



Autogenous deformation and RH-change in perspective

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Abstract

Autogenous deformation and change of the relative humidity (RH-change) have been described and registered for a century. However, it is only within the last decade that these phenomena have received appreciable attention. The reason for this is that autogenous deformation and autogenous RH-change are phenomena of special importance within high-strength (high-performance) concrete technology, and a significant utilisation of these concretes did not take place until the early 1980s. In the present paper an historical overview of autogenous deformation and RH-change is given. In addition, due to the present status of this research field both terminology and measuring techniques are described in detail. Finally, some expectations for future research in this field are given. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

A characteristic feature of high-strength concrete is a low porosity and a discontinuous capillary pore structure of the cement paste. This is encompassed by keeping a low water–cement ratio with the aid of superplasticisers and by adding silica fume to the mixture. From a material point of view these modern concretes generally possess some highly advantageous properties compared to traditional concrete. Examples of these include good workability in the fresh state, higher strength and improved durability. However, these types of concrete have also proved to present some problematic properties, such as autogenous deformation and change in relative humidity (RH-change).

Potentially, these properties may be used beneficially. Autogenous RH-change may improve the frost resistance and may be used to shorten the time until an impervious, moisture-sensitive covering can be applied to the concrete. Correspondingly, autogenous deformation may cause micro-cracking, which may increase the tensile strain capacity and have a stress equalising effect. Furthermore, autogenous deformation may lead to strength increase due to clamping pressure on aggregates or incorporated fibres [1]. However, these benefits are, generally, considered secondary to the

negative effect of cracking due to autogenous deformation. Microcracks due to restrained autogenous shrinkage may connect into a continuous crack pattern and form macro-cracks. Such cracks constitute a serious problem with regard to strength, durability and aesthetics.

No contemporary, international review paper exists on autogenous deformation and RH-change. A good overview of research on autogenous deformation carried out in Japan is given in a report from the Japan Concrete Institute [2]. A comprehensive state-of-the-art-report which was published in 1981 by a RILEM commission [3] is outdated.

2. Precursors through curiosity — milestones in the past

A very early description dates back to the year 1900. One of the pioneers of cement research, Le Chatelier, describes self-desiccation and commences a systematic registration of the material properties of cement paste (see Fig. 1). He states that it is fundamental to distinguish between the *absolute volume* and the *apparent volume* of a hardening cement paste [4]. With the terminology used in this paper (cf. Section 4.2) a change in the absolute volume means chemical shrinkage, and a change in apparent volume means autogenous deformation.

Early reported measurements can be found in the literature from the beginning of the 1900s. In 1927, Jesser [5] reported measurements of autogenous RH-change for

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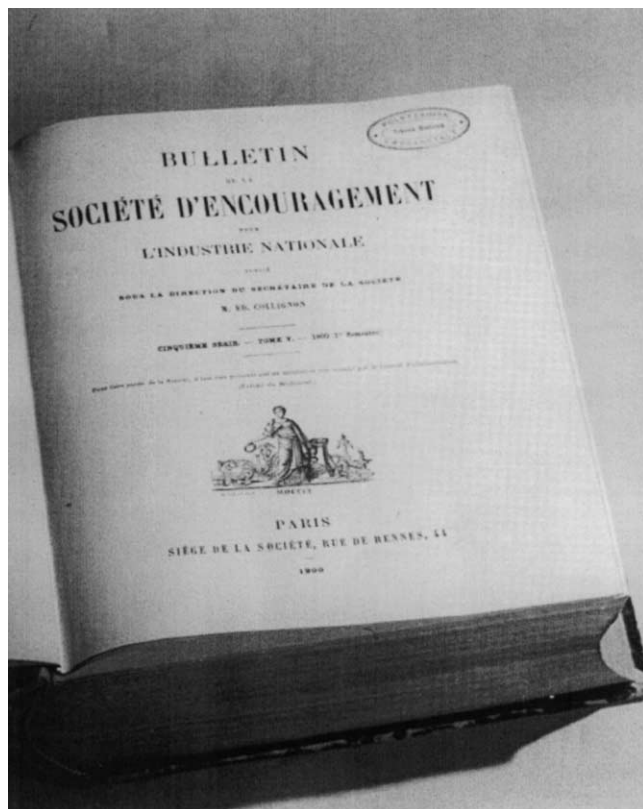


Fig. 1. In the year 1900 Le Chatelier published a paper [4] which dealt with the volume change of a hardening cement paste: *Sur les changements de volume qui accompagnent le durcissement des ciments*. Autogenous deformation is covered by the descriptions given by Le Chatelier in this paper. Since then this phenomenon has been treated regularly in the literature.

cement mortars with w/c ratios of 0.24–0.36 and noted that the internal RH may be 90% after 1 month of hardening. In 1928, Neville and Jones [6] described an apparatus for measurement of volumetric deformations of cement paste during sealed hardening at a constant temperature. In 1934, Lynam [7] was perhaps the first to define the term *autogenous shrinkage*; shrinkage which is not due to thermal causes or to loss of moisture to the air.

In 1940, Davis [8] published experimental results for autogenous deformation. He observed that the magnitude of autogenous shrinkage is in the range 50–100 μ strain after 5 years of hardening. Compared with thermal deformations and drying shrinkage this autogenous shrinkage is relatively small. For this reason little attention has been paid to autogenous deformation in both concrete practice and research for many years.

As a result of Powers' pioneering research [9] around 1940–1950, it became possible to describe and perform theoretical calculations of the phase composition of a hardening cement paste. This enabled Copeland and Bragg [10] and Powers [11] to perform a calculative analysis of self-desiccation measurements. It was realised that at sufficiently high w/c ratios self-desiccation will not take place. For pure

water–cement pastes undergoing sealed hydration, appreciable self-desiccation will only occur if the w/c is below 0.40–0.45.

Further insight was given by L'Hermite and Grieu [12] and Buil [13]. Based on a comparison of normal drying shrinkage with autogenous deformation they showed that self-desiccation shrinkage, which is a result of chemical shrinkage, is the major cause of autogenous deformation.

In 1981 a RILEM commission presented an elaborate exposition of the properties of set concrete at early ages [3]. Measuring techniques and data analysis of autogenous deformation were also thoroughly covered by this state-of-the-art-report. With respect to cracking at early ages, the summary and suggestions for further research focus on plastic shrinkage and thermal deformation and do not include autogenous deformation.

3. Successors out of necessity — the high-strength/high-performance (HSC/HPC) era

During the early 1980s a significant progress in concrete technology started: HSC/HPC. This was partly enabled through the development of effective superplasticisers that made it possible to produce workable concretes with low w/c ratios. However, the real breakthrough for the high-strength concrete technology was due to the arrival of silica fume. In less than 5 years, silica fume was accepted as a supplementary cementitious material, and compressive strengths of workable concretes of 100–150 MPa could be produced [14]. Today, silica fume appears as the de facto basis for HSC/HPC technology.

With respect to self-desiccation these new types of concrete are considerably different from traditional concretes. This is due to both microstructural and chemical factors. The tendency of concrete for self-desiccation is controlled by:

- the *chemical shrinkage* accompanying the cementitious reaction,
- the *sensitivity to the RH* of the cementitious reaction, and
- the *pore structure* of the concrete.

Low w/c ratio and silica fume addition lead to a significant refinement of the pore structure. Compared with the hydration of Portland cement, the pozzolanic reaction of silica fume has a high chemical shrinkage and is relatively insensitive to a drop in the RH [15]. All these factors promote self-desiccation and self-desiccation shrinkage. In addition, high-strength concretes also have a higher binder content per unit volume, which further increases shrinkage.

Despite effective control of both water-loss and temperature variations during hardening, cracking in these high-strength concretes was reported from concrete practice in the mid-1980s [16,17]. Subsequent laboratory investigations

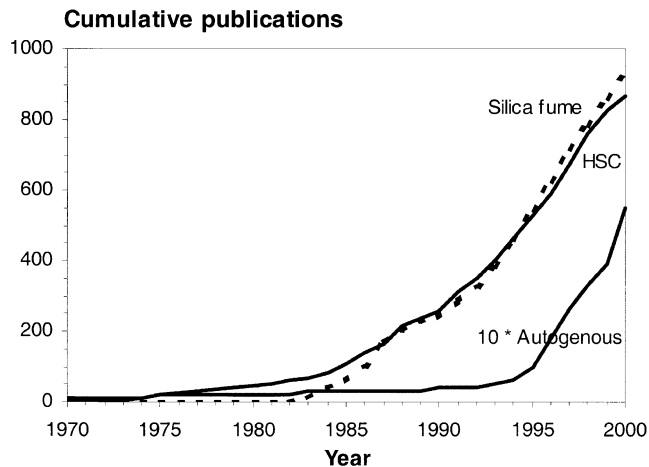


Fig. 2. Number of publications registered by Computerized Engineering Index [24] within different subfields of concrete technology: (1) silica fume, (2) high-strength concrete (HSC) and (3) autogenous deformation and RH-change. The number of publications within the latter subject has been multiplied by 10 for easy comparison. In the figure Compendex is used to illustrate the appearance and growth of different subfields of concrete technology — not to illustrate the complete amount of literature.

in the late 1980s clearly showed that the observed cracking phenomena were due to an increased autogenous deformation of high-strength concretes [18]. However, this did not become commonly recognised until the mid-1990s when a significant increase in the research on autogenous deformation and RH-change took place. Since 1996, international workshops entirely devoted to this subject have been held annually [19–23].

Fig. 2 illustrates this rendering. Note the 10 years' delay from the introduction of high-strength concrete until the importance of research in autogenous deformation and RH-change was generally accepted.

An important contribution to the understanding of self-desiccation and self-desiccation shrinkage was given by Hua et al. [25]. Based on measurements of autogenous deformation, degree of hydration and mercury intrusion porosimetry, they showed that capillary stresses in the pore water are the dominating physicochemical phenomenon that links self-desiccation and self-desiccation shrinkage.

4. Present status

Today the total amount of literature on autogenous deformation and RH-change is substantial. More than 100 papers deal entirely with these phenomena. Awareness of the importance of this subject has been established both in the scientific community and in concrete practice; research groups in more than 10 countries are presently investigating these phenomena. This was not the case 10 years ago.

According to measurements presented in the literature, autogenous deformation and RH-change are influenced by many factors, for example w/c ratio, cement composition,

silica fume content, fineness of cement and silica fume, volume of aggregate and exposure temperature. Unfortunately, there is a remarkable lack of agreement on the extent of influence of the different factors. Examples of apparently conflicting results include the applicability of the maturity concept to autogenous deformation [26], whether observed expansion after setting is an artefact [27] and the influence of silica fume addition [27–29].

Strictly speaking, consensus is limited to general characteristics such as:

- Autogenous RH-change (self-desiccation) is not able to proceed below approximately 75% RH.
- Dissolved salts in the pore solution may lower the RH by at least 1–3%.
- A lowering of the w/c ratio promotes autogenous shrinkage and RH-change.
- After setting, autogenous deformation developed during a couple of weeks hardening may amount to more than 1000 μ strain for a cement paste.
- Cracking may develop during restrained autogenous deformation.

4.1. Measuring techniques

Problems with the measuring techniques seem to be the cause of a large part of the disagreement found in the literature. Barcelo et al. [30] have demonstrated how difficult it is to interpret results based on different measuring techniques. It is fundamental to solve these problems with measuring techniques before a reasonable discussion of the influence of factors on autogenous deformation and RH-change can take place. When measuring results are presented and analysed in the literature, it should not be a matter of question to the reader whether the results were significantly influenced by, for example, bleeding, temperature variations, moisture loss or external forces. The measuring error may easily exceed the measured quantity if the measurements are not performed very carefully.

4.1.1. Techniques for measuring autogenous deformation

Measurements of autogenous deformation have been carried out in two fundamentally different ways, viz. measurement of volumetric deformation and measurement of linear deformation. Volumetric measurement of autogenous deformation is frequently performed by placing the fresh cement paste in a tight rubber balloon immersed in water. The change in volume of the cement paste is measured by the amount of water displaced by the immersed sample, for example, by measuring the weight change of the immersed sample (buoyancy). Linear measurement of autogenous deformation is frequently performed by placing the cement paste in a rigid mould with low friction. The length change of the cement paste is recorded by a displacement transducer at the end of the specimen.

Both methods of measurement have advantages and disadvantages. These have been debated for a long time [13,30–33]. One advantage of the volumetric method is the possibility of commencing the measurements immediately after casting. Before setting, measurements have to be volume based since the plastic state prevents an unambiguous definition of length. In contrast, the lack of a steady contact between the rubber balloon and the cement paste is a considerable disadvantage of the volumetric method. A film of water, e.g., due to bleeding, or entrapped air at the surface of the cement paste may obstruct this contact significantly. During the hydration process the water or entrapped air will be sucked back into the cement paste as a consequence of chemical shrinkage. In this way the internal volume reduction may also be erroneously measured as an outer deformation; the volume of the rubber balloon is the combined volume of the cement paste and the volume of the surface water or entrapped air. Since the chemical shrinkage is considerably larger than the autogenous deformation, this may lead to a substantial error. In addition, Buil [13] mentions that the pressure caused by a tight rubber balloon could damage the weak structure during setting. Furthermore, volumetric measurement results of autogenous deformation seem to be associated with large scatter.

One advantage of the linear method is the firm anchorage of the measuring points to the set cement paste. This reduces the above-mentioned problems greatly. At the same time, this is a disadvantage of the linear method since the measurements cannot be carried out before the cement paste has set. The linear method has an additional problem: the risk of restraining the cement paste. In the very first hours after setting the cement paste is too weak to overcome the friction against a rigid mould. However, lubricating the mould can reduce this problem.

A special corrugated mould system which combines the advantages of linear and volumetric measurement has been suggested by Jensen and Hansen [33] (see Fig. 3). Before set, the corrugated mould in fact transforms the volumetric deformation into a linear deformation, and after set a normal, well-defined linear deformation is measured. In this way it is possible to commence linear measurements directly after casting.

Gagné et al. [34] have suggested a volumetric technique where chemical shrinkage and autogenous deformation can be measured simultaneously on the same sample.

4.1.2. Techniques for measuring autogenous RH-change

From a point of view of measuring technique, autogenous RH-change has a significant advantage compared with autogenous deformation: The RH is a physicochemical state which can be measured on a given sample independently of the previous history of the sample. Contrary to this, a reference point has to be defined for autogenous deformation. But apart from that, major difficulties

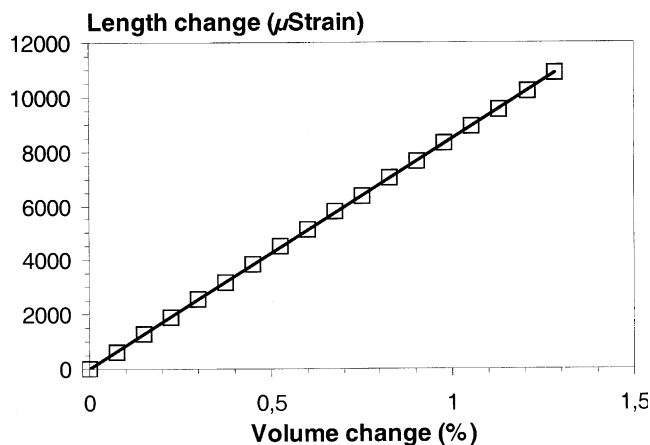


Fig. 3. With a special, corrugated mould it is possible to perform linear measurements directly after casting. This is due to a greater stiffness in the radial than in the longitudinal direction of the mould. Before set the volumetric deformation of the cement paste is, therefore, transformed into a linear deformation, as shown in the graph.

are also connected with measurement of autogenous RH-change.

Measurements of autogenous RH-change have been carried out in many different ways. A typical procedure is to place cement paste in a small, sealed and thermostated container. The internal RH of the cement paste will equilibrate the RH of the air inside the container, which in turn is measured by a humidity sensor. Normally, the cement paste is crushed in order to equilibrate the RH faster. The measurements of RH may be performed continuously or discretely.

RH can be measured in many different ways. To follow autogenous RH-change, however, only electronic sensors for continuous measurement are relevant. Unfortunately, they need frequent and extensive calibration in order to

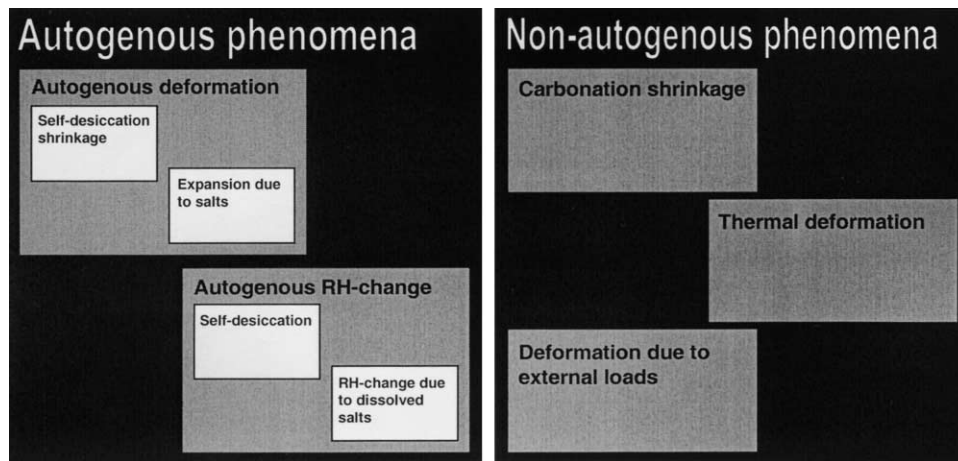


Fig. 4. Graphic representation of applied terminology; self-desiccation and self-desiccation shrinkage are proper subsets of autogenous RH-change and autogenous deformation, respectively [28].

bring down the measuring accuracy to about $\pm 1\%$ RH. Even for high-quality sensors drift may exceed 1% RH/month. A lack of thermal equilibrium between sensor and sample is also a source of errors. These gradients may be due to insufficient thermostatic control or heat of hydration. Near saturation at room temperature a temperature difference of 1°C will lead to a measuring error of 6% RH. Furthermore, condensation on the sensor may occur if the sample has a higher temperature than the sensor. As long as the condensation persists it will lead to measuring errors, and some sensors may in addition require a new calibration.

Moisture loss from the sample may lead to very significant measuring errors. Cementitious systems prone to self-desiccation will, typically, also be sensitive to moisture loss. This is because such cement pastes normally have a fine pore structure and a low amount of evaporable water. The moisture loss may arise from repeated measurements on the same sample, where the sealing is broken at each measurement, or from invisible cracks in the sealing and the like.

4.2. Terminology

The lack of agreement in the literature not only concerns the measuring techniques, but also the applied terminology. A confusion of nomenclature exists as different terms are used for the same phenomenon, and different phenomena are described by the same term [28]. A comparison of recent publications clearly illustrates this [2,27,35,36]. Below, a terminology is suggested based on definitions from physical chemistry (see Fig. 4).

Chemical shrinkage:

Internal volume reduction associated with the hydration reactions in a cementitious material.

Autogenous deformation:

The bulk deformation of a closed, isothermal, cementitious material system not subjected to external forces.

Autogenous relative humidity change:

The change of internal relative humidity in a closed, isothermal, cementitious material system not subjected to external forces.

Self-desiccation shrinkage:

Autogenous deformation of a set cementitious material system caused by chemical shrinkage.

Self-desiccation:

Autogenous relative humidity change of a set cementitious material system caused by chemical shrinkage.

4.2.1. Comments on the definitions

To define autogenous conditions, concepts from physical chemistry have been used here: a closed, isothermal system not subjected to external forces. The word *closed* signifies that no exchange of matter takes place between the cementitious material and the surroundings. Most important, exchange of water with the surroundings leads to nonautogenous deformation and nonautogenous RH-change, but other substances such as CO_2 and SO_4^{2-} may also be important in this connection. The word *isothermal* signifies that the temperature is kept constant. Autogenous deformation and RH-change also take place even though the temperature is not constant or when matter is exchanged with the surroundings. But in that case the autogenous phenomena are superimposed and modified due to the external influence. The autogenous phenomena may also be modified due to bleeding. However, the definitions here only concern a homogeneous, isotropic material system.

Chemical shrinkage is the consequence of reaction products occupying less space than the reacting materials in a hydrating cement paste. Before set this internal volume reduction may be completely converted into a bulk deformation of the system, so-called *setting shrinkage*. With the above definition setting shrinkage is a constituent part of autogenous deformation. After set chemical shrinkage creates inner, empty cavities if the cement paste is kept

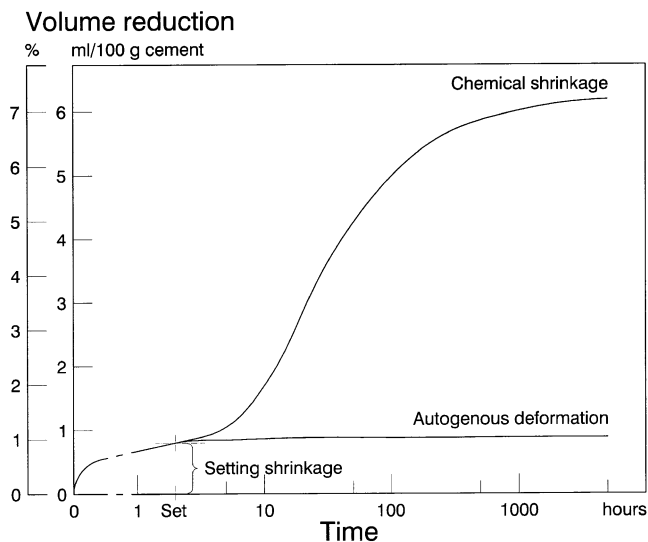


Fig. 5. Schematic development of volume changes, which take place in a sealed cement paste system. Before set chemical shrinkage and autogenous deformation may be identical. This volume reduction is referred to as setting shrinkage, and may amount to about 1%. After set the chemical shrinkage may be 50 times larger than the autogenous deformation on a volume basis.

sealed. Due to the formation of menisci, chemical shrinkage leads to an RH-decrease and a shrinkage of the cement paste, i.e., self-desiccation and self-desiccation shrinkage. Parallel with the chemical shrinkage, a change of the pore structure of the cementitious material takes place. As mentioned previously, this has importance for the magnitude of the developed self-desiccation.

Principally, the pore structure may change without a matching chemical shrinkage, e.g., due to the so-called Ostwald ripening of the hydration products. The deformation and RH-change linked to this are included in autogenous deformation and RH-change, but not in self-desiccation and self-desiccation shrinkage. Figs. 5 and 6 illustrate some of the phenomena discussed above.

5. Future

We think that the increased attention paid to autogenous deformation and autogenous RH-change will eventually lead to more consensus of nomenclature. Terms that lack logic or do not intuitively describe a specific phenomenon will inevitably disappear from the terminology.

The same fate will apply to the measuring techniques. In the literature there is an ongoing sound discussion, and awareness of the pitfalls and agreement on the usefulness of different measurement techniques must be the outcome of this. Perhaps, a round robin test could be useful in this process.

The major part of the reported research on autogenous deformation and RH-change is phenomenological. The lack of causal explanations limits the applicability of such

research. Especially for autogenous deformation and RH-change it is difficult to apply phenomenological research since these properties are strongly influenced by the experimental conditions and a large number of material parameters. Further research must be based on physical, chemical and thermodynamic examinations of underlying mechanisms for proper understanding of these phenomena and prediction of behaviour.

In some cases an analytical or experimental examination of these mechanisms may be very difficult to apply. However, during the last decade computer modelling has developed into a strong tool for simulation of the chemical and physical aspects of Portland cement hydration [37]. Recent application of computer modelling to autogenous deformation and RH-change indicates that this approach may be useful for the understanding and prediction of these phenomena [38].

Limitation of autogenous deformation and RH-change, for example by so-called internal curing, is another topic which may receive increased attention in the coming years. It has been known for a decade that incorporation of saturated lightweight aggregate into the concrete mixture may provide internal curing and, thereby, minimise the autogenous shrinkage [39,40]. However, major problems are connected to this technique, for the fresh, hardening and hardened concrete. Examples of these problems are change of consistency, separation of the light porous phase and strength reduction. Moreover, it should be borne in mind that the water curing only limits the autogenous shrinkage. If the RH of the hardened concrete is reduced later on due to equilibration with the surroundings, drying shrinkage will occur. Much additional research in this area is needed.

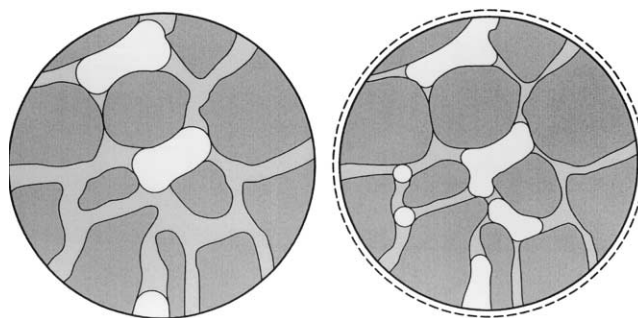


Fig. 6. Schematic representation of a cross section of a hydrating cement paste. Left: low degree of hydration. Right: high degree of hydration. Solid matter (hydration products, unhydrated cement, silica fume, etc.) is shown dark grey, pore water is light grey and empty pore volume is white. The figure illustrates the following consequences of the hydration process: (a) reduction of the amount of pore water due to binding in the hydration products, (b) increase of the amount of solid material, (c) refinement of the pore structure, (d) formation of empty pore volume due to chemical shrinkage, (e) decrease of the radius of curvature of the menisci, and (f) bulk shrinkage due to increased tensile stresses in the pore water, i.e., self-desiccation shrinkage.

The importance of autogenous deformation and RH-change for concrete practice seems to be commonly acknowledged today. As a result of this, we expect that a worldwide explicit implementation in building codes will take place. The first indications of this can already be found [35,41].

References

- [1] H. Stang, Significance of shrinkage-induced clamping pressure in fiber-matrix bonding in cementitious composite materials, *Adv. Cem. Based Mater.* 4 (3–4) (1996) 106–115.
- [2] Committee report, Technical Committee on Autogenous Shrinkage of Concrete, Japan Concrete Institute, 1998, pp. 1–67 in Ref. [21].
- [3] RILEM Commission 42-CEA, Properties of set concrete at early ages (state of the art report), *Matér. Const.* 84 (1981) 399–460.
- [4] H. Le Chatelier, Sur les changements de volume qui accompagnent le durcissement des ciments, *Bull. Soc. Encour. Ind. Natl. V* (5th Series) (1900) 54–57.
- [5] L. Jesser, Kolloidchemische Austrocknungsreaktionen der Portlandcementmörtel, *Berg- Hüttenmänn. Jahrb. Montan. Hochsch. Leoben* 75 (1927) 69–81.
- [6] H.A. Neville, H.C. Jones, The study of hydration changes by a volume-change method, *Colloid Symp. Monogr. VI* (1928) 309–318 (VI Symposium on Colloid Chemistry).
- [7] C.G. Lynam, Growth and Movement in Portland Cement Concrete, Oxford Univ. Press, London, 1934, pp. 26–27.
- [8] H.E. Davis, Autogenous volume changes of concrete, *Proc., Am. Soc. Test. Mater.* 32 (40) (1940) 1103–1112.
- [9] T.C. Powers, T.L. Brownyard, Studies of the physical properties of hardened portland cement paste, *Res. Lab. Portland Cem. Assoc., Bull.* 22 (1948).
- [10] L.E. Copeland, R.H. Bragg, Self desiccation in Portland cement pastes, *Res. Lab. Portland Cem. Assoc., Bull.* 52 (1955) 1–11.
- [11] T.C. Powers, A discussion of cement hydration in relation to the curing of concrete, *Proc. Highw. Res. Board* 27 (1947) 178–188.
- [12] R. L'Hermite, J.-J. Grieu, Études expérimentales récentes sur le retrait des ciments et des bétons, *Ann. Inst. Tech. Batim. Trav. Publics* 52–53 (1952) 491–514.
- [13] M. Buil, Contribution à l'étude du retrait de la pâte de ciment durcissante, *Rapp. Rech. — Lab. Ponts Chaussées (LPC)* 92 (1979) 1–72.
- [14] P.-C. Aïtcin, High-Performance Concrete, E & FN Spon, London, 1998, pp. 22–34, 192.
- [15] H. Justnes, E.J. Sellevold, G. Lundevall, High-strength concrete binders: Part A. Reactivity and composition of cement pastes with and without condensed silica fume, Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, *Am. Concr. Inst., SP* 132 (1992) 873–889 (Detroit).
- [16] T.C. Holland, A. Krysa, M.D. Luther, T.C. Liu, Use of silica-fume concrete to repair abrasion-erosion damage in the Kinzua Dam stilling basin, Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, *Am. Concr. Inst., SP* 91 (1986) 841–863 (Detroit).
- [17] E.-I. Tazawa, Preface, p. xi in Ref. [21].
- [18] A.M. Palliere, M. Buil, J.J. Serrano, Durabilité du béton à très hautes performances: Incidence du retrait d'hydratation sur la fissuration au jeune âge, in: J.C. Maso (Ed.), *From Materials Science to Construction Materials Engineering*, vol. 3, Chapman & Hall, London, 1987, pp. 990–997.
- [19] E.J. Sellevold, T.A. Hammer (Eds.), Early Volume Change and Reactions in Paste-Mortar-Concrete, Workshop NTNU/SINTEF Trondheim, Norway, 1996 (28–29 November).
- [20] B. Persson, G. Fagerlund (Eds.), International Research Seminar on Self-Desiccation and its Importance in Concrete Technology, Lund, Sweden, 10 June 1997, Report TVBM-3075, Lund University, 1997.
- [21] E.-I. Tazawa (Ed.), Autogenous Shrinkage of Concrete, Proceedings of the International Workshop, AUTOSHRINK'98, Hiroshima, 13–14 June, 1998, E & FN SPON, London, 1999.
- [22] B. Persson, G. Fagerlund (Eds.), 2nd International Research Seminar on Self-Desiccation and its Importance in Concrete Technology, Proceedings, Lund, Sweden, 18 June 1999.
- [23] V. Baroghel-Bouny, P.-C. Aïtcin (Eds.), Shrinkage 2000, International RILEM Workshop on Shrinkage of Concrete, October 16–17, Paris, France, 2000.
- [24] Engineering Index, Engineering Information Inc., New York, 1884–2000. For the searches the computerized form of this database has been used (Ei CompendexWeb — Search [Online], <http://pluto.ei.org/cpx/plsql/cpxwebsz.home>, accessed March 2000).
- [25] C. Hua, P. Acker, A. Ehrlicher, Analyses and models of the autogenous shrinkage of hardening cement paste: I. Modelling at macroscopic scale, *Cem. Concr. Res.* 25 (7) (1995) 1457–1468.
- [26] Ø. Bjøntegaard, Thermal dilation and autogenous deformation as driving forces to self-induced stresses in high performance concrete, PhD Thesis, Div. Struct. Eng. Norwegian University of Science and Technology, Trondheim, 1999, pp. 25–30 (Dec.).
- [27] H. Justnes, T. Hammer, B. Ardoullie, E. Hendrix, D. Van Gemert, K. Overmeer, E.J. Sellevold, Chemical shrinkage of cement paste, mortar and concrete, 1998, pp. 211–220 in Ref. [21].
- [28] O.M. Jensen, P.F. Hansen, Autogenous deformation and change of the relative humidity in silica fume-modified cement paste, *ACI Mater. J.* 93 (6) (1996) 539–543.
- [29] B. Persson, Experimental studies on shrinkage of high-performance concrete, *Cem. Concr. Res.* 28 (7) (1998) 1023–1036.
- [30] L. Barcelo, S. Boivin, S. Rigaud, P. Acker, B. Clavaud, C. Boulay, Linear vs. volumetric autogenous shrinkage measurement: Material behaviour or experimental artefact? 1999, pp. 109–125 in Ref. [22].
- [31] J. Baron, M. Buil, Remarques à propos de l'article "Mechanical features of chemical shrinkage of cement pastes" par N. Setter et D.M. Roy, *Cem. Concr. Res.* 9 (1979) 545–547.
- [32] H. Justnes, A. Van Gemert, F. Verboven, E. Sellevold, D. Van Gemert, Influence of measuring method on bleeding and chemical shrinkage values of cement pastes, *Proc. Int. Congr. Chem. Cem., 10th, Gothenburg, Sweden, June 2–6, vol. 2* (paper 2ii069).
- [33] O.M. Jensen, P.F. Hansen, A dilatometer for measuring autogenous deformation in hardening Portland cement paste, *Mater. Struct.* 28 (181) (1995) 406–409.
- [34] R. Gagné, I. Aouad, J. Shen, C. Poulin, Development of a new experimental technique for the study of the autogenous shrinkage of cement paste, *Mater. Struct.* 32 (223) (1999) 635–642.
- [35] Suggestions on the terminology and the test methods proposed by JCI, 1998, pp. 397–399 in Ref. [21].
- [36] M. Wicke (Ed.), Structural Concrete, Vol. 1, Updated knowledge of the CEB/FIP Model Code 1990, Fédération Internationale du Béton (fib), Lausanne, 1999, p. 41.
- [37] D.P. Bentz, Three-dimensional computer simulation of portland cement hydration and microstructure development, *J. Am. Ceram. Soc.* 80 (1) (1997) 3–21.
- [38] D.P. Bentz, K.A. Snyder, P.E. Stutzman, Microstructural modelling of self-desiccation during hydration, 1997, pp. 132–140 in Ref. [20].
- [39] S. Weber, H.W. Reinhardt, A new generation of high performance concrete: Concrete with autogenous curing, *Adv. Cem. Based Mater.* 6 (1997) 59–68.
- [40] D.P. Bentz, K.A. Snyder, Protected paste volume in concrete — Extension to internal curing using saturated lightweight fine aggregate, *Cem. Concr. Res.* 29 (11) (1999) 1863–1867.
- [41] Japan Society of Civil Engineers, Standard Specification for Design and Construction of Concrete Structure (in Japanese), 1996 (Referred in Ref. [21] p. 9).