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ANALYSES AND MODELS OF THE AUTOGENOUS SHRINKAGE OF HARDENING CEMENT PASTE

I. Modelling at macroscopic scale

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ABSTRACT

After having studied phenomena linked to hydration and self-desiccation, one notes that capillary depression is the main origin of the autogenous shrinkage of hardening cement paste. Based on this mechanism, modelling at macroscopic scale is undertaken for a commonly used cement paste (CPA 55) with a W/C ratio = 0.42. It consists in introducing a macroscopic stress due to the capillary depression and characterizing the viscoelastic aging behavior of the material. The result is in satisfactory agreement with measurements.

1. Introduction

Autogenous shrinkage is analogous to drying shrinkage, because the hardening cement paste, isolated from all external water sources, spontaneously undergoes, in the course of its hydration, drying due to hydration and notably to *Le Chatelier* contraction.

In the literature, there are three main mechanisms to explain shrinkage by drying (Baron /1982/):

1. Variation of capillary depression,
2. Variation of surface tension of colloidal particles,
3. Variation of disjoining pressure.

The last two mechanisms concern forces at colloidal particle scale and can explain drying shrinkage only qualitatively. The first mechanism often gives estimates of drying shrinkage that are much smaller than the measured values. Because of the complexity of the phenomenon, we try merely to model the autogenous shrinkage well enough for a rough fit to the measured values.

2. Mechanisms of shrinkage by drying and by self-desiccation

2.1 Phenomena linked to hydration and to self-desiccation

In the hydration of cement, the absolute volume of hydrates formed V_h is less than the sum of the volumes of the water consumed V_{wh} and the cement hydrated V_{ch}.

$$V_h = V_{wh} + V_{ch} - \Delta V \quad (1)$$

This phenomenon, discovered by *Le Chatelier*, is called "*Le Chatelier* contraction", denoted by "ΔV".

Consider a specimen of hardening cement paste protected by a waterproof membrane as schematized in Figure 1. As the specimen is not in communication with an external water source, when the skeleton has formed, *Le Chatelier* contraction inevitably causes the appearance of a gaseous volume in the porosity initially saturated in water. The more the hydration advances, the more empty spaces develop and the more the equilibrium pressure of water vapor with the water decreases, whence the term "self-desiccation".

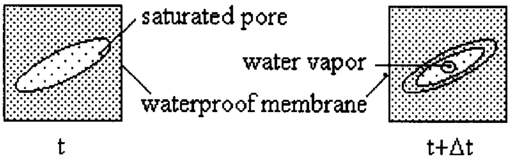

FIG 1. Self-desiccation by *Le Chatelier* contraction

From the viewpoint of the progressive structuring of hardening cement paste, one can divide hydration into three steps (Acker /1988/), suspension (solid grains isolated in the liquid phase), setting (the hydrates around cement grains establish mechanical connections between grains, a solid skeleton appears, and a capillary network is formed), and hardening (with the filling of the capillaries by the porous hydrate mass).

This progressive structuring therefore introduces two types of pores in the material : micro-pores (average size 18 Å) and capillaries. The micropores are the intrinsic part of hydrates and the capillaries are in fact vestiges of intergranular spaces of the fresh paste.

On the other hand, during hydration, the water retained by the micropores can practically no longer flow, and is no longer available for the chemical reaction. This part of the water is called "immobilized water". All of the phenomena mentioned above therefore indicate that :

- If there is not enough free water (in the capillaries), the hydration reaction stops no matter how much residual anhydrous cement there is in the paste. Consequently, self-desiccation can no longer continue.
- In the course of hydration, the micropores are always filled with water, and the part constituted by hydrates can therefore be regarded as a porous saturated material. On the other hand, the capillaries can become unsaturated because of self-desiccation.

2.2 Mechanisms of shrinkage by drying and by self-desiccation

For a porous material in interaction with water, the saturated state is taken as reference. The word "drying" or "self-desiccation" therefore means an increase of gaseous volume in pores initially saturated with water. It is admitted that this gaseous volume has the same mechanical effect for both drying and self-desiccation.

Mechanism of variation of capillary depression

This mechanism is deduced from the Laplace law and the Kelvin law :

$$p_v - p_c = \frac{2\sigma}{r}\cos\theta \qquad \text{(Laplace)} \tag{2}$$

$$p_c - p_v = \frac{RT}{Mv}\ln(h) \qquad \text{(Kelvin)} \tag{3}$$

where :

σ : surface tension of the water/water vapor interface
θ : moistening angle (Figure 2)
p_c: pressure in water
p_v: pressure in water vapor, often taken as zero
r : radius of the pore where there is a meniscus
v : specific volume of water
M : molar mass of water
R : ideal gas constant
T : temperature
h : relative humidity

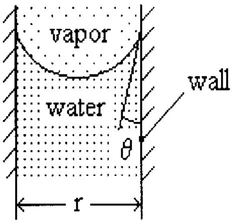

FIG 2. An unsaturated capillary

According to the Kelvin law and the Laplace law, for a given unsaturated state, there is an access radius r_0 such that all capillaries with access radius less than r_0 are filled with water and all capillaries with larger access radius are empty; such an access radius r_0 introduces a corresponding tension (or depression) in the liquid phase, so the solid skeleton undergoes a compression, whence the shrinkage.

The question posed is the validity of these laws and the reality of the meniscus surface tension at microscopic scale. Some specialists of the colloidal science (Fisher /1982/ and Crassous /1993/) have estimated that the meniscus effects can be precisely evaluated from the Laplace law and the Kelvin law for a meniscus radius greater than 50 Å. This means that these macroscopic laws are valid for a relative humidity above 80 %. It is in just this interval of relative humidity (100 % - 80 %) that hydration takes place under confined conditions, and consequently that self-desiccation can occur.

Mechanism of variation of surface tension of colloidal particles

Surface tension results from the asymmetry of attractive forces on atoms or molecules in the vicinity of the surface. It produces there a small variation in atomic or molecular distances that induces a tension tangent to the surface. For a given material, this surface tension depends on the surroundings; it is greatest when the surface is situated in a vacuum and cancels when the surface is in contact with the same material (Powers /1968/). In the general case, adsorption of foreign atoms or molecules on a solid surface causes a relaxation of the surface tension. In return, desorption engenders an increase of the surface tension, and so the solid is compressed. Whence shrinkage due to a change of relative humidity.

However this mechanism operates primarily at low relative humidity (Baron /1982/ and Buil /1979/) because, above a certain relative humidity, the whole solid surface is covered by adsorbed water molecules, and the variation of relative humidity can no longer vary the surface tension.

Mechanism of variation of disjoining pressure

This mechanism concerns the interaction between two solid surfaces, very close together, in the presence of adsorbed water molecules. At a given temperature, the thickness of a layer of adsorbed water depends on the relative humidity. But the layer of adsorbed water can no longer develop freely above a certain relative humidity because the distance between the two surfaces is too small. If the relative humidity is increased again, the adsorption of water tends to separate the two solid surfaces so as to increase the thickness of the adsorbed layer. The two solid surfaces therefore undergo a pressure called the "disjoining pressure". This pressure reaches its maximum value in the saturated state, so when the system goes from the saturated state to an unsaturated state, there is shrinkage because the disjoining pressure decreases and the two surfaces move closer together.

Measurements of the disjoining pressure have been made by Ferraris /1986/. The author noted that the disjoining pressure is practically constant when the relative humidity varies from 80 % to 100 %. In fact, when the relative humidity remains high, its variation does not cause much change between adsorbed and unadsorbed water molecules, so the disjoining pressure does not vary at high relative humidity.

From the reasonings based on the one hand on the three mechanisms found in the literature and on the other hand on phenomena linked to the progressive structuring of the cement paste during hydration, it may be noted that:

- The effect of the variation of capillary depression is large in the autogenous shrinkage of young, very deformable, cement paste, because the capillary depression can vary from 0 to 30 MPa as the relative humidity varies from 100 % to 80 %.
- The effect of the variation of surface tension of colloidal particles of hydrates and the effect of the variation of disjoining pressure are negligible in autogenous shrinkage.
- The autogenous shrinkage of young cement paste can be modelled either at macroscopic scale or at the scale where the details of colloidal hydrates do not intervene.

3. Modelling of autogenous shrinkage at macroscopic scale

3.1 Macroscopic stress due to capillary depression

Determination of the capillary depression during hydration

According to the Laplace law and the Kelvin law mentioned above, there exists, for a given unsaturated state, an access radius r_o such that all pores of access radius smaller than the radius r_o are full of water and all pores of access radius larger than the radius r_o are empty. It is this radius r_o that determines the meniscus curvature, and therefore the capillary depression.

In our model, the capillary depression $p_c(t)$ is regarded as a time function during hydration. The determination of the function $p_c(t)$ is undertaken using MIP (Mercury Intrusion Porosimetry). Recall that water is a wetting liquid, and that the evacuation of water under depression starts from the large pores and progresses to the small pores, while mercury is a non-wetting liquid and the invasion of mercury under pressure also starts from the large pores and progresses to the small pores.

Consider a simplified example. For a hardening cement paste at a given instant t_o the *Le Chatelier* contraction $\Delta V(t_o)$ can be known either by direct measurement or via the degree of hydration. Because of the self-desiccation that results from *Le Chatelier* contraction, we therefore have an unsaturated porous medium whose gaseous volume is equal to $\Delta V(t_o)$, and the liquid phase is under the depression $p_c(\Delta V(t_o))$. This is represented by Figure 3 (a).

Imagine the following process : we stop hydration at the instant t_o and we completely dry the cement paste; we therefore have a solid microstructure identical to that of Figure 3 (a). We then cause the same volume $\Delta V(t_o)$ of mercury to penetrate under the pressure $p_{Hg}(\Delta V(t_o))$ in MIP. This is shown in Figure 3 (b) and (c).

Since the pressure $p_{Hg}(\Delta V(t_o))$ and the depression $p_c(\Delta V(t_o))$ correspond to the same volume $\Delta V(t_o)$ and the solid microstructure in these two cases (Figure 3 (a) and (b)) is identical, the equality of the access radius $r_o(t_o)$ gives :

$$p_c(\Delta V(t_o)) = \frac{\gamma_w \cos\theta_w}{\gamma_{Hg}\cos\theta_{Hg}} p_{Hg}(\Delta V(t_o)) \tag{4}$$

where :

γ_w: surface tension of water/water vapor

θ_w: moistening angle of water on the solid walls (hydrates)

γ_{Hg}: surface tension of mercury/vacuum

θ_{Hg}: moistening angle of mercury on the solid walls (hydrates).

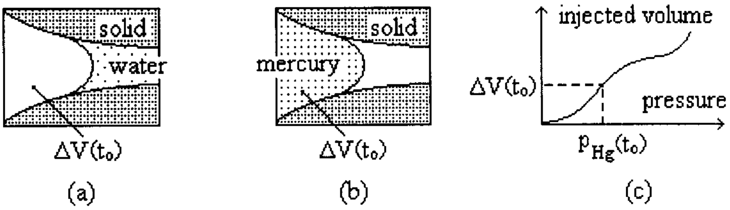

FIG 3. (a) : Diagram of evacuation of water under depression
(b) and (c) : Diagram of invasion of mercury under pressure

On the right-hand side of equation 4, only $\cos\theta_{Hg}$ is negative, and so this expression naturally gives a depression ($p_c < 0$). The function $p_c(t)$ can be obtained by a series of MIP tests at different stages of hydration.

Remark :

> It is very important to note that while MIP is often open to criticism when used to study the geometry of pores, the use made of it here is not based on any assumption concerning the geometry of the pores; it concerns only the concept of "access radius".

Macroscopic stress

Shrinkage is a deformation of the solid skeleton of cement paste and it is the solid skeleton that undergoes compression due to capillary depression. The solid partial macroscopic stress of the unsaturated porous medium is therefore defined by :

$$\Sigma_{ij}^{s}(X_g) = \frac{1}{V(X_g)} \int_{V_s(X_g)} \sigma_{ij}(y_l)\, dV_s(X_g) \tag{5}$$

where :

$\Sigma_{ij}^{s}(X_g)$: macroscopic stress of skeleton

$\sigma_{ij}(y_l)$: real stress at microscopic scale

$V(X_g)$: representative elementary volume (Figure 4)

$V_s(X_g)$: volume of the solid part in $V(X_g)$

$V_l(X_g)$: volume of the liquid part in $V(X_g)$

X_g and y_l : global and local variable (vectors)

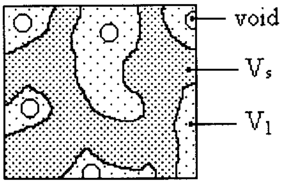

FIG 4. Representative elementary volume

Physically, the definition gives an average stress of the solid part in a representative elementary volume. In other words, the stress of the solid part is distributed throughout volume $V(X_g)$ because the solid skeleton is macroscopically considered as continuous and homogeneous, and it occupies the whole volume $V(X_g)$. By making the following two assumptions :

- *Assumption 1.* The liquid phase is continuous because there is a pore network. In the equilibrium state, the capillary depression p_c is therefore uniform in the liquid phase and the microscopic stress can be expressed in the following form (the negative value of p_c means a depression or tension in the liquid phase) :

  $$\sigma_{ij}(y_l) = -p_c\delta_{ij} \qquad y \in V_l(X_g)$$

- *Assumption 2.* The cement paste is macroscopically homogeneous and isotropic, the capillary depression p_c therefore produces a spherical and uniform macroscopic stress as follows (the negative value of Σ^s means a compression in the skeleton) :

  $$\Sigma^s_{ij}(X_g) = \Sigma^s\delta_{ij}$$

the Principle of Virtual Power gives (Hua /1992/) :

$$\Sigma^s = p_c\phi \tag{6}$$

with, for cases of high relative humidity, a total porosity of the material ϕ.

3.2 Behavior of the material and definition of autogenous shrinkage

On the macroscopic scale, the total system constituted by the hardening cement paste can be considered, in the presence of water, as a continuous medium with aging viscoelastic behavior, which is generally characterized by a tensor of creep functions $J_{ijkl}(t,t')$. If the paste is homogeneous and isotropic, its behavior can be characterized by two creep functions, one corresponding to the volumetric component $J^v(t,t')$ and the other corresponding to the deviatoric component $J^d(t,t')$. In practice, the Poisson ratio v varies very little, so it can be regarded as a constant. Therefore the aging viscoelastic behavior of the material can be described by a single function, the one-dimensional creep function $J(t,t')$, which represents the strain at time t produced by a unit constant stress that has been acting since time t' (Bazant /1982/) :

$$\begin{cases} J^v(t,t') = 3(1-2v)\,J(t,t') \\ J^d(t,t') = 2(1+v)\,J(t,t') \end{cases} \tag{7}$$

The solid skeleton of the hardening cement paste is macroscopicaly subjected to a spherical internal stress $\Sigma^s\delta_{ij}$ due to the capillary depression. By Boltzmann's principle of superposition, the linear autogenous shrinkage of the material, $\varepsilon_r(t)$, can then be defined by :

$$\varepsilon_r(t) = \int_{t_o}^{t} (1-2v)\,J(t,t')\,d\,\Sigma^s(t') \tag{8}$$

where :

$J(t,t')$: one-dimensional creep function

$\Sigma^s(t')$: macroscopic compression of the skeleton

t and t_o : current time and reference time

In general, the function $J(t,t')$ is experimentally determined; we use here an empirical function, proposed by Acker /1987/, a very supple formula that adjusts easily to experimental results comprising an inflexion in the long term.

(9) $$J(t,t') = \frac{1}{E(t')} + \varepsilon_\infty^o(t')\frac{(t-t')^{\alpha(t')}}{(t-t')^{\alpha(t')}+b(t')}$$

For a non-unit load, the creep part can be written :

(10) $$\varepsilon_{creep}(t,t') = \varepsilon_\infty(t')\frac{(t-t')^{\alpha(t')}}{(t-t')^{\alpha(t')}+b(t')}$$

Functions $\varepsilon_\infty(t')$, $\alpha(t')$, and $b(t')$ are determined by a minimization for a series of specimens at different ages t':

(11) $$\overset{\text{fixed } t'}{\underset{\varepsilon_\infty,\alpha,b}{\min}} \sum_{j=1}^{m}\left[\varepsilon_\infty(t')\frac{(t_j-t')^{\alpha(t')}}{(t_j-t')^{\alpha(t')}+b(t')} - \varepsilon_{creep}^{\text{exp.}}(t_j,t')\right]^2$$

4. Experiments and results

4.1 Behavior of hardening cement paste

Instantaneous Young's modulus

CPA 55 cement is used. Specimens are fabricated with a water/cement ratio (W/C) of 0.42 by weight. The specimens, having the dimensions ϕ11x22 *cm*, are removed from the mould at the age of 24 hours, protected by self-adhesive aluminium paper, then preserved in a room at 20°C and 50 % relative humidity, and surfaced just before testing.

The instantaneous modulus is measured, on two specimens, in compression, at a load between 1/3 and 1/2 of an approximately estimated breaking force. The duration of loading is approximately 20 seconds. Our measurement results are given in Table 1, and we can obtain a regression function $E(t')$.

TABLE 1. Evolution of instantaneous modulus

Age (day)	1	2	4	7	15	25
Instantaneous modulus E : (GPà)	7.88	12.75	14.88	16.60	17.63	17.63
Strength (GPa)	20.21	28.72	31.25	38.71	41.22	37.43

Creep tests

The manufacture of specimens is the same as above. The fresh paste is poured into a transparent plastic tube where the bottom plate is already in place; the top plate is then placed. The specimens can then be considered as protected against all desiccation. The specimen is shown in Figure 5 (a) in unit "*mm*" with : 1) cement paste, 2) transparent plastic tube, 3) sliding steel plate 10 mm thick, 4) basin to position the ball.

Given the young age of the specimens, we have imposed a weak compressive stress of 5 MPa (Figure 5 (b)). The steel plate was dimensioned so that the stress could be regarded as uniform throughout the specimen. The plastic tube, far more deformable than the cement paste, has no effect on the measured deformation.

Since the tests are long-term, it is necessary to take account of the shrinkage of hydration, because this deformation is not negligible compared to the creep with a compression of 5 MPa. So we prepared an unloaded identical specimen to be able to calculate the difference between the loaded and unloaded specimens and so obtain an *"intrinsic creep"*.

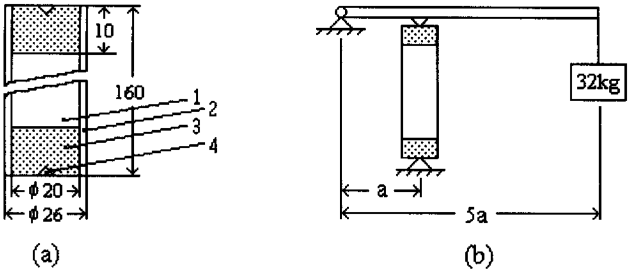

FIG 5. Simplified diagram of frame for creep test

The "intrinsic creep" curves for specimens having ages of 1, 3, and 28 days are given in Figure 6. The parameters ε_∞ , α, and b for each curve are given in Table 2.

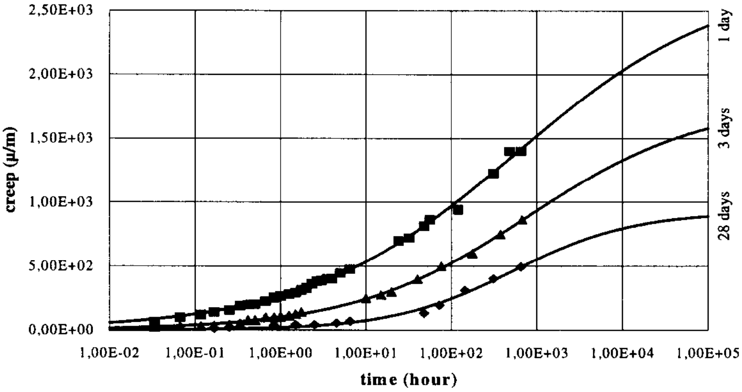

FIG 6. "Intrinsic creep" curves

We can therefore have three regression functions for $\varepsilon_\infty(t')$, $\alpha(t')$, and $b(t')$, so the creep function (equation 10) is determined with t in units of "days" :

$$\begin{cases} \varepsilon_\infty(t) = & 926.9 + 2707.8 \times 1.4667^{-t} \\ \alpha(t) = & 0.611 - 0.3024 \times 1.1675^{-t} \\ b(t) = & 6.6129 - 4.4624 \times 1.2599^{-t} \end{cases} \tag{12}$$

TABLE 2. Parameters calculated by the least squares method

Age t' (day)	ε_∞ (μ/m)	α	b: (t-t') in hours	b: (t-t') in days
1	2773	0.352	9.40	3.0771
3	1785	0.421	16.7	4.3817
28	927	0.611	46.1	6.6129

4.2 Direct measurement of shrinkage of hydration

According to Buil /1979/, the shrinkage of hydration can be confused with the autogenous shrinkage, so we measured the shrinkage of hydration in order to compare it with the estimates yielded by the model.

The fresh paste (W/C = 0.42) is poured in 4x4x16 *cm* moulds, removed from the moulds at the age of 24 hours, then protected by self-adhesive aluminium paper.

The measurement is made by retractometry in a room at 20°C and 50 % relative humidity. The results, presented in Table 6 (last column), are with respect to the initial length of the specimen at the age of 24 hours.

4.3 Degree of hydration

In this model the *Le Chatelier* contraction $\Delta V(t)$ is determined by the degree of hydration, since this contraction is directly related to the hydration reaction. A priori, it may appear surprising to speak of a degree of hydration when several reactions are in competition in the fresh cement paste. But in practice, most available results globalize the hydration reactions, and, more important, this approach gives a rather good correlation with the development of the mechanical properties of the material, probably because the reactions of C_3S and C_2S, which are major components of the anhydrous cement, give the same products while consuming approximately the same quantity of water (second column of Table 3). The degree of hydration can therefore be defined by the quantity of chemically bonded water :

$$(13) \qquad \alpha(t) = \frac{\text{chemically bonded water at time t}}{\text{chemically bonded water at time } t_\infty} = \frac{W_n(t)}{W_n(t_\infty)}$$

where :

$W_n(t)$: quantity of chemically bonded water at time t

$W_n(t_\infty)$: quantity of chemically bonded water for complete hydration

According to Bogue's method and the composition of the cement (CPA 55), we can estimate the quantity of water necessary for complete hydration, $W_n(t_\infty)$ (Table 3, where C_3S, C_2S, C_3A, and C_4AF are the main components of cement).

TABLE 3. Quantity of water necessary for the complete hydration of CPA 55

Composition	Chemically bonded water	Bogue composition (%)	Necessary water
C_3S	0.24	68.8	0.165
C_2S	0.21	7.50	0.016
C_3A	0.40	8.10	0.032
C_4AF	0.37	9.20	0.034
Others	/	6.40	/
$W_n(t_\infty)$ = 0.247			

The quantity of chemically bonded water at time t, $W_n(t)$, is conventionally determined by the weight difference between the specimen dried at 105°C and heated to 1050°C. Specimens for measurement of the degree of hydration are taken from the small pieces of large ϕ11x22 *cm* specimens recovered after each destructive mechanical test. The degree of hydration results (second column of Table 4), determined according to equation 13, are entirely consistent with what is found in the literature.

4.4 MIP (Mercury Instrusion Porosimetry) and capillary depression

The specimens are again the small pieces recovered from large specimens after each destructive mechanical test. To stop the hydration at a given instant, we immediately put these small pieces in acetone. Then the specimens are dried in a vacuum for 2 days before the MIP.

The degree of hydration results enable us to establish the compositions at each instant. They are given in Table 4 for 100 cm^3 of the fresh paste. The volumetric mass of anhydrous cement is 3.1 g/cm^3. To calculate these compositions, we used an empirical relationship proposed by Powers /1946/ concerning the *Le Chatelier* contraction and the degree of hydration :

$$\begin{cases} W_n(t) = 0.247\,C(t) \\ \Delta V(t) = 0.279\,V_{wh}(t) \end{cases} \tag{14}$$

where :

$W_n(t)$: quantity of chemically bonded water (by mass)
$C(t)$: quantity of hydrated cement (by mass)
$\Delta V(t)$: *Le Chatelier* contraction
$V_{wh}(t)$: volume of water consumed during hydration

TABLE 4. Evolution of components for paste having W/C = 0.42

Age (day)	α (%)	v_{anhydr}	v_{water}	v_{wh}	Void
0	0	43.44	56.56	0	0
1	46.68	23.16	41.03	15.53	4.33
2	54.72	19.67	38.36	18.20	5.08
4	60.59	17.12	36.41	20.15	5.62
7	63.45	15.88	35.46	21.10	5.89
15	67.89	13.95	33.98	22.58	6.30
25	67.96	13.92	33.96	22.60	6.31

In this table, the last column corresponds to the *Le Chatelier* contraction $\Delta V(t_o)$ at each given instant t_o. With the MIP curves, we can obtain the pressure $p_{Hg}(\Delta V(t_o))$ that corresponds to the volume of mercury injected $\Delta V(t_o)$, and using equation 4 deduce the capillary depression $p_c(\Delta V(t_o))$ provoked by the *Le Chatelier* contraction $\Delta V(t_o)$ with the parameters γ_w, θ_w, γ_{Hg} and θ_{Hg} found in the literature :

$$\gamma_w = 73\times10^3\ J/m^2 \qquad \theta_w = 0°$$
$$\gamma_{Hg} = 480\times10^3\ J/m^2 \qquad \theta_{Hg} = 135°$$

TABLE 5. Capillary depression and macroscopic stress (paste having W/C = 0.42)

Age (day)	α (%)	p_c (MPa)	Σ^S (MPa)	h (%)
1	46.68	-1.18	-0.535	99.1
2	54.72	-2.34	-1.02	98.3
4	60.59	-4.55	-1.91	96.7
7	63.45	-6.83	-2.82	95.1
15	67.89	-8.64	-3.50	93.8
25	67.96	-9.71	-3.91	93.1

The capillary depression $p_c(t)$ and macroscopic stress $\Sigma^S(t)$ results defined by equation 6 are given in Table 5. The last column of Table 5 presents the internal relative humidity h calculated from the capillary depression according to the Kelvin law. We clearly see the self-desiccation phenomenon. We also see that hydration takes place at high relative humidity. Even the specimen having an age of one month is still very humid. All this is consistent with direct observations. If we plot our results on the figure presented by Copeland et al. /1955/ and Wittmann /1968/, we obtain Figure 7.

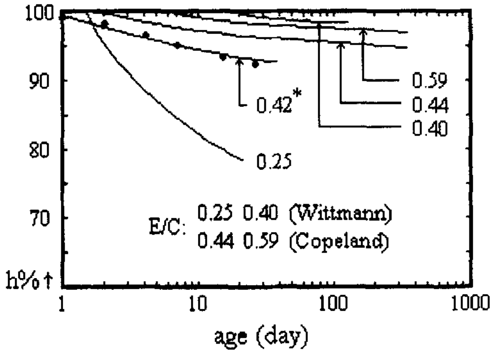

FIG 7. Comparison of self-desiccation results

4.5 Results of modelling

From the macroscopic stress $\Sigma^s(t)$ due to the capillary depression $p_c(t)$ and the macroscopic behavior $J(t,t')$, we can easily calculate the autogenous shrinkage defined by equation 8. Numerical results are given in Table 6. The shrinkage ε_r is presented in two parts, ε_{el} and ε_{cr}, corresponding respectively to the elastic part and the creep part in the function $J(t,t')$. The last column presents experimental results measured from the age of one day. For comparison, the ε'_r column is obtained by subtracting the deformation $\varepsilon_r(t = 1\ day)$.

TABLE 6. Comparison between the model and the measurement (W/C = 0.42)

Age (day)	ε_{el} (μ/m)	ε_{cr} (μ/m)	ε_r (μ/m)	ε'_r (μ/m)	$\varepsilon_{\exp}$ (μ/m)
1	72.24	23.72	95.96	/	/
2	106.67	46.87	153.54	57.58	60
4	142.73	88.32	231.05	135.09	160
7	171.23	141.18	322.41	226.45	260
15	202.24	247.66	449.90	353.94	400
25	212.37	332.11	544.48	448.52	480

5. Conclusions

- Self-desiccation is a consequence of hydration, and hydration takes place only at high relative humidity. So it is the variation of the capillary depression that plays the major role as compared to other physico-chemical phenomena.
- Calculated results show a very good agreement between estimates and measurements for the paste having W/C = 0.42. It proves that the capillary effect can explain autogenous shrinkage despite the existence of other physico-chemical phenomena.

- Calculated results also show that the viscous effect of cement paste is considerable, because the term ε_{cr} contributes the largest share of the autogenous shrinkage. According to our creep tests, the creep after one month under a load of 5 MPa can be as much as four to five times the instantaneous deformation. The creep will increase further if we let it continue.
- Based on our calculations, we confirm the conclusion reached by Buil /1979/, namely that autogenous shrinkage, under the effect of *Le Chatelier* contraction, can explain the shrinkage of hydration, and that it is not necessary, in the current state of our knowledge, to formulate, as mechanism of the shrinkage of hydration, any hypothesis in addition to that of self-desiccation.

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