approximately two weeks onwards there is no significant difference in the AD developments. However, one would have expected a slower rate in the concrete due to both the fact that concrete contains only about 30% volume paste, and a restraint effect of the aggregates. Bjøntegaard (1999) gave no explanation for this apparent contradiction. Although there are uncertainties about the role of the admixtures in the investigation, Bjøntegaard (1999) recommended exploring more systematically the contribution of normal density aggregate to internal curing.

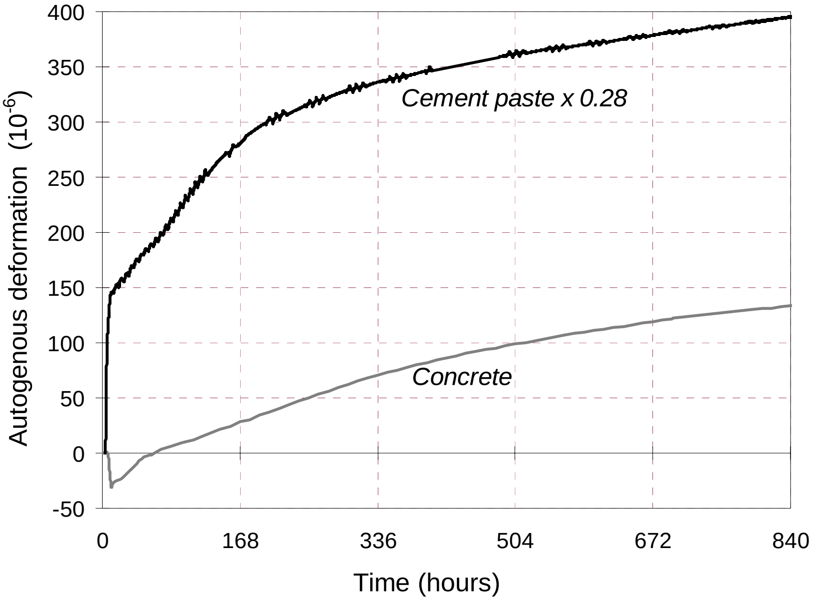


Fig. 12 Autogenous deformation (positive numbers is shrinkage) for a concrete with w/b = 0.40 and an equivalent paste (but without admixtures) converted to the paste content of the concrete (28 %) after Bjøntegaard (1999).

Zhutovsky et al. (2001) have tested the influence of water content of one normal aggregate on AD of a concrete with w/c of 0.33. One mix contained initially air dried aggregate and the other aggregate pre-wetted to saturated surface dry condition (SSD). The sand (< 0.6 mm) absorbed 0.4 % and the stone (2.4-9.5 mm) 1.5 % water. These numbers correspond to 19 litres of water per m^3 of concrete. The initially dried aggregate certainly absorbed an uncertain amount of mix water, which then causes both some internal water supply and a reduced effective w/c. Zhutovsky et al. (2001) did not quantify these effects. Nevertheless, the results show a slower AD development with the pre-wetted aggregate as reproduced in Fig. 13, but the 19 litres were not sufficient to fully eliminate AD, suggesting that not all of the water was available.

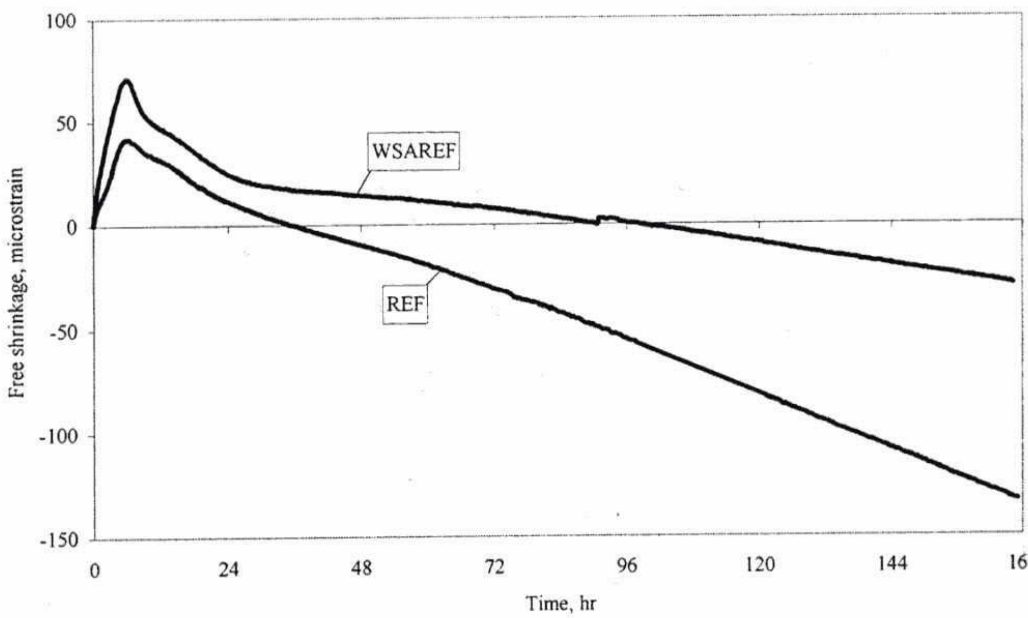


Fig. 13 Autogenous shrinkage of concrete with initially air dried aggregate (REF) and with the same aggregate pre-wetted to saturated surface dry condition (WSAREF)as reproduced from Zhutovsky et al. (2001).

The results from the two investigations mentioned above demonstrate that early age AD of concrete is influenced by absorbed water in normal density aggregate and furthermore that the AD of concrete cannot be predicted from paste measurements alone. Some Danish results (Jensen, 1997) indicated that AD of normal density concrete first start after 4 days under sealed conditions, which should imply that water in the aggregate play a role.

5.4 Light weight aggregate (LWA)

The concept of internal curing (IC) by LWA was apparently first suggested in the literature by Philleo (1991). He suggested the use of fine saturated light weight aggregate (LWA) nearly at the same time as Hammer (1992) published results on this concept and others followed up (Weber and Reinhardt, 1995). In 2005, the idea moved from being a laboratory concept to being a field reality at several job sites in the U.S., including a large paving project in Texas where 238,000 cubic yards (181,000 m^3) of concrete proportioned with IC via saturated LWA were batched and placed over the course of a few months (Villareal and Crocker, 2007). When Villareal and Crocker inspected this concrete in December 2005 (likely during its first freeze/thaw cycle); only two cracks were observed, one of which was located where an expansion joint was missing.

In addition to changing the size of the empty pores being created within the concrete microstructure, the IC water will also contribute to increased hydration of the surrounding cement paste. The efficiency and effectiveness of IC has thus been assessed by measurements of compressive strength, degree of hydration, internal relative humidity, autogenous shrinkage, and restrained shrinkage and creep (Lura, 2003, Jensen and Hansen, 2002, Geiker et al., 2004, Cusson et al., 2005). For example, Fig. 14 shows measured autogenous deformations vs. time for a series of high performance mortars prepared without and with several different IC reservoirs (Geiker et al., 2004). In each case, the addition of the IC water reservoirs resulted in a substantial reduction in the measured autogenous shrinkage at early ages. The ability of the LWA and SAP additions to significantly reduce autogenous shrinkage is clearly indicated.

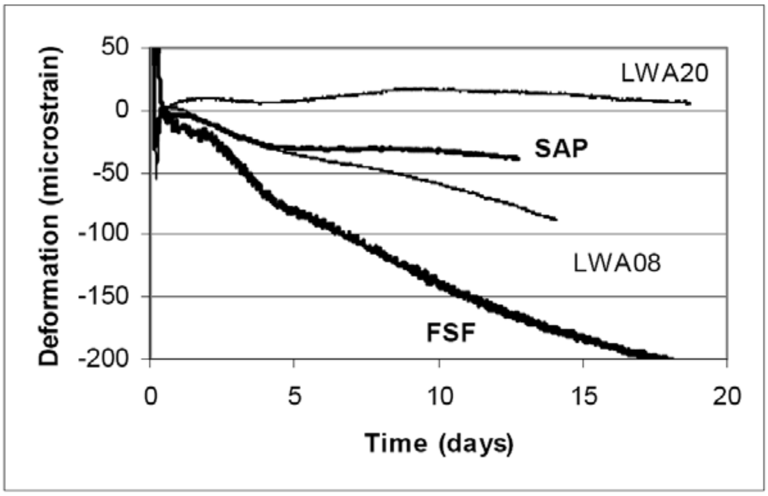


Fig. 14 Measured autogenous deformation vs. time for various mortars (*w/cm* = 0.3) with and without IC, during sealed hydration at 30°C; FSF marks control mortar prepared with cement blended with 8 % fine silica fume. SAP refers to the addition of 0.4 % super-absorbent polymer particles by mass of cement. LWA08 and LWA20 refer to LWA replacing 8 and 20 % of normal weight sand by mass, respectively (Geiker et al, 2004).

Recently, four-dimensional (3 spatial and time) X-ray micro-tomography experiments have been conducted to directly observe water movement from saturated fine LWA to the surrounding cement paste during the first two days of sealed isothermal hydration (30°C) by Benz et al. (2006).

Hammer (1992) investigated the effect of water content in LWA on the uniaxial shrinkage of sealed LWA concrete (8 % SF and nominal $w/c{+}s$ = 0.30) prisms by dilatometry from 1 to 180 days. Some results are replotted in Fig. 15. LWAC with dried and impregnated (prevents water suction) LWA shows high shrinkage, while LWAC with oven dried (105°C) LWA shows no shrinkage and late expansion since water absorbed by the LWA in the fresh state is released back to the matrix when pore water tension has become high enough. LWAC made with untreated LWA stored outdoors (moist) exhibit an expansion during the whole period due to the reservoir of extra water (i.e. absorbed during periods of rain) released to matrix.

Takada et al. (1999) investigated AD of concretes with a part replacement of the coarse normal aggregate by 4-8 mm LWA (type Liapor 10) with an initial moisture content of approximately 13 % by weight (see Fig 16). Fig. 16 reveals that there is a distinct effect of increased replacement levels, but 25 % (corresponds to 10 % of the concrete volume) is not enough to compensate for AD. In this concrete, the water content in the LWA corresponds to about 16 liter of water per m^3

of concrete, which is at least 50 % more than the amount needed to fill the self-desiccation pores at this expected maturity. It demonstrates that theoretical sufficient amount of water is not enough in practice, presumably because the water is not available either due to too lager particle spacing and/or too fine pore structure in the aggregate.

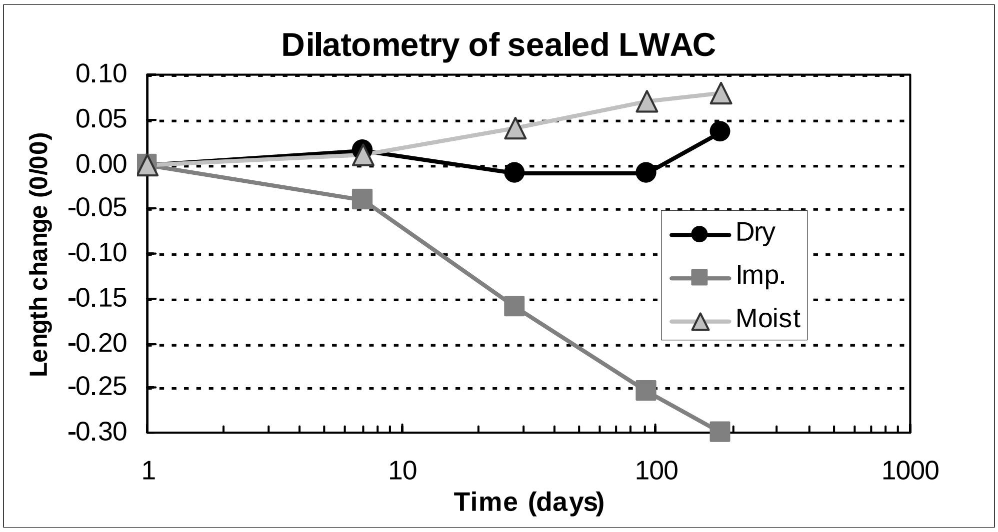


Fig. 15 Uniaxial length change of sealed LWA concrete prisms with LWA treated in different ways. Legends dry, imp. and moist refer to LWA dried at 105°C, dried LWA impregnated with stearic acid, and untreated LWA stored outdoors, respectively. Replotted from Hammer (1992).

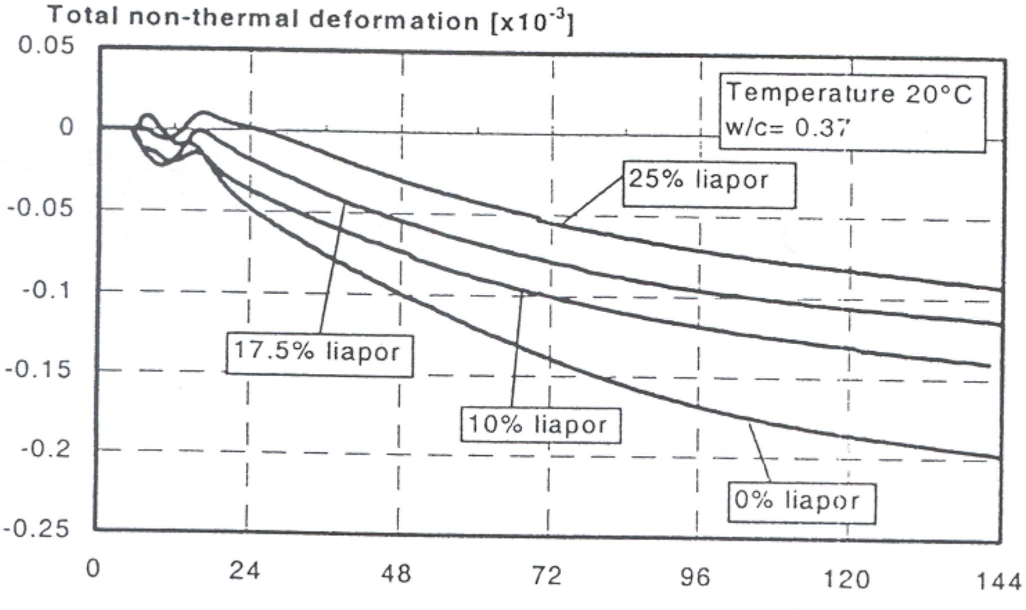


Fig. 16 Autogenous deformation of concretes with increasing replacement of the coarse normal density aggregate with coarse LWA (w/c = 0.37) after Takada et al. (1999).

Bentz (2007) studied the effect of internal curing (IC) on shrinkage of high-performance blended cement mortars using water saturated, surface dry (SSD) light weight aggregate (LWA) based on expanded shale. The SSD LWA had density 1.80 g/ml and an absorption capacity of 23.8 %. High performance mortars were made with w/cm (i.e. water-to-cementitious material ratio) = 0.30, and either 8 % silica fume (SF), 20 % ground blastfurnace slag (GBS) or 25 % siliceous fly ash (FA). Control mortars were produced without IC, and with 0.08 units IC water supplied by SSD LWA replacing coarse sand. IC was in particular beneficial for the mortars containing SF and GBS blended cements. For the mortars based on cement blended with FA, less autogenous shrinkage was observed, due to the maintenance of a more open (percolated) pore structure containing larger pores. In addition to providing a substantial reduction in autogenous shrinkage at early ages, IC also provided a significant increase in compressive strength at 28 days and beyond.

The amount of internal curing water needed to maintain saturation of the capillary porosity is directly related to the chemical shrinkage of the cementitious materials in a concrete. For LWA reservoirs this amount can according to Bentz et al. (2005) be calculated to

$$M_{LWA} = C_f \cdot CS \cdot \alpha_{max} / S \cdot \varphi_{LWA} \qquad [11]$$

where M_{LWA} is mass of dry LWA needed per unit volume of concrete (kg/m^3), C_f is the cement content (factor) in the concrete mix (kg/m^3), CS is the chemical shrinkage of the cement at 100 % degree of hydration (g water/g cement), α_{max} maximum expected degree of hydration of cement (0-1), S is degree of saturation of the aggregate and φ_{LWA} is the absorption of light weight aggregate (kg water/kg LWA) or more appropriately desorption from saturated surface dry (SSD) conditions down to 93 % relative humidity (RH). Similar calculations can be applied for SAPs or other sources of IC water. In addition to supplying the needed volume of curing water, the spatial distribution of the water is also important. In this respect, using fine LWA as opposed to coarse LWA is preferable due to its more homogeneous and closer spaced distribution of the individual IC reservoirs throughout the concrete volume (Bentz and Snyder, 1999, and Breugel and Lura, 2000).

Durán-Herrera et al. (2007) investigated the partial substitution of natural sand by a lightweight sand to reduce autogenous shrinkage in concretes having a low water/binder ratio. But, when this substitution is combined with quasi adiabatic curing conditions during the first 24 hours, they found that autogenous shrinkage could be eradicated. During an experiment on large concrete blocks measuring 0.6 × 0.6 × 0.6 m where 20 % by mass of the natural sand in the concrete was replaced by the same mass of saturated lightweight sand, having an absorption around 20 %, it was found that autogenous shrinkage was eliminated at depths of 10 and 30 cm within the concrete blocks. The size effect of blocks versus prisms is shown in Fig. 17. Moreover, they found that the compressive strength and the elastic modulus of the substituted concrete were not affected by this substitution. Thus, the autogenous shrinkage can be eliminated without the help of any chemical product added to the concrete to induce initial expansion in order to neutralize autogenous shrinkage. It seems that adiabatic conditions favour the development of larger crystals that result in the swelling of the apparent volume of the concrete block, and that increased temperature also contributes to reduce chemical shrinkage.

Cusson (2007) acknowledged the size effect and concluded optimistically that internal curing may be more effective in real structures than in laboratory experiments.

Internal curing using LWA is now well established in practise in Texas according to Villareal (2007) where TXI Ready mix concrete in Dallas, Texas, had produced < 2 million cubic yards of such concrete by the summer 2000. Number one application is pavement, with residential post-tensioned slabs coming second. They typically substitutes 0.19 m^3/m^3 of coarse and fine normal aggregate with 2.0-9.5 mm expanded shale LWA with 20 % absorbed water.

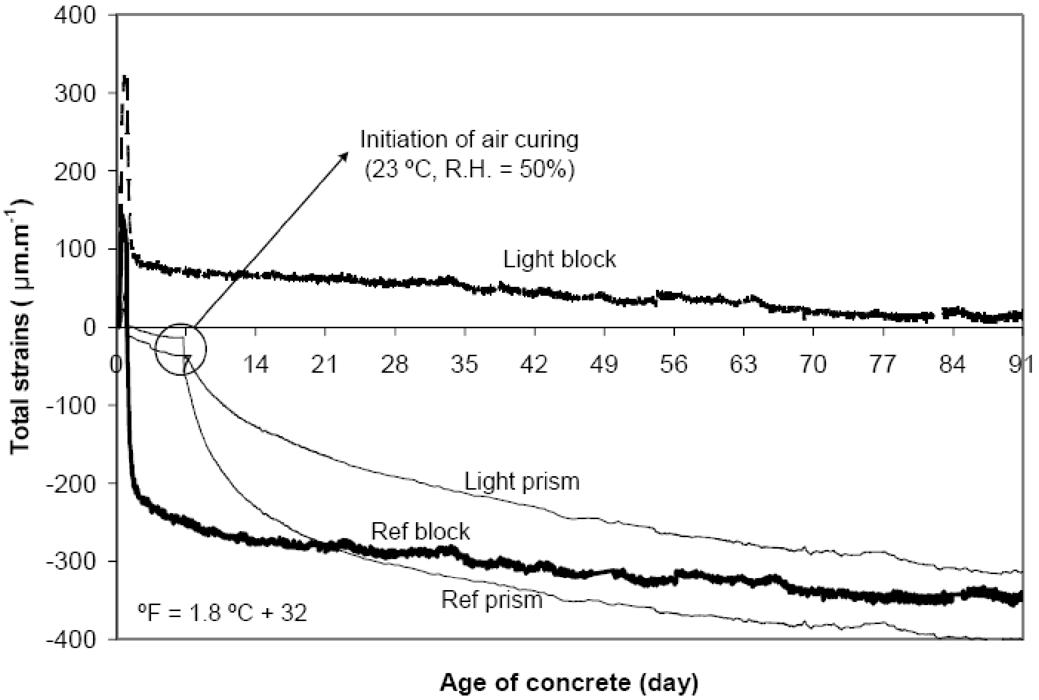


Fig. 17 Total strains measured until 91 days at the centre of reference (Ref) and sand substituted (Light) concretes, on 100×100×400 mm prisms and 600 mm cubic blocks (Durán-Herrera et al., 2007).

A lot more research has been done world wide using LWA for internal curing of concrete and Hoff (2002) made a thorough review for different countries on this matter. It can be obtained via internet or upon request to the author of the present report.

5.5 Other materials than LWA for internal curing

A part from artificially produced LWA (expanded clay, shale or slate), perlite may be used for IC as well as some natural occurring porous, inorganic materials like pumice of volcanic origin and diatomaceous earth (i.e. porous silica skeleton deposits from prehistoric algae). Their performances are compared in Table 1 and 2. Diatomaceous earth may be difficult to use in practice, though, as it tend to hamper flow of concrete.

Zhutovsky et al. (2001) used pumice stone with different size fractions, but with the same total content of absorbed water, to give different particle spacing. The size fractions were 0.15-1.2 mm, 1.2-2.4 mm and 2.4-4.8 mm. The water content of the pumice stone was always 20 liters corresponding to more than the theoretical volume needed to fill the self-desiccation pores. The influence on AD is shown in Fig. 18. It can be seen that the coarsest pumice stone, i.e. the one giving the largest spacing, proved to be the most efficient one. The authors suggested that different pore size distributions of the LWA in the different fractions (coarser with increasing size) was the main reason, as seems likely, but not yet verified. Neither of the fractions fully counteracted AD, again demonstrating lack of availability of the water in the aggregates.

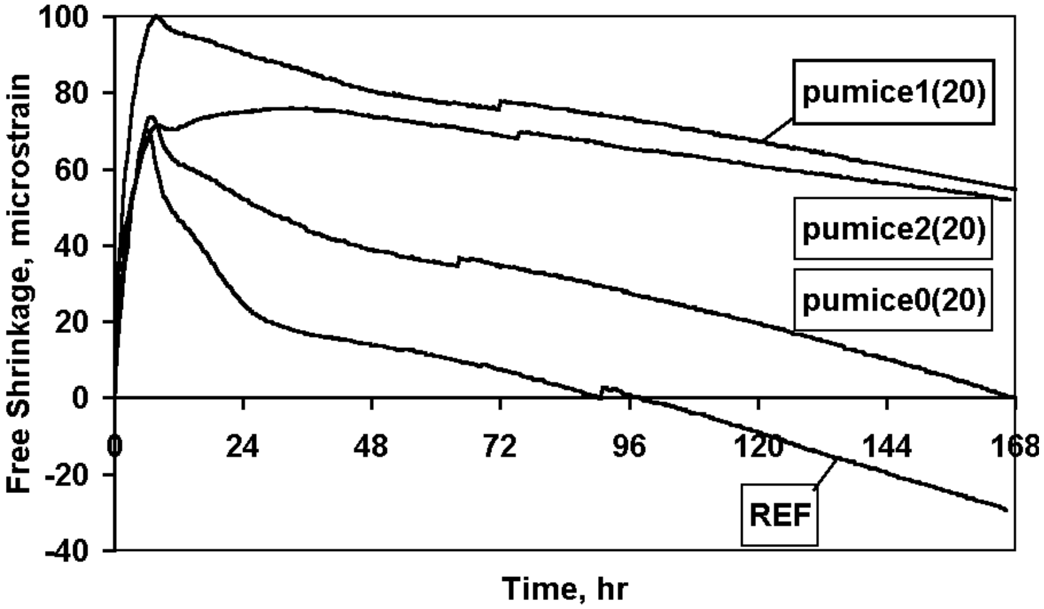


Fig. 18 Effect of the size of fine pumice aggregate (Pumice0 = 0.15-1.2 mm; Pumice1 = 1.2-2.4 mm; Pumice2 = 2.4-4.8 mm) on the autogenous deformation, in comparison with the reference concrete (REF) with normal density aggregate. The parenthesis (20) indicates that each pumice fraction contains 20 liters of water per m^3 concrete. (Zhutovsky et al. , 2001).

Jensen and Hansen (2001, 2002) introduced super-absorbent polymer using the term “water-entrainment”. The concept consisted of using fine super-absorbent polymer (SAP) particles as a concrete admixture (expanded diameter some 100 µm). This lead to the formation of water filled macro pore inclusions in the cement paste. This type of water entrainment mitigates self-desiccation shrinkage based on the same principle as water saturated LWA, but the technique is claimed to be more straightforward and to produce a highly controlled microstructure. Furthermore, it is possible that the spherical voids left behind as water is drawn from the water filled SAP to the hydrating cement paste could function as part of an effective air void system to protect the concrete from freezing and thawing damage.

Kraft and thermo-mechanical pulp fibres as well as cellulose and wood powders - which vary in size and morphology, - have been investigated by Mohr et al. (2005) for use as internal water curing agents in cement based materials. They reported water absorption of 1-3.3 kg/kg for these wood-derived products (see also Table 1).

Liu et al. (2007) used 0.12 % hydroxyethyl methylcellulose of cement weigh to mitigate drying shrinkage cracking of mortars. Drying shrinkage also form water menisci in pores as autogenous shrinkage. However, they explained their findings by polymer film bridging interfacial zone between aggregate and paste. The author of this report, however, believes that the mechanism could have been water being held by the polymer until set and thereafter released when menisci were formed in the pores, as 0.12 % seems to be too small dosage to matter as polymer film.

Jensen and Lura (2006), as well as Batey and Mohr (2007), made a comparison of different materials that can be used for internal curing (IC) and estimated the price for the IC water they supplied (See Tables 1 and 2, respectively. The cheapest price is actually for water supplied by

Perlite, followed by wood powder (Table 2). However, price is not the only important issue. It should not be forgotten that the more water a material can absorb, the less you need to add and the concrete properties are likely less affected.

Table 1 Estimated price (Euro) for internal curing water supplied with different materials (Jensen and Lura, 2006).

Material	Water content (kg/kg)	Material price (€/kg)	IC water price (€/kg)
Super-absorbent polymer (SAP)	15	6	0.4
Pumice	0.27	0.06	0.2
Perlite	4.5	0.3	0.07
Leca LWA	0.15	0.06	0.4
Liapor LWA	0.17	0.1	0.6
Stalite LWA	0.06	0.04	0.7
Diatomaceous earth	1	1	1

Table 2 Estimated price (USD) for internal curing water supplied with different materials (Batey and Mohr, 2007).

Materials	Water content (kg/kg)	Material price ($/kg)	IC water price ($/kg)
Super-absorbent polymer (SAP)	15	7	0.5
Pumice	0.27	0.07	0.3
Perlite	4.5	0.3	0.07
Expanded slate	0.06	0.05	0.8
Diatomaceous earth	1	1.1	1.1
Wood powder	3.3	0.3-0.5	0.09-0.15
Cellulose powder	1	0.3-1.1	0.3-1.1
Bleached Kraft pulp	1	0.5	0.5
Thermo-mechanical pulp (TMP)	3.3	0.4	0.12

5.6 Using LWA as internal reservoirs for admixtures

The FLAIR (Fine Lightweight Aggregates as Internal Reservoirs) concept of utilizing pre-wetted fine lightweight aggregates for the autogenous distribution of shrinkage reducing admixtures in mortars and concretes was presented by Bentz (2005). Potential benefits of FLAIR include the mitigation or avoidance of potentially detrimental influences of the admixture in the fresh concrete and a possibly increased efficiency of the admixture performance at later ages if it is partially absorbed during cement hydration. Further research is needed to determine the applicability of FLAIR to other admixtures such as corrosion-inhibiting admixtures and admixtures for mitigating alkali-silica reaction, and the practicality of utilizing the technology at ready-mix plants and pre-casting facilities. FLAIR might be a concept to pursuit in COIN.

Bentz (2005) tested a control mix and a mix with LWA and shrinkage reducing agent (SRA) either added to the mixing water or added as a 10 % solution in the LWA according to the FLAIR principle as outlined in Table 3. The way of adding the SRA was equivalent with respect to reducing strain as plotted in Fig. 19, but unfortunately it was not compared to saturated LWA without SRA. Thus, the question remains, if LWA saturated with pure water is sufficient or if there is an extra benefit in combining it with SRA.

Table 3 Mortar mixture proportions used in FLAIR study by Bentz (2005)

Material	Mixture 1 CONTROL	Mixture 2 FLAIR	Mixture 3 CONVENTIONAL
w_O/c^A	0.30	0.30	0.30
Cement	1250 g	1250 g	1250 g
Water	365.4	365.4	359.01
Water-reducing admixture	16.0	16.0	16.0
Shrinkage-reducing admixture (SRA)	---	---	6.39
F95 (fine) sand	593.75	593.75	593.75
Graded sand (C778)	451.25	451.25	451.25
20-30 sand (C778)	451.25	451.25	451.25
S15 (coarse) sand	878.75	279.65	279.65
Prewetted fine LWA containing:	---	383.33	383.33
Water for LWA	---	---	63.89
10 % SRA solution for LWA	---	63.89	----

$^A w_O/c$ calculated assuming 60 % water content for the water-reducing admixture and considering any SRA added to the mixing water as replacing an equal mass of water.

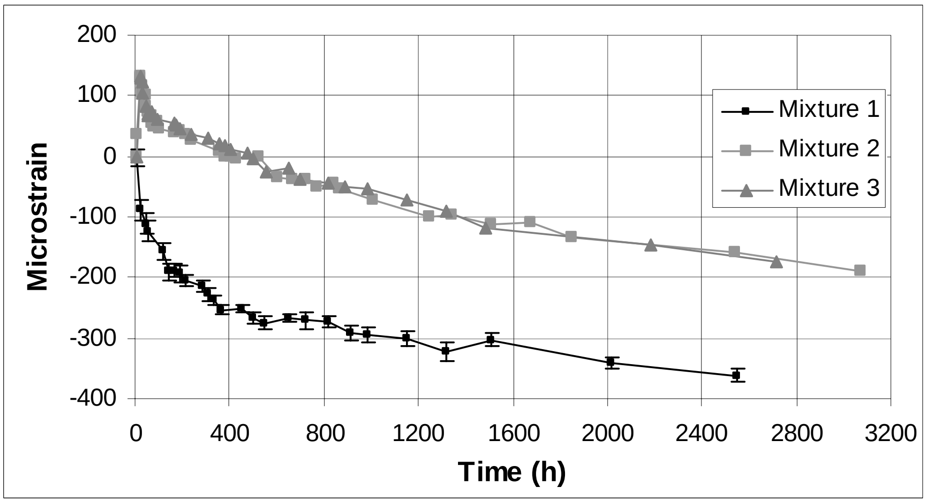


Fig. 19 Measured (average of two samples) autogenous deformations vs. time for the three mortar mixtures in the FLAIR study by Bentz (2005). Error bars on lower curve indicate range of values for the two Mixture 1 specimens (control).

6 FUTURE RESEARCH

The mitigation of autogenous shrinkage cracks by saturated, surface dry LWA is well documented. The potential of saturating the LWA with solutions of admixtures that otherwise would have interfered with the initial setting and hardening has however not yet been fully exploited. The obvious test would be to saturate LWA with a solution of a shrinkage reducing admixture (SRA) to see if this would give something extra over saturation with plain water.

Other materials that have been very limited investigated are derivatives of wood; from wood powder, through cellulose fibres to cellulose derivatives. With the potential supplier of Borregaard it is recommended that these materials are studied within COIN.

7 CONCLUSION

The literature on mitigation of autogenous shrinkage cracking by internal curing (i.e. internal supply of water NOT belonging to the mix water) of concrete has been reviewed.

The use of saturated, surface dry (SSD) lightweight aggregate (LWA) is extensively investigated and proven to work as internal curing agent relieving stresses in concrete. It is now also used in practice in USA to combat shrinkage cracking in pavement and slabs.

There seems to be a size effect, so SSD LWA as internal curing agent function better in practice with large objects than in laboratory investigations on small specimens.

However, the potential of saturating the LWA with solutions of admixtures (e.g. shrinkage reducing admixture) that otherwise would interfere with the initial setting and hardening has not yet been fully exploited and is recommended for pursuit in COIN.

Very limited investigations have been performed on water saturated derivatives of wood; from wood powder, through cellulose fibres to cellulose derivatives, as agents for internal curing. Such materials are also recommended for studies within COIN.

8 REFERENCES

Baroghel-Bouny V. “Texture and Moist Properties of Ordinary and High-Performance Cementitious Materials”, Proceedings of Séminaire RILEM “Betón: du Matérial à la Structure”, 11-12 sept. 1996, Arles, France

Batey, K. and Mohr, B.: “Internal curing water movement in high performance cement based materials”, Slides hand-out at the ACI Fall Concention 2007, October 15, 2007, San Juan, Puerto Rico, 13 slides.

Bentz, D.P.: “Capitalizing on Self-desiccation for Autogenous Distribution of Chemical Admixtures”, Proceedings of the 4th International Seminar on Self-Desiccation and Its Importance in Concrete Technology, NIST, Gaithersburg, MD, 2005, 8 pp.

Bentz, D.P.: “A review of early-age properties of cement-based materials”, Proceedings of the 12th International Congress on the Chemistry of Cement, July 8 - 13, 2007, Montreal, Canada Paper 501 at session WPL-1, 23 pp.

Bentz, D.P.: “Internal curing of high-performance blended cement mortars”, ACI Materials Journal, Vol. 104, No. 4, July-August 2007, pp. 408-414.

Bentz, D.P. and Jensen, O.M.: “Mitigation strategies for autogeneous shrinkage cracking”, Cement and Concrete Coposites, Vol. 26, 2004, pp. 677-685.

Bentz, D.P. and Snyder, K.A.: “Protected paste volume in concrete: Extension to internal curing using saturated lightweight fine aggregates”, Cement and Concrete Research, Vol. 29, 1999, pp. 1863-1867.

Bentz, D.P., Lura, P. and Roberts, J.W.: “Mixture proportioning for internal curing”, Concrete International, Vol. 27, No. 2, 2005, pp. 35-40

Bentz, D.P, Halleck, P.M., Grader, A.S. and Roberts, J.W.: “Direct observation of water movement during internal curing using X-ray micro-tomography, Concrete International, Vol. 28, No. 10, 2006, pp. 61-67

Berke**,** N.S. and Li, L.: “Effectiveness of Shrinkage Reducing Admixtures in Reducing Total Shrinkage”, Proceedings of the International Conference on Advances in Cement and Concrete, Engineering Conferences International (ECI), Copper Mountain, Colorado, USA, August 10-14, 2003, pp. 101-109.

Bjøntegaard, Ø., Thermal dilation and autogenous deformation as driving forces to self-induced stresses in high performance concrete. Dr.ing. theses 1999:121, the Norwegian University of Science and Technology, Trondheim 1999.

van Breugel, K. and Lura, P.: “Effect of initial moisture content and particle size distribution of lightweight aggregates on autogenous deformation, in: S. Helland, I. Holand, S. Smeplass (Eds.), Proceedings of the 2nd International Symposium on Structural Lightweight Concrete, Kristiansand, Norway, 2000, pp. 453-462

Charron, J.-P., Marchand, J., and Bissonette, B.: "Early-Age Deformations of Hydrating Cement Systems: Comparison of Linear and Volumetric Shrinkage Measurements", Proceedings of RILEM International Conference on Early Age Cracking in Cementitious Systems (EAC'01), Haifa, Israel, March 12-14, 2001, pp. 245-257.

Copeland, L.E. and Hayes, J.C.: "The determination of non-evaporable water in hardened Portland cement paste", ASTM Bulletin No. 194, Dec. 1953, pp. 70-74.

Cusson, D.: "Effect of blended cements on the effectiveness of internal curing of high performance concrete", Slides hand-out at the ACI Fall Concention 2007, October 15, 2007, San Juan, Puerto Rico, 11 slides.

Cusson, D., and Hoogeveen, T.: "Internally-cured high-performance concrete under restrained shrinkage and creep", in CONCREEP 7 Workshop on Creep, Shrinkage, and Durability of Concrete and Concrete Structures, Nantes, France, 2005, pp. 579-584.

Durán-Herrera, A., Petrov, N., Olivier, B., Khayat, K. and Aïtcin, P.-C.: "Autogenous elimination of autogenous shrinkage", Hand-out at the ACI Fall Concention 2007, October 15, 2007, San Juan, Puerto Rico, 1 page.

Geiker, M.: "Studies of Portland cement hydration. Measurements of chemical shrinkage and systematic evaluation hydration curves by means of dispersion model", Ph.D. Thesis, Technical University of Denmark, 1983.

Geiker, M.R., D.P. Bentz, D.P and Jensen, O.M.: "Mitigating autogenous shrinkage by internal curing, in: J.P. Ries, T.A. Holm (Eds.), ACI SP-218, High Performance Structural Lightweight Concrete, American Concrete Institute, Farmington Hills, MI, 2004, pp. 143-154

Hammer, T.A. "High Strength LWA Concrete with Silica Fume – Effect of Water Content in the LWA on the Mechanical Properties", Proceedings of the Fourth International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolana in Concrete, Istanbul, Turkey, 1992, Supplementary papers, pp. 313-328.

Hammer, T.A., "Test Method for Linear Measurements of Autogenous Shrinkage before setting", Autogenous Shrinkage of Concrete: Proceedings of the Int. Workshop, organised by the JCI, Hiroshima, June 13-14, 1998 / Ed. by Ei-ichi Tazawa, © 1999 E & FN Spon, ISBN 0-419-23890-5, pp. 143-154.

Hammer, T.A.: "The Relationship between Settlement and Plastic Shrinkage of High Strength Concrete", Proceedings of RILEM International Conference on Early Age Cracking in Cementitious Systems (EAC'01), Haifa, Israel, March 12-14, 2001, pp. 89-102.

Hammer T.A., Bjøntegaard Ø. and Sellevold E.J.: "Internal Curing - Role of Absorbed Water in Aggregates". ACI Special Publication SP-218: High Performance Structural Lightweight Concrete, Ed. J.P. Ries and T. Holm, 2004, pp. 131-142

Hoff, G.C.: "The use of lightweight fines for the internal curing of concrete", Report prepared for Northeast Solite Corporation, 13204 Hawthorne Avenue, Richmond, VA 2322, August 20th, 2002, 44 pp.

Jensen, O.M.: "Autogenous Deformation and RH change – Self-desiccation and Self-desiccation Shrinkage" (in Danish), PhD thesis, Building Materials Laboratory, The Technical University of Denmark, Lyngby, Denmark, 1993, TR 284/93.
Jensen, O.M.: "HETEK - Control of early age cracking in concrete - Phase 2: Shrinkage of mortar and concrete", Danish Road Directorate, Report No. 110, 1997.

Jensen, O.M. and Hansen, P.F.: " Autogenous Deformation and Change of the Relative Humidity in Silica Fume Modified Cement Pastes", ACI Materials Journal, Vol. 93 (6) 1996, pp. 539-543.

Jensen, O.M. and Hansen, P.F: "Water-entrained cement-based materials: I. Principle and theoretical background", Cement and Concrete Research, Vol. 31, 2001, pp. 674-54.

Jensen, O.M. and Hansen, P.F: "Water-entrained cement-based materials: II. Experimental observations", Cement and Concrete Research, Vol. 32, No. 6, 2002, pp. 973-978

Jensen, O.M. and Lura, P.: "Techniques for Internal Curing of Concrete", Proceedings of the International Conference on Advances in Cement and Concrete, Engineering Conferences International (ECI), Copper Mountain, Colorado, USA, August 10-14, 2003, pp. 67-78.

Jensen, O.M. and Lura, P.: "Techniques and materials for internal water curing of concrete", Materials and structures, Vol. 39, 2006, pp. 817-825.

Jiang, Z., Sun, Z. and Wang, P.: "Autogenous Relative Humidity Change and Autogeneous Shrinkage of High-performance Pastes", Cement and Concrete Research, Vol. 35 (2005), pp. 1539-1545.

Justnes, H.: "Autogenous Shrinkage of Cementitious Paste – State-of-the-Art", Proceedings of the Seventh CANMET/ACI International Conference on Recent Advances in Concrete Technology (Ed. V. Mohan Malhotra), Las Vegas, USA, May 26-29, 2004, CANMET/ACI SP-222-14, pp. 199-213.

Justnes, H. and Kjellsen, K.O.: "Bulk Structure of CSH from C_3S/Alite Hydration as a Function of Time", Extended Abstracts from the Cement and Concrete Science Seminar organized by The Institute of Materials, Minerals and Mining, Dept. Civil Engineering and Materials, University of Leeds, Leeds, UK, 8-9th September 2003, 4 pp.

Justnes, H., Reyniers, B., Van Loo, D., and Sellevold, E.J.: "An Evaluation of Methods for Measuring Chemical Shrinkage of Cementitious Paste", Nordic Concrete Research, Publication No. 14, 1994, pp. 45-61.

Justnes, H., Van Gemert, A., Verboven, A., and Sellevold, E.J.: "Total and External Chemical Shrinkage of Low W/C-ratio Cement Pastes", Advances in Cement Research, Vol. 8, No. 31, 1996, pp. 121-126.

Justnes, H., Sellevold, E.J., Reyniers, B., Van Loo, D, Van Gemert, A., Verboven, F., and Van Gemert, D.: "The Influence of Cement Characteristics on Chemical Shrinkage", Proceedings of International Workshop on Autogenous Shrinkage of Concrete, Hiroshima, Japan, June 13-14, 1998a, pp. 67-76.

Justnes, H., Ardoullie, B., Hendrix, E., Sellevold, E.J., and Van Gemert, D.: “The Chemical Shrinkage of Pozzolanic Reaction Products”, Proceedings of the 6th International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolana in Concrete, Bangkok, Thailand, May 31-June 5, 1998b, ACI SP 179-11, pp. 191-205.

Justnes, H., Sellevold, E.J., Reyniers, B., Van Loo, D., Van Gemert, A., Verboven, F., and Van Gemert, D.: “Chemical Shrinkage of Cementitious Pastes with Mineral Additives”, Proceedings of Second International Research Seminar on Self-desiccation and its Importance in Concrete Technology, Lund, Sweden, June 18, 1999, pp. 73-84.

Justnes, H., Clemmens, F., Depuydt, P., Van Gemert, D., and Sellevold, E.J.: “Correlating the Deviation Point Between External and Total Chemical Shrinkage with Setting Time and Other Characteristics of Hydrating Cement Pastes”, RILEM proceedings Pro17; Shrinkage of concrete, International RILEM workshop Shrinkage 2000, 16-17 October, 2000a, Paris, France, 17 pp.

Justnes, H., Sellevold, E.J. and Lundevall, G.; "High Strength Concrete Binders. Part A: Reactivity and Composition of Cement Pastes with and without Condensed Silica Fume." 4th International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolana in Concrete, Istanbul, May 3-8, 1992, CANMET/ACI SP 132-47 (Volume 2) pp. 873-889.

Justnes, H., Sellevold, E.J., Van Gemert, D., Van Gemert, A., and Verboven, F.: “Influence of Plasticizers and Super-plasticizers on Chemical Shrinkage of Cement”, Proceedings of the Sixth International Conference on Superplasticizers and Other Chemical Admixtures in Concrete, Nice, France, 11-13 October, 2000b, CANMET/ ACI SP-195, pp. 601-614.

Justnes, H., Sellevold, E.J., Reyniers, B., Van Loo, D., Van Gemert, A., Verboven, F., and Van Gemert, D.: “Chemical Shrinkage of Cement Pastes with Plasticizing Admixtures”, Nordic Concrete Research, Publication No. 24, 1/2000c, pp. 39 – 54.

Koenders, E.A.B. and de Rooij, M.R.: “Moisture Flow by Microstructural Contraction”, Proceedings of the International Conference on Advances in Cement and Concrete, Engineering Conferences International (ECI), Copper Mountain, Colorado, USA, August 10-14, 2003, pp. 79-88.

Kompen, R.: “High Performance Concrete: Field Observations of Cracking Tendency at Early age, RILEM International Symp. on Thermal Cracking in Concrete at Early Ages”, Munich, October 10-12th, 1994, pp. 449-456.

Kovler, K. and Jensen, O.M.: “Novel Technologies of Concrete Curing”, Concrete International, Vol. 27, No. 9, 2005, pp. 39-42.

Liu, L.F., Wang, P.M. and Yang, X.J: “Effects of hydroxyethyl methylcellulose on the shrinkage cracking of cement mortars”, Proceedings of the 12th International Congress on the Chemistry of Cement, July 8 - 13, 2007, Montreal, Canada, Paper 25 at session TH6-08.5, 9 pp.

Lura, P.: “Autogenous deformation and internal curing of concrete”, Ph.D. Thesis, Technical University of Delft, Delft, The Netherlands, 2003

Lura, P., Jensen, O.M., and van Breugel, K.: “Autogenous Shrinkage in High-Performance Cement Paste: An Evaluation of Basic Mechanisms”, Cement and Concrete Research, Vol. 33 (2003) pp. 223-232.

Mitani, H., Bournazel, J.P., and Rafaï, N.: “Autogenous Shrinkage – from Experiments to the Understanding of Physical Origin”, Proceedings of Concreep-6@MIT Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-Brittle Materials, Edited by F.-J. Ulm, Z.P. Bažant, and F.H. Wittmann, 20-22 August, 2001, Cambridge, USA

Mohr, B., Premenko, L., Nanko, H. and Kurtis, K.E.: “Examination of wood derived powders and fibers for internal curing of cement-based materials”, in: B. Persson, D. Bentz, L.-O. Nilsson (Eds.), Proceedings of the 4th International Seminar on Self-Desiccation and Its Importance in Concrete Technology, NIST, Gaithersburg, MD, 2005, pp. 229-244

Page, C.L. and Vennesland, Ø.: “Pore Solution Composition and Chloride Binding Capacity of Silica-fume Pastes”, Materilas and Structures, Vol. 16, No. 91, 1983, pp. 19-25.

Philleo, R.E: ” Concrete science and reality”, in: J. Skalny, S. Mindess (Eds.), Materials Science of Concrete II, American Ceramic Society, Westerville, OH, 1991, pp. 1-8

Powers, T.C and Brownyard, T.L.: Studies of the physical properties of hardened Portland cement paste. Bulletin 22, Research Laboratories of the Portland Cement Association, Chicago, 1948.

Radochea, A.: “A Study on the Mechanism of Plastic Shrinkage of Cement Based Materials”, PhD Thesis, Chalmers Technical University, Gothenburg, Sweden, 1992.

Relling, R.H. (1999) Coastal Concrete Bridges: Moisture State, Chloride Permeability and Aging Effects. Doctoral thesis 1999: 74, NTNU, Department of Structural Engineering, Trondheim, Norway.

RILEM Technical Committee 181-EAS: “Early Age Shrinkage Induced Stresses and Cracking in Cementitious Systems”, Edited by A. Bentur, RILEM Report 25, 2003, 337 pp.

Sellevold, E.J.: “Resistivity and Humidity Measurements of Repaired and Non-Repaired Areas in Gimsøystraumen Bridge”, Proceedings of the International Conference "Repair of Concrete Structures - From Theory to Practice in a Marine Environment", Svolvær, Norway, 28-30 May, 1997.

Sellevold, E. J. and Justnes, H.; "High-Strength Concrete Binders. Part B: Non-evaporable Water, Self-desiccation and Porosity of Cement Pastes with and without Condensed Silica Fume." 4th International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolana in Concrete, Istanbul, May 3-8, 1992, CANMET/ACI SP 132-48 (Volume 2) pp. 891-902.

Sellevold, E.J., Bjøntegaard, Ø., Justnes, H., and Dahl, P.A.: “High Performance Concrete: Early Volume Change and Cracking Tendency”, RILEM International Symposium on Thermal Cracking in Concrete at Early Ages, Munich, October 10-12th, 1994, pp. 229-236.

Smeplass, S.: “LettKon, report 4.4 Drying of LWAC”. SINTEF report STF22 A98782, Trondheim, Norway 1998 (in Norwegian).

Takada, K., van Breugel, K., Koenders, E.A.B. and Kaptijn, N.: “Experimental evaluation of autogenous shrinkage of light weight aggregate concrete”, Autogenous Shrinkage of Concrete: Proceedings of the Int. Workshop, organised by the JCI, Hiroshima, June 13-14, 1998 / Ed. by Ei-ichi Tazawa, © 1999 E & FN Spon, ISBN 0-419-23890-5, pp. 221-232.

Tazawa E. and Miyazawa S.: "Effect of Constituents and Curing Conditions on Autogenous Shrinkage of concrete", Autogenous Shrinkage of Concrete: Proceedings of the Int. Workshop, organised by the JCI, Hiroshima, June 13-14, 1998 / Ed. by Ei-ichi Tazawa, © 1999 E & FN Spon, ISBN 0-419-23890-5.

Thomas, J.J. and Jennings, H. M.: “Chemical Aging and The Colloidal Structure of the CSH gel: Implications for Creep and Shrinkage”, Proceedings of Concreep-6@MIT Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-Brittle Materials, Edited by F.-J. Ulm, Z.P. Bažant, and F.H. Wittmann, 20-22 August, 2001, Cambridge, USA.

Toma G., Pigeon M., Marchand J., Bissonnette B. and Barcelo L., “Early Age Restrained Shrinkage: Stress Build Up and Relaxation”, International research seminar: “Self-desiccation and Its Importance in Concrete Technology”, Lund, Sweden, June 18th, 1999, pp. 61-71

Villareal, V.: “Internal curing - Real world ready mix production and applications - A practical approach to Light weight modified concrete”, Slides hand-out at the ACI Fall Concention 2007, October 15, 2007, San Juan, Puerto Rico, 70 slides.

Villareal, V. and Crocker, D.: “Building better pavements through internal Hydration”, Concrete International, Vol. 29, February 2007

Weber, S. and Reinhardt, H.W.: “A blend of aggregates to support curing of concrete”, in: I. Holand, T.A. Hammer, P. Fluge (Eds.), Proceedings of the International Symposium on Structural Lightweight Aggregate Concrete, Sandefjord, Norway, 1995, pp. 662-671

Wittmann, F.H.: “Mechanisms and Mechanics of Shrinkage”, Proceedings of Concreep-6@MIT Creep, Shrinkage and Durability Mechanics of Concrete and other Quasi-Brittle Materials, Edited by F.-J. Ulm, Z.P. Bažant, and F.H. Wittmann, 20-22 August, 2001, Cambridge, USA

Zhutovsky, S., Kovler, K. and Bentur, A., “Efficiency of aggregates for internal curing of high strength concrete to eliminate autogenous shrinkage”, Proceedings of RILEM International Conference on Early Age Cracking in Cementitious Systems (EAC’01), Haifa, Israel, March 12-14, 2001, pp. 365-374. RILEM Publication “Early Age Cracking in Cementitious Systems”, Eds. K. Kovler and A. Bentur, 2001.