Autogenous Shrinkage of HPC and Ways to Mitigate it

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Abstract. Autogenous shrinkage strains may cause cracking of brittle cement-based systems. The lower the water/cement ratio of a mixture, the higher the autogenous shrinkage and the higher the probability of cracking. Cracking increases the probability of ingress of aggressive substances into the concrete, jeopardizing the durability of the material. Low water/cement ratios, however, result in a dense microstructure, which is one of the desired features of high performance concrete because of the assumed increase in durability. This results in a kind of dilemma: the high density of low water/cement ratio concretes is desired, but the increased risk of (micro)cracking of these mixtures, of course, not. This dilemma is discussed in this contribution. The search for ways to get out of this dilemma starts with understanding the mechanisms of autogenous shrinkage. It is shown that autogenous shrinkage is not only an issue in low water/cement ratio mixtures. In normal strength concretes, with w/c ratios between 0.40 – 0.50, autogenous shrinkage can make out a substantial part of the total strain. Ways to mitigate autogenous shrinkage of mixtures with water/binder ratios ranging from 0.18 to 0.50 are discussed. Finally brief comments are made on autogenous shrinkage values prescribed in current design codes.

Concrete as a System

“A material does not perform” was the provocative statement of A.M. Vaysburd in a discussion at the 2nd International Symposium on Advances in Concrete through Science and Engineering in Quebec in 2006. If this were true – and, in a way, it is! – the terms high performance, ultra-high performance or low performance become meaningless. What is meant is, at least, that a material only performs *in a structure*. One of the most simple structures is a standardized test specimen, for example a cube or cylinder for a compressive test. We know that even small deviations from the standard test protocol affect the outcome of a compressive test. How the structure, i.e. the cube or cylinder, perform under an applied load depends on the geometrical soundness of the test specimen, the stiffness of the test device and the loading rate, to mention only a few test parameters. What we *want* to get from a simple compressive test is the strength of concrete in Newton/mm². What we in fact *get* from this test is the response of a highly *heterogeneous system* loaded in uniaxially direction. The failure load divided by the cross section of the specimen is defined as the compressive strength of the concrete. This, in essence, virtual axial stress deviates a lot from the actual stresses in this heterogeneous system. This already holds for a very simple ‘structure’, like a cube or cylinder under a well-defined load. In a real structure, where the concrete can be loaded bi- or tri-axially, the actual stresses in the system may deviate even more from the calculated nominal stresses.

There are more reasons for a discrepancy between the calculated virtual stresses and the actual stresses in the heterogeneous system subjected to an external load. Before any external load is applied the concrete is already full of internal stresses. The cement paste shrinks due to hydration-induced chemical shrinkage and autogenous shrinkage. Autogenous shrinkage strains are larger for mixtures made with a low water/cement

ratio (w/c). Larger shrinkage will lead to a higher risk of microcracking. These microcracks are known to jeopardize the durability of concrete. High performance concrete, desired for its high density and resistance against aggressive agents, loses much of its advantages because of its proneness to microcracking. Obviously the performance of concrete is neither defined exhaustively by its density nor by any other single mixture parameter.

For a definition of high performance concrete Hoff [1] quotes the US High Performance Concrete Committee: “HPC is a concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using only conventional constituents and normal mixing, placing and curing practices. These requirements may involve long-term mechanical properties, early-age strength, toughness, volume stability and long-life in severe conditions. Basic objectives in introducing HPC are corrosion protection, to resist deterioration of the material (durability), providing high strength or early strength and reduction of materials use” [1]. Indeed, conventional constituents *alone* are inadequate for producing HPC. Additional or alternative components have to be used for achieving performance *beyond* what we are used to get with conventional constituents only. Protection against corrosion and resistance against deterioration require dense concrete. A straightforward way to increase the density is reducing the water/binder ratio (w/b). However, as mentioned already, a low w/b will make the material prone to (micro) cracking. If we want to get rid of the proneness to cracking we have to look deeper into the microstructure of concrete. A ‘systems approach’ is considered the most promising way to understand the autogenous shrinkage and can provide us with ideas to solve the problem or mitigate its consequences [2].

Autogenous Shrinkage on the Agenda.

In the early eighties of the past century much research projects on early-age concrete had started. In those days thermal cracking was the main issue, while autogenous shrinkage was hardly mentioned yet. Thermal cracking was also the main topic of the RILEM committee TC 119 on Avoidance of Thermal Cracking at Early Ages [3]. The activities of that committee ended with an international symposium in Munich. In the proceedings of that symposium autogenous shrinkage was still hardly mentioned. Only the paper of Tazawa et al [4] was entirely devoted to autogenous shrinkage. Autogenous shrinkage was seen as an upcoming issue. He stated: “Recently, a large amount of autogenous shrinkage of concrete is reported for a certain type of concrete and evaluation of the new factor with respect to thermal cracking problem is considered to be one of the most urgent subjects”. Since then numerous studies on autogenous shrinkage have been carried out and many papers were published. The increasing use of high strength concretes, made with a low w/c, have certainly stimulated the interest in this topic. On top of that new experimental techniques and the availability of increased computation power needed to deal with complex non-linear phenomena have further contributed to the interest in autogenous shrinkage. In 1999 the proceedings of an international workshop on autogenous shrinkage in Hiroshima in 1998 was published [5]. In the late nineties two seminars on “Self-Desiccation and its Importance in Concrete Technology” were held in Lund, both dealing with autogenous deformations in concrete [6,7]. Autogenous shrinkage was a big topic during the international RILEM conference on early-age cracking in cementitious systems EAC’01 in Haifa in 2001 [8]. ACI Special publication SP-220, 2004, was completely devoted to autogenous deformation of concrete [9]. Besides these special events many conference on HPC, UHPC and creep and shrinkage in the past two decades illustrate an increasing attention for autogenous shrinkage.

It’s clear: autogenous shrinkage is on the map as a most challenging subject. First of all because of its practical relevance, i.e. its importance in view of durability of concrete structures. Secondly because of its complexity. Autogenous deformations occur in a hardening system that gradually gains strength and stiffness while generating stresses. This high complexity is a real challenge for scientists and modellers, who try to develop quantitative models for predicting stresses and risk of cracking in hardening cement-based systems.

Autogenous Shrinkage in Low Water-to-Cement Ratio Concretes

Concrete is a porous material of which the pores are filled with water in whole or in part. The material can dry out due to loss of water to the environment (drying shrinkage) or consumption of water by the hydration process (self-desiccation). The water will accumulate in the narrow pores. With progress of the hydration process the relative humidity in the system further decreases. In low w/b concretes the relative humidity can drop to 75% [10]. This drop in relative humidity is accompanied by capillary tension in the pore water. The tensile stresses are equilibrated by the compressive stresses in the solid skeleton of hydration products [11,12]. The compressive stresses in the skeleton are accompanied by deformations of the skeleton. These deformations may consist of an elastic and time-dependent part [13,14,15]. Shrinkage measurements on sealed specimen have revealed that shrinkage proceeds over a very long time, until long after cessation of the hydration process. Setter [16] observed shrinkage deformations until three years after casting. Similar observations have been reported by Davis in 1940 already [17].

The lower the initial w/c of the mixture the more pronounced autogenous shrinkage will be. For mixtures made with Portland cement Baroughel-Bouny observed that, for a given cement and at a given age, the magnitude of autogenous shrinkage increased linearly with decreasing w/c [18]. This correlation was found for mixtures with w/c ranging from 0.2 to 0.6. Substantial autogenous shrinkage in mixtures with w/c higher than 0.4 was also found by Van Cappellen [19] and Mors [20]. In mixtures with w/c 0.50 autogenous shrinkage strains up to 170 $\mu\text{m/m}$ after 90 days were measured. This data indicates that autogenous shrinkage is not only an issue in HPC and UHPC, but can be an issue in currently used normal strength mixtures as well.

The fact that not only the w/c determines the magnitude of the autogenous shrinkage, but also the type cement, complicates the interpretation of autogenous shrinkage tests. In case of a combination of autogenous and drying shrinkage, the effect of the type of cement on the resulting deformations further complicates the interpretation of test results. In massive concrete structures, where drying shrinkage only gradually affects the overall shrinkage of the concrete, shrinkage strains are dominated by the joint effect of autogenous shrinkage caused by self-desiccation and other additional cement-type related deformations.

The fact that autogenous deformations are the net result of both shrinkage and swelling mechanisms complicate (numerical) modelling of this phenomenon [21]. This is true indeed, but modelling of the mutual interaction between shrinkage and swelling mechanisms is considered the only promising way to unravel this complex deformational behaviour of hardening cementitious systems.

Mechanisms of Autogenous Deformations

Autogenous Shrinkage. Many experimental studies have shown a strong correlation between autogenous shrinkage and the drop relative humidity in the pore system of the material. This correlation has been studied intensively by Powers in the sixties of the past century [11]. He discussed three main mechanisms triggered by changes in the relative humidity, viz. changes in the surface tension of the solid gel particles, disjoining pressure and hydrostatic tension. Powers' work is still relevant and a source of inspiration for both experimentalists and modellers of autogenous shrinkage. The main characteristics of these three mechanisms are briefly presented in the following.

Changes in surface tension. Due to the presence of surface tension γ_s a solid colloidal particle with radius r will experience a compressive stress P :

$$P = \frac{2 \gamma_s}{r} \quad [\text{MPa}] \quad (1)$$

For tobermorite particles values for the surface tension have been mentioned between 0.38 to 0.45 N/m [22], whereas for gel particles in general a value of 1.35 N/m has been proposed [23]. With $\gamma_s = 1.35$ N/m the compressive stresses in gel particles with a radius of 100 to 1000 Å would be 270 to 27 MPa.

Adsorption of a water layer changes the surface tension in the solid particle by an amount $\Delta\gamma$. According to Gibbs [24] the change in surface tension $\Delta\gamma$ is related to the change in vapour pressure h . For a change in relative vapour pressure from h_1 to h_2 , the Gibbs equation gives:

$$\Delta\gamma = RT \int_{h_1}^{h_2} \frac{w_a}{V_s} d \ln h \quad (2)$$

where R is the universal gas constant, T the temperature in [K], w_a the amount of water adsorbed at the solid particles, V_s the volume to the adsorbent and h the relative vapour pressure. Based on this principle Powers derived for the volume change in a solid particle the following equation

$$\frac{\Delta V}{V} = \frac{2}{3} K \frac{RT}{M} \int_{h_1}^{h_2} \frac{w_a}{V_s} d \ln h \quad (3)$$

where K is compressibility coefficient of the solid particle, M the molecular weight of the adsorbate, i.e. the water.

Volume changes caused by changes of surface tension of the solid particles as result of changes of the RH cannot explain the volume changes observed over the full RH-range from 0 to 100% [25]. Measured volume changes are found 15 to 200 times the expansion roughly calculated on the basis of changes in surface tension of spherical solid particles. The discrepancy between the predictions based on volume changes of individual particles and deformations of a microstructure originates from several factors. A major assumption concerns the shape of the particles. Hydration product may appear as foil-like particles of variable thickness, which may exhibit significant shape changes, causing much higher macro-level strains than can be explained by the change in surface tension of sphere-shaped particles. Moreover, the role of adsorbed water layers is not described exhaustively when we restrict ourselves to changes in the surface tension of the solid particles. Wittmann emphasised that the correlation between volume changes, i.e. length changes, and the changes of the surface tension is of a semi-phenomenological type [26]. For this correlation Bangham has proposed the empirical equation [27]:

$$\frac{\Delta L}{L} = \lambda \Delta\gamma \quad (4)$$

For the proportionality factor λ Hiller [27] proposed:

$$\lambda = \frac{\Sigma \rho}{3 E} \quad (5)$$

with Σ the internal surface area of the material, ρ the specific mass and E the modulus of elasticity of the material.

Disjoining pressure. A second mechanism that has been proposed to account for autogenous shrinkage is disjoining pressure. This disjoining pressure is active in areas of hindered adsorption between gel particles and could also be called load-bearing water. For the change in disjoining pressure ΔP_d when the humidity drops to $h < h_0$ it holds:

$$\Delta P_d = \frac{R T}{M v_w} \ln h \quad (6)$$

with v_w the specific volume of the adsorbed water. For the volume changes caused by disjoining pressure if the relative vapour pressure drops from a maximum value $h_0 = 1$ to h , Powers proposed the equation:

$$\left(\frac{\Delta V}{V} \right)_d = \beta f(w_a) \frac{R T}{M v_w} \ln h \quad (7)$$

in which β is the compressibility coefficient of the specimen, $f(w_a)$ the fraction of internal surface area over which the disjoining pressure is acting and is considered a function of the adsorbed water content w_a . By assuming that the simple relationship $f(w_a) = k(w_a/V_s)$ would hold, where k is a proportionality constant depending on the internal geometry of the system, equation (7) can be combined with equation (3). For the humidity range from 0 to h the volume change can then be represented with the equation:

$$\frac{\Delta V}{V} = \lambda \int_0^h \frac{w_a}{V_s} d \ln h \quad (8)$$

with:

$$\lambda = \left(\frac{2}{3} K + \frac{k \beta}{v_w} \right) \frac{R T}{M} \quad (9)$$

Powers remarks that equation (8) is identical with the empirical relationship proposed by Bangham for the relationship between expansion of colloid materials and the relative humidity. He further emphasized that ‘the volume change is not due directly to changes in the surface energy of the solid phase, but to the circumstance that the effective area for disjoining pressure is proportional to the total amount of adsorbed water in the system. The observed linearity is, therefore, due to an *internal geometry* that accounts for the proportionality between $f(w_a)$ and w_a ’. He further postulated that it would be quite possible that in cement gel the volume change due to change in surface tension is only of minor importance, even at low humidity where the surface tension effect would be relatively large. From the foregoing citation it can be inferred that Powers assumed the internal geometry of the system to be a factor for understanding autogenous shrinkage. Hence, it seems important to have a good description of the geometrical features of the microstructure if quantitative modelling of autogenous shrinkage is our goal.

Hydrostatic tension in capillary water. For the volume changes caused by the third mechanism, i.e. hydrostatic tension in the capillary water, Powers proposed the following equation:

$$\frac{\Delta V}{V} = \beta \left(\frac{R T}{M v_w} \ln h \right) \quad (10)$$

where β is again the compressibility coefficient of the specimen. This equation is similar to equation (8) derived for quantification of the volume changes caused by the combined effect of changes in surface tension and disjoining pressure.

Evaluation in view of quantitative modelling of autogenous shrinkage. According to Wittmann [29] and Setzer [30] volume changes in the range of relative humidity up to 50% could be attributed to changes in the surface tension of the solid according to the Bangham equation. For $RH > 50\%$ the disjoining pressure would

be the dominant mechanism. According to Hua et al. [15] capillary depression is the main cause of volume changes in the high relative humidity region, say from RH = 70% up to saturation. Hua further states that creep contributes significantly to the volume and length changes caused by self-desiccation in hardening pastes.

The fact that equations of similar shape are proposed for quantifying volume changes over the whole range of relative humidity is of great interest in view of numerical modelling of volume changes in hardening cement-based systems. With the Gibbs equation (2), equation (8) and (9) can be rewritten as:

$$\frac{\Delta V}{V} = \lambda^* \Delta \gamma \quad (11)$$

with:

$$\lambda^* = \left(\frac{2}{3} K + \frac{k \beta}{v_w} \right) \frac{1}{M} \quad (12)$$

In the latter expression the factor k is a proportionality factor dependent of the internal geometry of the system and β a compressibility coefficient of the system as a whole. In hardening concrete these two quantities will change with progress of the hydration process, i.e. $k = k\{\alpha\}$ and $\beta = \beta\{\alpha\}$, with α the degree of hydration. Particularly the factor $k\{\alpha\}$ is of great interest, since this factor is primarily a function of the microstructure and, therefore, only a function of the degree of hydration *in so far* the latter determines the microstructure. Besides the degree of hydration, also the w/c, the particle size distribution (psd) of the cement and the curing temperature will affect the microstructures, hence $k = k\{w/c, T, \text{psd}, \alpha\}$. In equation (2) the factor w_a and h will also change with progress of the hydration process. From these observations it can be inferred that for comprehensive and realistic modelling of volume changes in hardening cement-based systems quantification of the microstructure and of the changes thereof with progress of the hydration process are a prerequisite.

Autogenous Swelling. From the engineering point of view autogenous shrinkage is a much bigger issue than autogenous swelling. If restrained, *shrinkage* may lead to *cracking* and loss of resistance against deterioration of the concrete. Restrained *swelling*, on the contrary, will result in *compressive* stresses, which can easily be resisted by the concrete. For understanding autogenous shrinkage and for correct interpretation of measured strains and deformations, however, it is of utmost importance also to know the cause and magnitude of swelling. Neglecting the contribution of swelling to deformations measured in experiments will inevitably lead to wrong interpretations of the measurements and underestimation of autogenous shrinkage.

Experimental studies on autogenous shrinkage have revealed that both the type of cement and w/c are influencing factors [31]. Expansion has been observed particularly in low w/c pastes prior to the occurrence of volume reduction [32,33,34]. Classic work of Steinour [35] showed for w/c 0.55 an expansion before final set of 0.09...2.1%. For low w/c mixtures the volume increase may reach up to 2.7 % [36]. This expansion has been attributed to the formation of ettringite [37]. However, if the formation of ettringite were the cause of expansion, a similar increase in volume should also occur in case of hydration in suspension. Suspension tests carried out by Czernin [38], however, did not reveal an increase in volume. Obviously the situation is more complicated than hoped.

In more recent work the formation of ettringite *and* large *crystals of calcium hydroxide* have been mentioned as cause of expansion [39,40]. Moreover, it has been remarked that swelling would occur predominantly in pastes with medium or high w/c and that, for a given cement, the swelling increases with increasing w/c [18]. It could be that in pastes with high w/c expansion is higher than in mixtures with low w/c because in the former autogenous shrinkage strains are not large enough to cancel out the expansion.

Also microcracking in hardening systems has been mentioned as a cause of expansion in low w/c mixtures [34]. The question is, however, what has caused the stresses that have resulted in microcracks. Cracking presupposes the existence of stress and stresses presuppose the existence of deformations. So, before cracking-induced expansion can occur, stresses and associated deformations must have been created somehow. Autogenous shrinkage could have been the cause of these tensile stresses and associated cracking.

Another reason for expansion could be the formation of reaction products under constraint conditions [32, 41]. When a cement particle dissolves many small particles are produced. The space needed to accommodate a large number of small particles is larger than the space occupied by the large particle from which the small particles are formed, the volume of all the small particles together being equal to the volume of the large particle. This 'hydration expansion' is schematically shown in Fig. 1.

Figure 1 Hydration-induced expansion mechanism

Mitigating Autogenous Shrinkage

The hydration-induced drop of relative humidity in the pore system of cement-based materials is a major reason for the occurrence of autogenous shrinkage. For concretes with w/c not less than 0.36, curing in the presence of an external source of water would be effective to prevent this drop in RH and early-age cracking [42]. Even though external water curing has shown to be effective in preventing early-age cracking, it should be born in mind that autogenous shrinkage strains may continue to develop over a long time [19,20]. These late strains cannot be prevented by water curing in the early stage of the hydration process.

For concrete mixtures with w/c < 0.36 the density of the concrete is so high that the presence of external water is unable to prevent a substantial drop of the internal RH in the concrete and early-age cracking is almost unavoidable then [43]. A straightforward way to reduce autogenous shrinkage in these low w/c mixtures is *internal curing*. Internal curing can be accomplished by adding water-saturated lightweight aggregate particles to the cement [44,45,46,47,48]. When the internal RH drops the water stored in the LWA particles is released to the drying matrix, thus maintaining the RH at a relatively high level. A similar effect can be achieved with mixed-in super absorbing polymers (SAP), a technology promoted by Jensen et al [49] and subject of the RILEM committee 225-SAP on this subject [50].

In a search for producing UHPC with rice husk ash (RHA) as an alternative for silica fume (SF), Tuan [51] found that RHA had a shrinkage mitigation effect. He compared the performance of mixtures made with SF and with RHA. The mixtures made with RHA exhibit much lower autogenous shrinkage than the mixtures made with SF. Tuan suggested that the RHA-particles had acted as internal curing agent, mitigating the autogenous shrinkage. Details of his findings will be discussed later in this contribution.

From the earlier presented formula's (1) to (12) it can be inferred that besides the relative humidity also the surface tension in the pore solution is an important parameter in autogenous shrinkage. Reducing the surface tension will result in lower capillary stresses and hence lower autogenous shrinkage. The reduction of surface

tension can be realised by adding shrinkage reducing admixtures (SRA's). There is a mitigating effect indeed of these products [52], but they can have some negative side effects as well, for example a (small) drop in compressive strength [53,54,55].

Passive internal restraint of shrinkage strains has been suggested for mitigating autogenous shrinkage by Soliman et al. [56]. Unhydrated cores of cement particles or finely ground inert powders can act as restraining components. Soliman used partially hydrated cementitious materials for this purpose. Indeed a shrinkage mitigating effect could be observed. Note that reducing autogenous shrinkage by internal restraint goes along with creating internal stresses of which the effect on the long-term properties need to be checked!

Autogenous shrinkage is different for different types of cement. Hence, a proper choice for a certain cement could be a straightforward way to mitigate shrinkage problems on the construction site. Concrete, w/c 0.35, made from composite cement with low clinker content (CEM II A-L 42.5R, 15% limestone) had a smaller autogenous shrinkage after 21 days than concrete made with OPC (CEM I, 42.5R) [57]. Concrete made with a slag cement (CEM II B-S 42.5R, 27% slag) expanded initially. However, between 1 and 10 days after mixing the shrinkage in that period was larger than in the CEM I 42.5R and the CEM II A-L 42.5R. Jensen [58] found that a high C_3A or gypsum content leads to a marked reduction of autogenous deformation of cement paste. Based on that observation he suggested that potentially the crack tendency of HPC may be reduced by increasing the C_3A or gypsum content of the cement. Jensen's observations were in contrast with those of Tazawa et al. [59]. From his experimental work Tazawa had concluded that an increase of the C_3A -content would lead to an *increase* in autogenous shrinkage. As possible reasons for the discrepancy between results of Jensen and Tazawa Jensen mentioned the way in which the C_3A -content had been determined, the way of testing and the influence of minor components in the cement. Schachinger et al [60] found that autogenous shrinkage of cement pastes made with blastfurnace cement (CEM III B 42.5 NW/HS) was smaller than that of OPC pastes (CEM I 42.5 R/HS). The w/b of the pastes ranged from 0.20 to 0.33. Schachinger also found that autogenous shrinkage was still continuing after 56 days.

Barrett et al [61] studied autogenous shrinkage of mortars made with Portland cement blended with fine ground limestone powder. Limestone percentage was 15%. w/b between 0.34 and 0.39. Fine powders are generally supposed to result in higher autogenous shrinkage because of the built-up of a finer pore structures and corresponding higher capillary forces (follows from Kelvin-Laplace equation). However, hardly any difference was found in the autogenous shrinkage of mortars made with Portland cement (OPC), Portland Limestone cements (PLC) and Portland Limestone cements blended with slag (PLC-Slag). It was noted that despite of the higher fineness of the PLC binders, the pore size distribution was similar for OPC, PLC and PLC-Slag mortars. It seems as if the type of binder is a parameter in autogenous shrinkage *in so far* it affects the pore structure of the material.

In the next sections emphasis will be on autogenous shrinkage and internal curing of HPC and UHPC. For internal curing of HPC water-saturated LWA particles were used, whereas rice husk ash is suggested as internal curing agent of UPHC.

Internally Cured HPC

Introduction. In the eighties and nineties of the past century the use of HPC was considered for several concrete bridges in The Netherlands. The prevailing Dutch design code covered concrete strength classes up to C55/65. These strengths could be produced with mixtures with w/c $\approx$ 0.4. For those mixtures autogenous shrinkage is generally considered not to be a point of concern (see also [62]). Also the codes did not require designers to consider autogenous shrinkage in their designs. Hence, designers could use the prevailing Dutch code for designing bridge in HPC - C55/65 concretes. However, the future owner of the bridges, the Ministry of Transportation, still required a check of the overall performance of the mixtures, including a check of the autogenous shrinkage.

Mixture Design of HPC. Four mixtures were tested with w/b ranging from 0.34 to 0.39. In mixture I, 60 kg limestone powder was used while the amount of cement was reduced by the same amount. In mixture IV, 25% of the coarse aggregate was replaced by water-saturated lightweight aggregate, Liapor F10. The mix compositions are given in Table 1. The autogenous shrinkage was measured on sealed specimens, 100×100×400 mm³, placed vertically. For each mixture two prisms were used.

Table 1 Mixture compositions of HPC

Component	Unit	Mixture			
		I	II	III	IV
Water	kg/m ³	133	153	156	156
CEM III/B 42.5 LH HS	kg/m ³	248	340	300	300
CEM I 52.5 R	kg/m ³	112	110	100	100
Limestone powder ¹⁾	kg/m ³	60	--	--	--
Water/cement ratio		0.37	0.34	0.39	0.39
Sand 0 – 4 mm	kg/m ³	942	860	830	830
Crushed aggregate 4–16 mm	kg/m ³	997	980	975	730
Liapor F10, 4-8 mm	kg/m ³	--	--	--	156
HR Superplast. CON 35	kg/m ³	5.0	--	--	--
Cretoplast CON 35	kg/m ³	--	1.8	--	--
Cretoplast SL01 CON 35	kg/m ³	--	7.2	--	--
Addiment BV1	kg/m ³	--	--	1.6	1.6
Addiment FM 951	kg/m ³	--	--	4.8	4.8

1) Fineness 530 m²/kg

Measured Autogenous Deformation and Evaluation. The autogenous deformations of the mixtures are presented in Fig. 2. The measurements started after 1 day. This implies that part of the autogenous deformation is not included in the measurements. The aim of the test series was, however, to quantify how autogenous deformation would affect the drying shrinkage. In the practice drying shrinkage will generally not start during the first day after casting. For the purpose of this study it was appropriate, therefore, to measure only the autogenous deformation after 1 day.

Autogenous shrinkage is highest for mixture II, the mixture with the lowest w/c and a high cement content. Unlike the mixtures I, II and III, the mixture with 25% replacement of crushed aggregate by saturated lightweight aggregate particles hardly exhibited any autogenous deformation.

Figure 2 Autogenous deformation mixture I to IV. 20°C. Measurements starting after 1 day.

The shrinkage curves of the mixtures I, II and III show that a greater part of autogenous shrinkage occurs in the first few days after mixing. But even after 28 days autogenous shrinkage still continues. From 28 to 91 days the autogenous shrinkage of the mixtures I, II and III varies from 70 to 90 $\mu\text{m}/\text{m}$. In [63] these shrinkage strains were compared with drying shrinkage measured over the same period when the prisms were exposed to drying (50% RH) after 28 days. It was concluded that autogenous shrinkage was about 30% to 50% of the observed drying shrinkage. In the prevailing Dutch design codes *autogenous* shrinkage of C55/65 concrete mixtures was not considered. Code values for *drying* shrinkage were based on experimental data from the past. Those measured strain values have always been interpreted as drying shrinkage, ignoring any possible contribution of autogenous shrinkage. In fact the drying shrinkage values have always been overestimated (see also [70]).

Test results further demonstrated that replacing 25% of the dense aggregate by water-saturated lightweight aggregate particles was sufficient to eliminate autogenous shrinkage of this paste. Obviously the internal curing of the paste with saturated lightweight aggregate particles (Liapor F10, 4-8 mm) is very effective. The effectiveness was supposed to depend on the size of the LWA-particles. The smaller the size of the particles, the more homogenous the additional water in the particles will be distributed in the hydrating paste. This hypothesis was tested and confirmed by Lura et al [64]. For LWA-mixtures, made with 100% LWA particles and w/c 0.37, he even found swelling instead of shrinkage. Tests were carried with mixtures with Liapor F8, 8-16 mm, Liapor F8, 4-8 mm, and Liapor sand, 0-4 mm. The swelling was highest for the mixture made with Liapor sand and lowest for the mixture with Liapor F8, 8-16 mm.

Rice Husk Ash: An Internal Curing Agent of UHPC?

UHPC with Rice Husk Ash (RHA). Most often UHPC is made with a very low w/c and silica fume for improving the particle packing. Silica fume, however, is an expensive component and cheaper alternatives would be welcome. Tuan [51] tried the application of finely ground rice husk ash (RHA) as alternative for silica fume. The use of RHA as replacement for cement is known for many years already [65,66]. However, its use as replacement of silica fume for production of UHPC is new and, at first sight, a bit surprising. From the chemical point of view the materials exhibit much similarity with SF. The structure of the particles, however, is completely different. Silica fume particles are spherical, whereas RHA particles are porous, have an irregular shape, generally ground to a size between 5 μm to 10 μm [67]. Hence, RHA is not an ultra-fine material like SF. Combinations of silica fume and RHA, however, were found to result in even higher strength values, beyond 200 MPa, than mixtures where either only silica fume or RHA were used as reactive filler [51].

Mix Design of UHPC with RHA. The materials used by Tuan were Portland cement (CEM I 52.5N) with a Blaine specific surface area of 4500 cm^2/g , silica sand with a mean particle size of 225 μm , condensed silica fume, rice husk ash, and polycarboxylate based superplasticizer with 30% solid content by weight. Rice husk was burnt in a drum incinerator developed by Pakistan Council of Scientific & Industrial Research [68] under uncontrolled combustion conditions. The obtained ash was ground in a vibrating ball mill for 90 min. The ash contained 88.0% amorphous SiO_2 , 3.81% loss on ignition. The mean size of the RHA particles is 5.6 μm .

For studying the effect of fineness of RHA on the autogenous shrinkage of UHPC in more detail, three other types of RHA were considered as well, with mean particle sizes of 3.6 μm , 6.3 μm and 9.0 μm . The mix compositions are shown in Table 2. The cement replacement percentages of the SF and RHA were 10% and 20% by weight of the cement.

Effect of RHA on Autogenous Shrinkage of UHPC. The autogenous shrinkage of UHPC mixtures was measured according to the ASTM C1698 standard (ASTM Standard 2009). All samples and the test device were kept in a thermostatically controlled room during the whole test. The ambient temperature was

Table 2. UHPC mixtures for autogenous shrinkage measurements (after Tuan [51])

Mix No.	Amount of cement, [kg/m ³]	w/b ratio (by weight)	Sand/binder ratio (by weight)	RHA (% by weight)	SF (% by weight)	The mean article size of RHA [μm]
REF	1140	0.18	1	0	0	--
RHA10 (5.6)	1010	0.18	1	10	0	5.6
SF10	1010	0.18	1	0	10	--
RHA20 (3.6)	885	0.18	1	20	0	3.6
RHA20 (5.6)	885	0.18	1	20	0	5.6
RHA20 (6.3)	885	0.18	1	20	0	6.3
RHA20 (9.0)	885	0.18	1	20	0	9.0
SF20	885	0.18	1	0	20	--

maintained at $(23 \pm 1)^\circ\text{C}$.

Figure 3 shows the development of autogenous shrinkage of UHPC with 0% (REF), 10% and 20% RHA(5.6). The figure shows that most of the autogenous shrinkage occurs in the first 12 hours after casting. There is a big influence, however, of the added RHA. After 12 hours the autogenous shrinkage of the mixture with 20% RHA(5.6) is significantly lower than that of the reference mixture. The autogenous shrinkage of the mixture with 10% RHA(5.6) is found between that of the reference mixture and mixture RHA20(5.6). After 14 days mixture RHA20(5.6) even showed a slight expansion. This tendency to expand is not observed for the reference mixture (REF) and the mixture with 10% RHA (RHA10(5.6)).

In Fig. 4 the effect of the mean particle size of the RHA is shown for mixtures with 20% replacement of cement by RHA. The autogenous shrinkage of mixtures RHA20(9.0) and RHA20(5.6) are almost identical. Similar to mixture RHA20(5.6) also mixture RHA20(9.0) exhibits a tendency to slightly expand in the period between 14 and 22 days. The autogenous shrinkage of the mixture with the fine ground ash, i.e. mixture RHA20(3.6), is found between the reference mixture and the two mixtures RHA20(5.6) and RHA20(9.0).

Figure 3. Autogenous shrinkage of UHPC-mixtures (Table 2). Reference (REF) and RHA-pastes with 10% and 20% replacement of cement by RHA (Tuan [51]).

Effect of SF on Autogenous Shrinkage of UHPC. In Fig. 5 the autogenous shrinkage of mixtures with 10% and 20% SF are shown, together with the autogenous shrinkage of the reference mixture. The curves show that the effect of silica fume on autogenous shrinkage is completely different from that of RHA. The difference is largest for the mixtures with coarser RHA particles (compare Fig. 4 and Fig. 5). The autogenous

Figure 4. Autogenous shrinkage of UHPC mixtures containing RHA (20%) with different mean particle sizes measured from the final setting time until 28 days (Tuan [51]).

Figure 5. Autogenous shrinkage of UHPC mixtures containing different amounts of SF measured from the final setting time until 28 days (Tuan [51]).

shrinkage of mixture SF20 is close to that of the reference mixture, whereas the mixtures with 20% RHA, i.e. RHA20(5.6) and RHA20(9.0), hardly show any net autogenous shrinkage after 12 hours.

Autogenous Shrinkage of UHPC with HRA – Evaluation. In foregoing paragraphs it has been reported that water-saturated porous Liapor sand drastically reduces the autogenous deformations of hardening low w/c mixtures. It is suggested that such an internal curing mechanism also explains why autogenous shrinkage of RHA-modified mixtures is substantially smaller compared to the reference mixture and the SF-containing mixtures. RHA particles are porous and may release absorbed water once the self-desiccation process starts. The mixtures with RHA20(5.6) and RHA20(9.0) appear to be more effective in this respect than RHA20(3.6) (see Fig. 5). This may be caused by the collapse of the porous microstructure of the RHA particles during grinding of the ash to very small particles sizes. The collapse of the microstructure reduces the amount of water that can be absorbed by the RHA particles. This hypothesis is supported by measurement of the specific surface area (BET nitrogen absorption) of the RHA particles. The data are presented in Table 3. The specific

surface area of RHA(5.6) was found to be higher than that of the finer RHA(3.6) and also higher than that of the coarser ashes. In the range of investigated ashes mixture RHA(5.6) appears to exhibit an optimal pore structure in view of internal curing and mitigation of autogenous shrinkage. A mitigating effect on RHA on autogenous shrinkage of cement has also been found by de Sensale et al. [69] in Portland cement pastes with $w/b = 0.3$.

Table 3 Properties of different types of RHA (after Tuan [51])

Property	RHA(3.6)	RHA(5.6)	RHA(6.3)	RHA(9.0)
Mean particle size [μm]	3.6	5.6	6.3	9.0
Specific surface area (BET) [m^2/g]	15.0	20.6	19.7	18.3

Autogenous Shrinkage of HPC and Design Codes

The interest for autogenous shrinkage started to increase with the increasing use of HPC and UHPC, i.e. with the use of low w/c mixtures. For decades autogenous shrinkage was not considered a serious problem as long as mixture were used with $w/c > \approx 0.4$ [62]. In design codes autogenous shrinkage was hardly considered, if at all. In experimental data on drying shrinkage of mixtures with $w/c > 0.4$, which had formed the basis for codes values for drying shrinkage, autogenous shrinkage has often been ignored. As a consequence, autogenous shrinkage was interpreted as drying shrinkage, thus overestimating drying shrinkage and underestimating autogenous shrinkage (also [70]). Recent versions for design codes do better in this respect. In the new EuroCode 2 and the Japanese code autogenous shrinkage is considered also for mixtures in strength classes $< \text{C}55/65$. Mors [71] found, however, that for mixtures with w/c 0.44 – 0.50 these codes still underestimated the autogenous shrinkage. Figure 6 shows autogenous shrinkage based on both the EuroCode 2 and the JSCE-Code, together with the measured autogenous shrinkage of normal strength concrete C28/35 and C35/45. Both the *measured* autogenous shrinkage and the curve after *correction* for small moisture loss through the sealant are presented. The autogenous shrinkage as considered by EuroCode 2 is presented for C28/35 and C35/45 mixtures, i.e. mixtures with strengths similar to the measured strength of the mixtures in view. In both cases the autogenous shrinkage according to EuroCode 2 is about 30% of the measured autogenous shrinkage. Underestimation of autogenous shrinkage by EuroCode 2 was also observed by

Figure 6 Comparison of measured autogenous shrinkage with predictions with the EuroCode 2 [73] and the Japanese Code [74] (after Mors [71]).

Darquennes et al. [72]. The predictions with the Japanese code are closer to the measured values, but still underestimate the measured autogenous shrinkage.

Most designers are aware of the presence and effects of autogenous shrinkage of HPC and UHPC. Hence, adequate measures, either technological or structural, can be taken to mitigate autogenous shrinkage or the consequences of it. Underestimating autogenous shrinkage in *normal* strength concrete mixtures can result in unexpected cracking. This is most likely in mass concrete. Substantial drying shrinkage requires a long period of drying. Most of the autogenous shrinkage strains will occur in the early phase of the concrete's lifetime. It was observed, however, that even after weeks or months autogenous shrinkage still increases. If restrained, autogenous shrinkage will result in tensile stresses and may cause cracking of the concrete. The type of cement may be decisive in this case.

Concluding remarks

In the first half of 20th century autogenous shrinkage was an issue in mass concrete used for dams. The w/c in those mixtures was generally low and, apart from thermal problems, autogenous shrinkage contributed to the risk of cracking. Since the eighties autogenous shrinkage became an issue again, but now for high strength and ultra-high strength concrete. These mixtures were also made with low w/c's, which made them prone to cracking. Recent studies confirm that self-desiccation and capillary tension in the pore water are driving forces of autogenous shrinkage.

How large the deformations caused by capillary forces are depends on the ability of the microstructure to carry, or resist, these forces. The evolution of the resistance against deformation, i.e. of the mechanical properties, is different for different types of cement and different mix compositions. Not only the chemical composition, but also the fineness of the cement and the curing temperature determine how the microstructure of the system and the associated mechanical properties develop with progress of the hydration process. On top of that, and in parallel with the shrinkage triggered by capillary forces, the *dissolution* of cement grains and the *formation of reaction products* may go along with *expansion* of the system. What is observed on the macroscale is the net result of shrinkage and expansion mechanisms. In other words, what we observe is not a material property, but the response of a complex *system* to several parallel processes. It is difficult to 'isolate' these mechanisms and to measure their contribution to the overall deformation of the system individually. To make a step forward in this respect systematic experimental research should go hand-in-hand with advanced modelling of the relevant mechanisms and their mutual interactions. Currently available microstructural models are not able to model autogenous deformations of hardening systems comprehensively yet. Still it is believed that parallel execution of experimental research and (numerical) modelling is the way to go.

In the absence, yet, of comprehensive quantitative models for autogenous shrinkage it is important that experimental and theoretical research is performed with a sound perception of the dominant mechanisms and influencing parameters. This perception is not mature yet and would certainly benefit from internationally coordinated research. The possible role of creep on long-term values of autogenous deformation is mentioned here as one of the most challenging research topics.

For the time being autogenous shrinkage is an *inconvenient truth*. It is emphasized that autogenous shrinkage is not only an issue for low w/c mixtures, but for some cements also for mixtures with w/c > 0.4. There are, fortunately, efficient ways to mitigate autogenous shrinkage. Some of these mitigating measures have been dealt with in this contribution.

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