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Consequences of desiccation on mechanical damage of concrete

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ABSTRACT: Desiccation shrinkage of concrete leads to formation of microcracks that damage mechanically concrete structures. It can be characterised by time variations of the material elastic properties. The main purpose of this study is to propose a simple modelling of this phenomenon, and to validate it by experimentation. We first explain the basic hypothesis of our model, and propose to formulate hydric damage by using an isotropic scalar variable, proportional to decrease in water content. We assume the hypothesis of uncoupling between drying induced damage and classical mechanical damage. Solving the diffusion equation of water transfers in the cylindrical case, and after integration, we obtain the expression of the dimensionless stiffness of a concrete cylinder as a function of time, and function of mass loss. These calculations are compared to experimental results performed on cylindrical specimen with 110 mm diameter and 220 height. The parameters needed by the model are given by experimental kinetics of mass loss. A good adequacy between experimental results and modeling in term of drying induced damage is established. The impact of hydric damage on tensile behavior is presented.

1 INTRODUCTION

Some major present preoccupations in civil engineering concern the long-term behavior of concrete structures. The designers require from those structures more and more stability in time of their mechanical, physical or chemical features. It is the case of storage containers of radioactive waste, airport tracks and also bridges. These requirements oblige the engineers to search for some compositions of concrete which increase durability.

The aggressive agents that could damage a concrete structure as sulfates, chlorides, water, carbon dioxide are known. The difficulty consists in foreseeing with sufficient precision the impact of these aggressions, and modeling them in order to propose some formulations and making techniques to avoid them.

According to Wittmann, (Wittmann 1997), structure durability could be highly improved if desiccation phenomenon were correctly taken into account. It is the main purpose of our survey. Its effects are multiples: cracking and microcracking due to hydric gradients (Bazant & Wittmann 1982, Khelidj et al. 2000) which can be important and facilitate aggressive agents penetration (Sadouki & Wittmann 2000), reduction of the stiffness of structures (Burlion et al. 2000). There is besides creation of cement hydration gradients, with insufficient hydration near the outer parts (Khelidj et al. 2000), some potential deterioration of superficial repairing of constructions can occur (Bissonnette & Pigeon 2000). Generally, calculation does not take into account more than inclusive or empirical values of desiccation shrinkage. To the worse, the effects of drying of concrete are omitted.

We study here the effects of desiccation on the mechanical behavior of concrete. A study of choice of pattern of drying is made from (Bazant & KIM 1991, Mainguy 1999). Drying leads to hydric gradients that engender creation of microcracks (Bazant 1999, Acker 1988). Some experiments showed a loss of stiffness of cylinder pieces submitted to the drying only (Burlion et al. 2000).

These different results lead us to define an hydric damage proportional to the reduction of local water content. We then introduce a scalar variable in order to describe this hydric damage supposed isotropic, in parallel with (Carde & François 1997, Gérard 1996, Pijaudier-Cabot et al. 1998). A general formulation of the model is presented in the framework of thermodynamic of non-reversible processes. An evolution law of the hydric damage is proposed. The evolution of the mechanical damage is described by a yield function in term of energy restitution proposed by Bodé (Bodé 1994). A simplified version at unidimensional case is developed. Finally, experimental tests that allow to identify the parameters of the material and the structure are presented. The comparison between the test results and those from calculation confirm the validity of our model.

2 HYDRIC DAMAGE: BASIC HYPOTHESIS OF THE PROPOSED MODEL

2.1 Modelisation of drying

Concrete is a material of which pores have small diameters and a high specific surface. So, interactions between the solid matrix and pore water are important. Several phenomena exist: adsorption of water moleculars on solid partition-wall, which by repulsion between themselves generate disjunction pressures which effect is maintaining the partitions of the pores afar off (Bazant 1972), surface tension at the liquid-solid interfacing that creates tensile microstresses between moleculars (Wittmann 1997), capillary depressions with apparition of menisci. The consequences of these phenomena at macroscopic level are quite important. Beddoe (Beddoe & Lippok 1999) measured uniaxial tensile stresses on a hardened cement paste cylinder submitted to capillary suction on the order of 8 MPa.

At macroscopic level, drying of concrete is also a complex phenomenon. Several types of transfers intervene, in two different states: liquid and vapor.

Three types of hydrous transfers exist (Mainguy 1999): Darcy flow of liquid water, Darcy flow of vapor, and diffusive transfer of vapor. Considering the experimental results that allowed (Baroghel-Bougny 1994) to identify sorption-desorption isotherm of cylindrical test bars, Mainguy (Mainguy 1999) analyzed the influence of the three kinds of transfers on mass loss kinetics of a concrete. He showed that for vapor, the Darcy movements are negligible compared to diffusive movements and that diffusive transfer of vapor is small. A description of transfers as a liquid form with evaporation to the sides of the structure and the use of a non-linear diffusion equation expressed as a function of water content are sufficient to describe correctly kinetics of mass loss during time (Coussy et al. 2000).

For this reason, we do not distinguish the different types of hydric transfers. We take them into account globally with a coefficient of hydric diffusion C expressed in m^2/s, and we use the classical pattern proposed by Bazant (Bazant & Kim 1991). The expressions translating the conservation of water mass and the flux of relative humidity are

$$\frac{\partial w}{\partial t} = -divJ \qquad J = -Cgradh \tag{1}$$

where t is time, h relative humidity inside the pores, w the water content , C the coefficient of hydric diffusion which depends on h. The identification of the parameter C evolution requires to carry out drying tests on concrete. The results show that C decreases with relative humidity inside the material (Baroghel-Bougny 1994).

The sorption-desorption isotherm is written under the $w=g(h)$ shape, and thus (Bazant & Wittmann 1982)

$$\frac{\partial h}{\partial t} = \frac{1}{g'(h)}\frac{\partial w}{\partial t} \tag{2}$$

in which

$$\frac{\partial w}{\partial h} = g'(h) \tag{3}$$

with $g'(h)$ hydric capacity (slope of the desorption isotherm).

If hydration of cement is accomplished, there is no more consumption of water by chemical reaction. The only migrations of water are due to an hydric unbalance between outside and inside the specimen. From relation (1), we obtain the non-linear diffusion equation which is a function of h.

$$\frac{\partial h}{\partial t} = \frac{1}{g'(h)} div(C(h)gradh) \tag{4}$$

This equation requires, for its resolution, on one hand the sorption-désorption isotherm of the studied material, and on the other hand the values of coefficient of hydric diffusion, function of h, and finally limit conditions. The characterization of the sorption-desorption isotherm is very long and delicate because the possibilities of errors in the measurement are important (Baroghel-Bougny 1994). The results obtained by the desorption isotherm influence totally the numerical results of the modelisation of hydric transfers from the specimen to the outer environment.

The value of C is assumed to be constant in this first study, and that will correpond to the phase of drying where liquid transfers are still occurring, knowing that in our climates only 50% of the evaporable water inside a structure is liable to do it (Acker 1988) This range of variation of water contents is a limit of our pattern because it is the presence of liquid water that allow to assume a proportionally relation between hydric damage and mass loss. The diffusion equation becomes therefore linear. It would be necessary in theory to take in counts the effects of carbonation which decreases the value of diffusion coefficient (Pihlajavaara 1982). We disregard its effects in our survey supposing that the duration of our tests were sufficiently short in order to avoid any interactions.

2.2. Existence of an hydric damage

The drying of concrete is not uniform within structures in time. Whereas the outer layers are to the same relative humidity that the one of the outside environment, the core of the specimen keeps being water saturated. There is therefore existence of hydric gradients. At the microstructural level, some capillary depressions, variations in disjunction pressure and superficial tensions are generated and induce tensile stresses. In the part where the hydric gradient is high, and notably near the skin of concrete, there is cracking as soon as hydric tensile stresses reach the limit tensile strength of the concrete (Bazant 1972, Sadouki & Wittmann 2000, Acker 1988). Besides, some microcracks proceed of fact that the Young modulus is higher than the one of the cement matrix retracting, that provokes differential deformations and microcracks (Hearn 1999).

Furthermore, Bazant (Bazant & Raftshol 1982) showed that in order to avoid any drying crack it was necessary to decrease the relative surrounding humidity sufficiently slowly and gradually so that there is no difference of relative humidity inside the specimen superior to 2% and to use test specimen unreasonably thin (order of the millimetre of thickness). In case of brutal exhibition to an outside relative humidity, only structures with 0.1 mm thickness would be exempt of microcracks.

One will observe an heterogeneous microcracking (Bazant & Raftshol 1982, Sadouki & Wittmann 2000, Colina & Acker 2000). This cracking appears first to the level of the skin, and then their depth and their width increase. When the front of drying penetrates progressively toward the core of the specimen, a network of parallel cracks is created which width and spacing are proportional to the distance of penetration of the drying (Bazant & Raftshol 1982). There is therefore cracking in the breast of the material. We suppose in the following that for a given cross section the presence of cracks leads to a loss of resistant surface. We can make a parallel with mechanical damage, of which one definition is the diminution of load resistant surface (Lemaître & Chaboche 1988). We then formulate the existence of an hydric damage. The comparison between those two kinds of damage stops here because the size and the distribution of the cracks is quite different for each case. Besides, we assume that drying induced cracking is diffuse in the material and locally proportional to decreasing of water content. The damage is by elsewhere supposed isotropic.

For this first pattern, we take into account hydric damage with a simplified manner, under the shape of an ageing function similar to those already proposed by (Carde & François 1997, Gérard 1996, Pijaudier-Cabot et al. 1998) in order to describe damage induced by leaching of concrete, or by (Nechnech 2000) in order to describe damage caused by thermal effects.

2.3 General formulation of the model

We stand in the setting of thermodynamic of non-reversible processes, more precisely the one of isotropic damageable ageing elasticity. We will suppose that the Poisson ratio υ keeps constant. The variable of hydric damage is assumed to be isotropic.

The potential of free energy Ψ describes the reversibility of the processes (recuperation of the energy when unload).

$$\Psi = \Psi(T, \varepsilon_e, d_m, d_h) \tag{5}$$

In isothermal condition, we could write

$$\rho\Psi = \frac{1}{2}\varepsilon^e : E : \varepsilon^e \tag{6}$$

with E stiffness tensor, defined as following, with E_0 tensor of initial stiffness

$$E = (1-d_m)(1-d_h)E_0 \tag{7}$$

The damage variables d_h and d_m (respectively hydric damage and mechanical damage) are internal variables, non directly observable.

The Clausius-Duhem inequality gives:

$$(\sigma - \rho\frac{\partial\Psi}{\partial\varepsilon^e}) : \dot{\varepsilon} - \rho\frac{\partial\Psi}{\partial d_m}\cdot\dot{d}_m - \rho\frac{\partial\Psi}{\partial d_h}\cdot\dot{d}_h \geq 0 \tag{8}$$

The state laws can be deduced from (8)

$$\sigma = \rho\frac{\partial\Psi}{\partial\varepsilon^e} = E : \varepsilon^e = (1-d_m)(1-d_h)E_0 : \varepsilon^e \tag{9}$$

The force variables relative to internal variables are called Y and Z. Y is the rate of dissipated energy due to mechanical damage

$$Y = \rho\frac{\partial\Psi}{\partial d_m} = -\frac{1}{2}(1-d_h)\varepsilon^e : E_0 : \varepsilon^e \tag{10}$$

$$\text{so } Y \leq 0 \tag{11}$$

Z is the rate of dissipated energy due to hydric damage

$$Z = \rho\frac{\partial\Psi}{\partial d_h} = -\frac{1}{2}(1-d_m)\varepsilon^e : E_0 : \varepsilon^e \tag{12}$$

$$\text{so } Z \leq 0 \tag{13}$$

The rate of dissipation of energy $\dot{\Phi}$ is equal to

$$\dot{\Phi} = \sigma : \dot{\varepsilon} - \dot{\Psi} \tag{14}$$

The second principle of thermodynamic imposes that

$$\dot{\Phi} \geq 0 \tag{15}$$

In using uncoupling hypothesis between mechanical and hydric damage,

$$\begin{cases} -Y\dot{d}_m \geq 0 \\ \\ -Z\dot{d}_h \geq 0 \end{cases} \text{ and so } \begin{cases} \dot{d}_m \geq 0 & (16) \\ \\ \dot{d}_h \geq 0 & (17) \end{cases}$$

Relation (16) tells us that mechanical damage can not decrease. Neither skinning nor complete closure of the cracks is possible. The non reclosure might be explained by friction of the lips of the cracks between them (Ragueneau et al. 2000).

In case of unloaded drying only structure, the equation (17) shows us that hydric damage can only grow or remain the same. The uncoupling hypothesis between the two types of damage allow to point them. It could be discussed since on one hand the hydric cracks modify the mechanical damage of concrete structures (Burlion et al. 2000), and on the other hand we can assume that the increase of porosity (caused by microcracking induced by mechanical loading) modify interactions between liquid and solid and therefore the distribution of cracks bond to drying.

2.4 Evolution of mechanical damage

In order to describe mechanical damage several yield functions can be used. For our model we have chosen the yield function used by Bodé (Bodé 1994), expressed in term of rate of energy restitution. Bodé showed that calculation could be done on already damaged structures. It is our case, since structures will be hydrically damaged before mechanical loading.

$$F(Y) = Y - K^m(Y) \quad (18)$$

with $K^m(Y)$ variable of hardening (by analogy with plasticity), $K^m(Y)=Y_0$ initially and $K^m(Y)=sup(Y, Y_0)$ then. Y_0 is the yield of initial damage. We stand in the setting of standard generalised materials. The yield function is supposed to be a pseudo-potential of dissipation. The complementary evolution laws explaining the normality property come from

$$F(Y) = 0 \quad et \quad \dot{F}(Y) = 0 \quad (19)$$

and

$$\begin{cases} \dot{d}_m = \dot{\lambda}\dfrac{\partial F}{\partial Y} \\ \dot{z} = \dot{\lambda}\dfrac{\partial F}{\partial K^m} \end{cases} \Leftrightarrow \begin{cases} \dot{d}_m = \dot{\lambda} \\ \dot{z} = -\dot{\lambda} \end{cases} \quad (20)$$

with $\dot{z}$ hardening function associated to $K^m(Y)$ chosen under the shape

$$\dot{z} = -H\dot{K}^m \quad (21)$$

The relation (20) gives

$$\dot{d}_m = -\dot{z} \quad (22)$$

Therefore, we have

$$\begin{cases} F(Y) = 0, \quad \dot{F}(Y) = 0 : \dot{d}_m = H\dot{Y} \\ F(Y) < 0 \quad or \quad F(Y) = 0, \dot{F}(Y) < 0 : \dot{d}_m = 0 \end{cases} \quad (23)$$

with H function of Y that can be identified by experiments. We took the following relation for H (Bodé 1994):

$$H(Y) = \frac{b_1 + 2b_2(Y - Y_0)}{\left[1 + b_1(Y - Y_0) + b_2(Y - Y_0)^2\right]^2} \quad (24)$$

where b_1 and b_2 are parameters.

Integrating $H(Y)$, we get the evolution of mechanical damage

$$\begin{cases} F(Y) = 0, \dot{F}(Y) = 0 : d_m = \Gamma(Y) \\ F(Y) < 0 \quad or \quad F(Y) = 0, \dot{F}(Y) < 0 : \dot{d}_m = 0 \end{cases} \quad (25)$$

with

$$d_m = \Gamma(Y) = 1 - \frac{1}{\left[1 + b_1(Y - Y_0) + b_2(Y - Y_0)^2\right]} \quad (26)$$

2.5 Evolution of hydric damage

In order to describe the evolution of the hydric damage, we stand in the same framework of formulation as that proposed by Mazars (Mazars 1984) (18). We introduce a yield function

$$F_h(w, d_h) = f(w) - K^h(d_h) \quad (27)$$

with $K^m(d_h)$ history variable, and $f(w)$ a function of water content.

This relation translates the link between hydric damage d_h and the evolution of water content in the material.

We define the evolution of d_h by

$$\dot{d}_h = \Re(w) \cdot \dot{w} \quad (28)$$

We assume a proportionality between $\dot{d}_h$ and $\dot{w}$, that translates physically the impact of water content decreases upon cracking of the material.

$$\dot{d}_h = -a\dot{w} \quad (29)$$

with a constant. After integration of this relation with time, and by supposing that there is no hydric damage when the material is initially saturated i.e. $d_h = 0$ at initial state.

Thus we obtain the expression of hydric damage function of water content:

$$d_h = -a\langle w - w_0 \rangle \quad (30)$$

with w_0 initial water content, at saturation equal to 1.

3. SIMPLIFIED HYDRIC DAMAGE MODEL: UNIDIMENSIONAL CASE

We developed a simplified model in order to test the validity of our hypothesis and to compare its responses to experimental results. We studied the classical unidimensional case corresponding to the drying of a cylindrical test specimen supposed of infinite length. The sorption-desorption isotherm was identified from experimental measures of mass loss of concrete cylinders with 110 mm diameter and 220 mm height performed by (Burlion et al. 2000).

3.1 Drying model

Diffusion equation (4) is written, with C constant, in the cylindrical case, with r radius which origin is at the core of the piece

$$\frac{\partial h}{\partial t} = \frac{C}{g'(h)}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial h}{\partial r}\right) \quad (31)$$

The resolution of this equation was done with finite differences method. It gives relative humidity and water content as functions of r.

3.2 *Evolution of hydric damage*

Drying times will be far longer in case of massive structure than for thin one because they are proportional to the square thickness of pieces (Bazant & Raftshol 1982). Hydric damage will occur more quickly and intensely with a structure of short dimensions.

Hydric damage can be expressed in the case of cylindrical symmetry, with r spatial variable

$$d_h(r,t) = -a(w(r,t) - w_0) \tag{32}$$

To the moment when starts the drying, the test bars are considered like an homogeneous material, with a uniform water content equal to w_0. During drying, water content distribution changes and is no more homogeneous. The specimen then must be regarded as a structure. Thus, during uniaxial compression tests on the concrete cylinders, we will accede to the stiffness values of the structure in time. At time t_0, the stiffness $K(t_0)$ can be related to the average hydric damage of the structure $\bar{d}_h(t_0)$

$$\bar{d}_h(t_0) = 1 - \frac{K(t_0)}{K_0} \tag{33}$$

with K_0 initial stiffness of the structure.

Our test pieces being cylindrical, and supposed of infinite length for the experimental analysis, we will assume that for any transversal cut, the distribution of the material hydric damage is the same. We finally suppose that the stiffness of the structure is equal to the surfacic average on a cross section of the damaged rigidities of the material. It is the same as to say that the global stiffness loss of the structure is equal to surfacic average of damage for a cross section. Let us translate this condition now, so as to identify a

$$\bar{d}_h(t_0) = \frac{1}{A}\int_A d_h(x,t_0)dA \tag{34}$$

The constant a value is known, and for the cylindrical case

$$a = -\frac{\bar{d}_h(t_0)}{\frac{2}{R^2}\int_0^R w(x,t_0)xdx - w_0} \tag{35}$$

The scale effects remain to study in the framework of this modelisation. It is likely that its influences upon parameters identification is rather important. For large specimens, it would be very difficult to demonstrate the existence of an hydric damage (Colina & Acker 2000).

3.3 *Expression of stiffness loss function of time*

We stand to the level of the specimen, considering it as a structure. The stiffness K of this structure can be written as (34) with K_0 initial stiffness of the specimen, supposed to be equal to the initial rigidity E_0 of the material. We study the dimensionless stiffness so as to compare correctly several specimens. The dimensionless stiffness in cylindrical case using relation (35) can be expressed like

$$\frac{K(t)}{K_0} = 1 - aw_0 + \frac{2a}{R^2}\int_0^R w(r,t)rdr \tag{36}$$

where R is the radius of the cylinder.

3.4 *Expression of mass loss function of time*

Mass loss is a data directly observable during the tests. Liquid water mass inside the test specimen at t time is written

$$M_w(t) = \int_V \phi\rho_w S_w dV \tag{37}$$

with ϕ porosity of the volume element, ρ_w volumetric mass of water supposed to be constant, and S_w water saturation degree.

The distribution of porosity is assumed to be uniform in the volume, and constant. This assumption remains questionable, since cracking with mechanical origin increases the porosity (Bazant et al. 1986).

The initial saturation is equal to 1, therefore

$$S_w(r,t) = \frac{w(r,t)}{w_0} \tag{38}$$

Mass loss is supposed equal to the only decrease of liquid water in the pores (Mainguy 1999). For a cylinder, the remaining water mass is

$$M_w(t) = 2\pi l\frac{\phi\rho_w}{w_0}\int_0^R rw(h(r,t))dr \tag{39}$$

with l height of the specimen.

From relations (41) and (42), we express dimensionless stiffness as function of loss in mass.

$$\frac{K(t)}{K_0} = 1 + \frac{aw_0M_0}{100M_{w0}} * \left(100\frac{\Delta M(t)}{M_0}\right) \tag{40}$$

where M_0 is total mass at starting of drying, M_{w0} initial liquid water mass, and $\Delta M(t)$ the mass loss.

4. COMPARISON BETWEEN EXPERIMENTAL RESULTS AND THE MODEL RESPONSE

For testing and validating the simplified model, we need the experimental curve of loss in mass function of time. It will give the parameters that have to be known. Then, we will compare the results in term of evolution of the dimensionless stiffness function of time and of mass loss.

4.1 *Experimental investigation*

The parameters we have identified so as to test the pattern are coefficient of hydric diffusion, sorption-desorption isotherm, and porosity. The coefficient of hydric diffusion C was estimated from (Pihlajavaara 1982). The sorption-desorption isotherm was recreated from kinetics of weight losses in time. The shape of the curve found was similar to the experimental one from (Baroghel-Bougny 1994). For the identification of the parameter a, we used the value reached by the dimensionless stiffness at 60 days, value issued from uniaxial compression tests.

The test specimens were designed so as to obtain high hydric transfer kinetics. In order to get an important porosity, the concrete was formulated with a classical W/C ratio equal to 0.6. The formulation displayed in the following table will allow to reach a compressive resistance under 30 MPa at 28 days.

Table 1: Concrete composition

Cement CEM-II-B	324 kg/m3
Water	205 kg/m3
Gravel 4/8 mm	1110 kg/m3
Sand 0/4 mm	668 kg/m3
W/C	0.63

The test pieces cast are cylindrical, with 110 mm diameter and 220 mm height. After 28 days curing in a pool at 20°C allowing to get a quasi total hydration of the cement, the specimen were conserved under a relative humidity of 60% ± 5%, and a temperature of 21°C ± 1°C.

The specimens are submitted to the drying only. In this curing conditions, we can assume that there is no more thermal shrinkage or endogenous shrinkage (Colina & Acker 2000, Burlion et al. 2000).

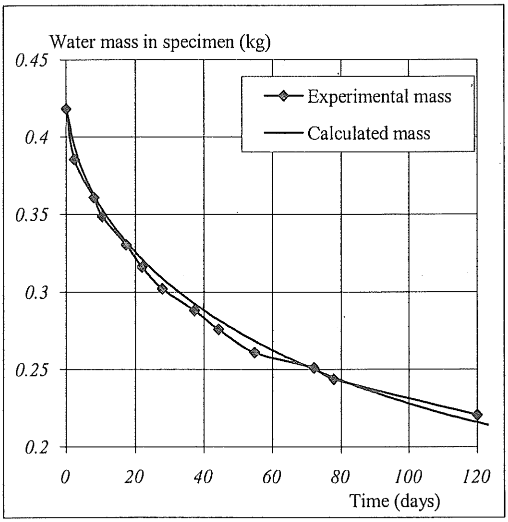

Figure 1: Recreation of loss in mass kinetics

4.2 Identification of the parameters

For the coefficient of hydric diffusion we took from (Pihlajavaara 1982) $C=10^{-11} m^2/s$. The porosity was estimated at $\phi=0.2$.

Figure 1 shows the curve of experimental variations of water mass as a function of time, and the curve issued from the model. Uniaxial compression tests were done at different times of drying. It gave initial stiffness value and the evolution of stiffness during drying. This allow to calculate parameter $a = 5{,}5687$.

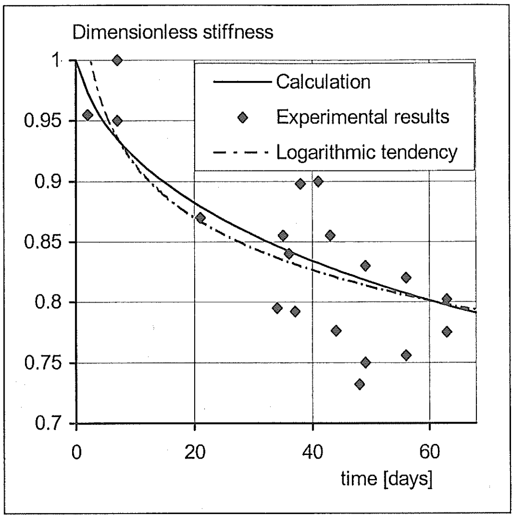

Figure 2: Comparison between dimensionless stiffness calculated and from experiments

4.3 Comparison between calculation and experiment

We then plotted the dimensionless stiffness versus time and versus loss in mass in percentage curves. The curves are showed in the following figure 2 and figure 3.

These curves show a very good agreement between logarithmic tendency curve of experiments and model response.

If we now study variations of dimensionless stiffness versus mass loss, plotting the following curve.

We can see on this curves a good adequacy between modeling and test results. Our model gives a linear response. It is due to our hypothesis. This shape can be discussed.

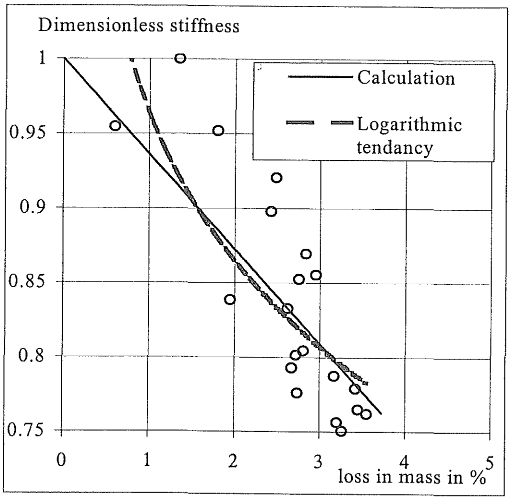

Figure 3: Dimensionless stiffness versus loss in mass

4.4 *Consequence of hydric damage on tensile behavior of concrete*

Hydric damage will decrease, as showed in this paper, stiffness. It will also modify other parameters, like maximal tensile stress. We can see it in the following figure 4, where are plotted three curves. First curve was plotted with only mechanical damage from (Bodé 1994). Second curve with an additional hydric damage equal to 0.1, and third with hydric damage at 60 days, equal to 0.2. The maximal tensile stress is decreased by hydric damage.

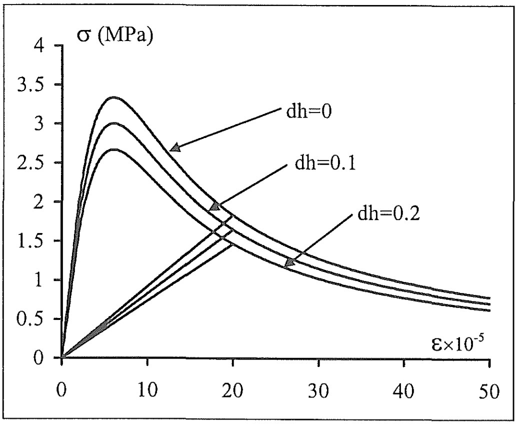

Figure 4: Tensile behavior of coupled hydric damaged and mechanical damaged concrete

5. CONCLUSION

An original modeling is presented in this paper so as to study the influence of drying on mechanical behavior of concrete. Drying induced damage can be assumed isotropic and proportional to local decrease in water content. It can be modeled as a scalar damage variable. The evolution of stiffness function of time or mass loss is known with good adequacy.

A discussion can be done about the hypothesis we took. First, a non constant coefficient of hydric diffusion could be introduced, estimated from (Bazant & Raftshol 1982) for instance. The hydric damage was assumed to be isotropic. Experiments could show an anisotropic distribution of the microcracks. Finally, mechanical damage and hydric damage should be coupled (Burlion et al. 2000) in order to show up their interactions.

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