Hygro-mechanical modelling of self induced stresses during the service life of concrete

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ABSTRACT

The prediction of concrete's long-term properties is of great importance for durability issues. The development of internal stresses generated by drying affect these latter especially the mechanical strength or the Young's modulus. In this paper, internal stresses due to drying are considered explicitly. In agreement with experimental results (not presented), the drying effects are modelled in a process taking into account the evaluation of the water state of the material, the modelling of the induced shrinkage strains and ending in mechanical computation. The evolution of the mechanical characteristics, the cracking induced by drying and the residual transport properties of the material can thus be determined.

Keywords: Drying, Hydro-mechanical coupling, Cracked concrete, Numerical modelling, Permeability

1. INTRODUCTION

Cementitious materials are the most widely used in civil engineering works. Whether in the fields of housing, transport or energy, they are used heavily and have to face a various and sometimes aggressive environments. Today, the durability of buildings is a major challenge and to answer this problem it is necessary, among other things, to predict the long-term behaviour of the structures. Nevertheless, this task remains difficult. The great heterogeneity of the material combined with multiple origins of stresses (thermal, chemical, drying, mechanical) make the work complex.

The aim of this work is to take into account the effects of desiccation in the determination of the mechanical properties and macroscopic behaviour of concrete structures. Indeed, conventionally, when the mechanical properties of concrete are characterized, the internal stresses are not considered and the phenomena of desiccation are not taken into account. Unfortunately , all structures naturally dry. The water gradient between the surface and the core of a concrete structure leads to a heterogeneous stress state and generates micro cracking. In some cases (durability, tightness), this phenomenon may be of major importance.

Although it seems remarkable, the impact of drying and micro cracking on mechanical properties is not so much studied. If we are interested in Young's modulus, many authors find a reduction of the order of 4 to 30% after drying [1]. Regarding the compressive strength, no consensus was found. Some authors report an increase [2] while others a decrease [3]. In terms of tensile strength, a slight increase was observed in splitting tests [3], while an initial decrease followed by a gradual increase until a relative humidity of 0% was reached was noticed in bending [4]. A decrease followed by an increase is also measured on direct tensile tests [5]. It is noteworthy that in the description of the phenomenon three predominant factors can be identified. One of them, capillary pressure improves the strength of the material. The water gradient as well as the incompatibility of deformation between the cement paste and the aggregates (and at a lower level between anhydrous cement and C-S-H for instance), decreases the mechanical characteristics in the long term.

Few studies compare the influence of desiccation on mechanical properties by comparing the results obtained according to the different standard characterization methods. Moreover regarding modelling, some authors model these effects [6], but it is not a widespread approach since few studies try to predict the impact of drying on mechanical properties. This communication develops a hydro-mechanical models in order to investigate the impact of drying. Simulations results are then compared with experimental campaigns not presented in this paper (see [7] for the presentation of test's results).

2. NUMERICAL MODELLING

2.1 Drying modelling

The drying of cement-based materials is a complex phenomenon. Several, more-or-less coupled, mechanisms are involved: permeation, diffusion, adsorption-desorption and condensation-evaporation. Drying can be analysed through the resolution of liquid water, vapour and dry air mass balance equations. The use of several hypotheses [8,9] allows for considering only the mass balance equation of liquid water:

$$\frac{dS_l}{dP_c}\frac{dP_c}{dt} = div\left(k_{rl}(S_l)\frac{K}{\mu_l \phi} grad(P_c)\right) \tag{1}$$

where S_l, P_c, ϕ, K, k_{rl} and μ_l are, respectively, the saturation degree, the capillary pressure, the porosity, the intrinsic permeability, the relative permeability and the viscosity of the liquid water.
It is shown [8,9] that this equation is sufficient for an accurate prediction of the drying of ordinary and high-performance concretes at 20°C with a relative humidity greater than 50%. The capillary pressure and the relative permeability are related to the degree of saturation through van Genuchten's relations [10]:

$$S_l = \left(1 + \frac{P_c}{P_0}\right)^{1-\gamma} \tag{2}$$

$$k_{rl}(S_l) = S_l^{nk}\left(1 - \left(1 - S_l^{\frac{1}{\beta}}\right)^{\beta}\right)^2 \tag{3}$$

where nk, P_0 and β are materials parameters.
Depending on the studied sample, modelling was based on 2D or 3D meshes. Drying at surfaces were modelled using a convection-type approach. In addition, it was found numerically that the evolution of humidity conditions in the climatic chamber (used for the conservation of the experimental samples) did not have a significant impact on the evolution of drying, with respect to the assumption of a constant relative humidity (disregarding hysteresis effects). Therefore it was not taken into account and an average value was used in the simulations. Finally, an inverse identification tool was implemented to determine *nk*, *K*, P_0 and β values thanks to experimental mass lost results.

2.2 Drying shrinkage modelling

There are different ways to model drying shrinkage. Some of these are based on the theory of porous media mechanics. The development of this kind of modelling could be easily found in literature. See [11] for instance. Other models are based on phenomenological observations. Indeed, following experimental results [12,13] found a proportional relation between water content variation and drying shrinkage rate:

$$\underline{\underline{\dot{\epsilon}}}_{ds} = k_{ds}\,\dot{w}\,\underline{\underline{1}} \tag{4}$$

where k_{ds} is a hydrous compressibility factor and $\underline{\underline{1}}$ is the unit matrix. It is possible to find alternative approaches but in this present work this modelling approach was chosen. It is easy to implement and gives satisfactory results in our case. Moreover, the modelling of the drying shrinkage takes into account basic and drying creep. This allows a relaxation of the stresses and then decreases of the damage induced by the drying gradients. Creep models used are not developed here. The reader can refer to [14] for more information.

2.3 Mechanical modelling

This study is based on 3D modelling of all samples. It involves non-explicit modelling of concrete cracking using a damage theory. The variable D, a scalar damage variable ranging from 0 to 1, is considered in the stress-strain relation:

$$\sigma_{ij} = (1 - D)C_{ijkl}\epsilon_{kl}^{elas} \tag{5}$$

where σ_{ij}, C_{ijkl}, ϵ_{kl}^{elas}, are respectively stress, elastic stiffness and elastic strains. The evolution of the damage relies on an equivalent strain criterion, calculated from the equivalent strain ϵ_{eq} introduced by Mazars [15]. It was shown [16] that the evolution of damage in tension could be taken as an exponentially decreasing:

$$D = 1 - \frac{\epsilon_{d0}}{\epsilon_{eq}}.\exp\left(-B_t\left(\epsilon_{eq} - \epsilon_{d0}\right)\right) \tag{6}$$

where $\epsilon_{d0} = f_t/E_c$, with f_t the tensile strength ,E_c the Young modulus and B_t a parameter controlling the softening behaviour of the concrete.

Softening behaviour of concrete may lead to non-unity of solutions and mesh dependency. Energetic regularization prevents these difficulties [17]. Regularization is then based on the parameter B_t, which is a function of h the size of the finite element, f_t the tensile strength, G_f the fracture energy and a parameter for the initiation of the damage ϵ_{d0} as described above.

$$B_t = \frac{h.f_t}{G_f - \frac{h.\epsilon_{d0}.f_t}{2}} \tag{7}$$

Finally, a random field for the tensile strength generated by the Turning Band Method [18] is used in order to take into account the variability of the material. The chosen parameters are:

- A variation coefficient equal to 10 %;
- A correlation length three times larger than the biggest aggregate.

2.4 Crack opening routine

To get crack openings, models usually rely on two main classes of techniques: post process technics from a continuous damage field [19] or the use of discontinuous models (XFEM, discrete or cohesive elements for instance). In this work, a post processed cracking method based on the damage field of the continuous model presented in the section (2.3), taking into account delayed deformations was used.

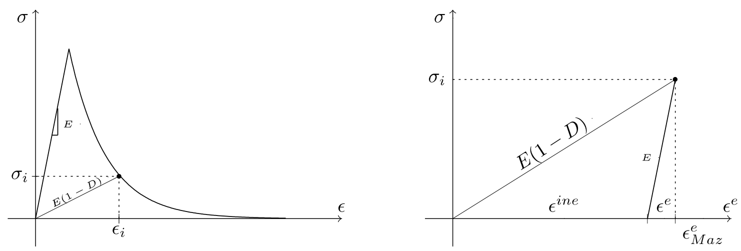

Figure 1. Uniaxial tension test with Mazars model

We can consider a strain partition as in (8) with ϵ^e_{Maz} the mechanical strain given by the Mazars' model.

$$\epsilon_{ij} = \epsilon^e_{Maz} + \epsilon^{drying}_{kl} + \epsilon^{creep}_{kl} + \cdots \tag{8}$$

This mechanical strain is given by the equation (9) coming from equation (5):

$$\epsilon^e_{Maz} = ((1-D)C_{ijkl})^{-1}\sigma_{ij} \tag{9}$$

with D the damage, C_{ijkl} the stiffness matrix and σ_{ij} the stresses. We can easily find the elastic strain, which is link to the stress state by the stiffness matrix (equation (9)). We can make the assumption that the total strains can be divided into two parts. An "elastic" part and another "inelastic" parts (as it is shown in figure 1).

$$\epsilon^e_{Maz} = \epsilon^{elas}_{kl} + \epsilon^{in}_{kl} \tag{10}$$

It is thus possible to calculate the various strains necessary for the quantification of the crack opening. The "elastic" strains is given by (11) while the "inelastic" strains is given as the difference between the total deformation field and the "elastic" deformation field (12)

$$\epsilon^{elas}_{kl} = {C_{ijkl}}^{-1}\sigma_{ij} \tag{11}$$

$$\epsilon^{ine}_{kl} = \epsilon^e_{Maz} - \epsilon^{elas}_{kl} \tag{12}$$

Final the crack opening is then the product of the inelastic strains times the size of the element.

$$U_k = \epsilon^{ine}_{kl}.h_l \tag{13}$$

3. RESULTS

The results presented in this section try to simulate the behaviour of 10x10x84 cm specimens tested in three point bending. They were kept under drying conditions (50% RH under a temperature of 21°C) for 70 days before testing. Parallel to this, other test pieces (similar in terms of geometry as well as concrete used) are kept in wet conditions. The results are then compared in order to characterize the impact of drying.

3.1 Drying results

The specimens' drying conditions (i.e. 50% RH) allow to only take into account the permeation in the modelling process. After an identification of the drying parameters by an inverse method based on the mass loss curves, the specimens are characterized with respect to the drying. The experimental mass losses as well as the gradients within the test pieces are obtained.

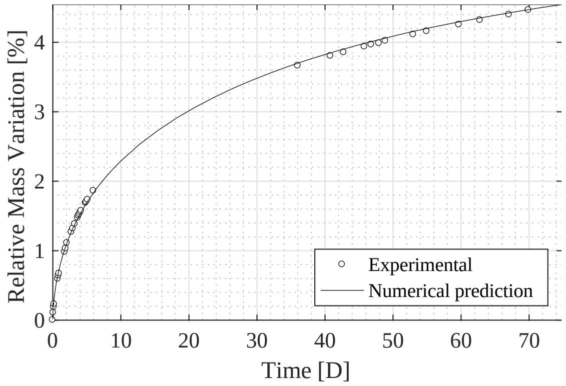

Figure 2. Evolution of Relative Mass Variation

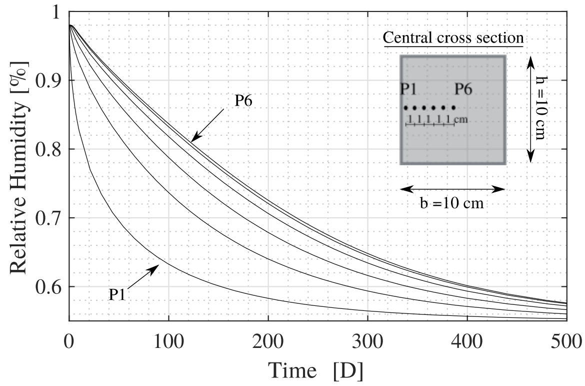

Figure 3. Evolution of RH gradient along the sample thickness

Figure 2 shows that the relative mass variation is well predicted. The gradient of moisture within the test piece (figure 3) is strong in the first moments and then tends to decrease over time. This difference between the core of the sample and the edge will therefore generate differential strains which will induce micro cracking. In addition, a structural effect will be brought due to the non-homogeneity of the concrete with respect to moisture. This difference will generate additional strength.

3.2 Shrinkage

Phenomenological modelling of the drying shrinkage is based on the determination of water content gradients. The latter are obtained from the moisture gradients determined by the modelling of the drying process. Thus, the drying shrinkage and the state of internal stresses generated are obtained.

The drying shrinkage is calibrated on 7x7x28 cm specimens. The phenomenological model can correctly predict the evolution of drying as shown in figure 4. The final value is consistent nevertheless the initial part at the short term seems not well predicted. This is mainly due to the mistake made in the prediction of drying. Indeed, the short-term behaviour is strongly impacted by the boundary conditions, difficult to characterize and rather variables depending on the case

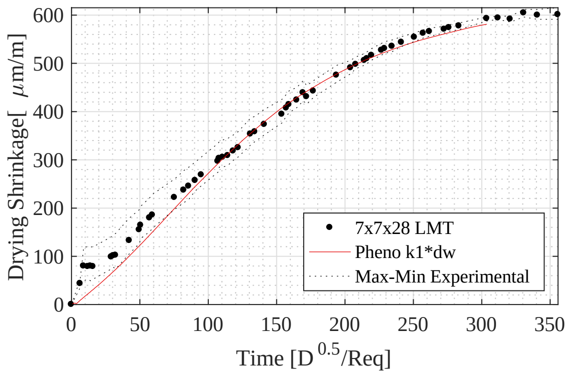

Figure 4. Evolution drying shrinkage

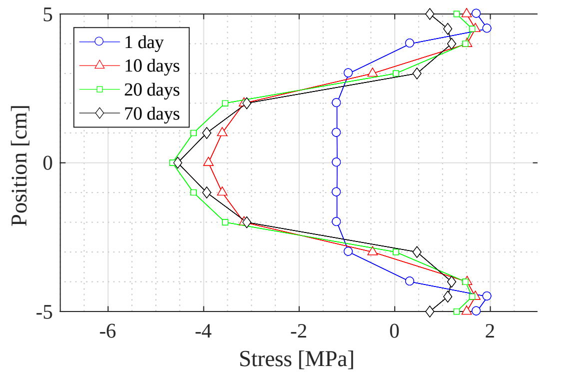

Figure 5. Evolution of normal stress along the center line

If one is interested in the state of initial stresses, in the short term (1 day), tensile areas on the edge of the sample appear (figure 5). The stresses are initially strong then the areas impacted by tension are damaged and the stress decreases in the short time. As time goes by, the thickness impacted by drying increases and the compressive stress at the center tends to increase. The internal stresses imposed on the mechanical model correspond to the state of stress after 70 days. The section is visibly not at equilibrium.

3.3 Mechanical

Finally, the mechanical modelling is divided into two parts. It starts by the identification of the models parameters on wet beams' experimental curves (figure 6) and then follow by the modelling of the drying process on similar beams exposed to drying.

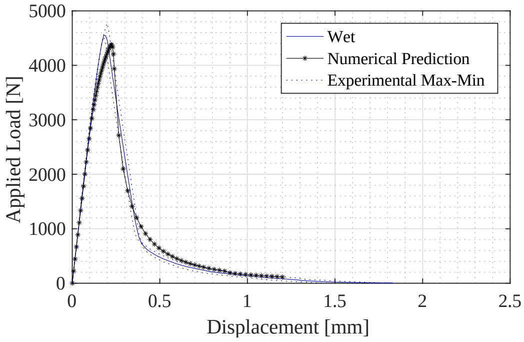

Figure 6. Calibration of model parameters

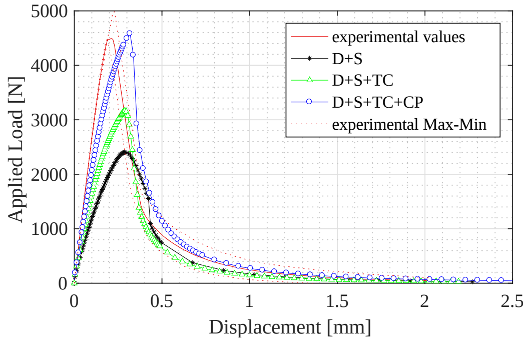

Figure 7. Prediction of the behaviour after drying

It is shown in figure 7 that taking into account the state of initial stresses due to drying strongly influences the macroscopic behaviour. If only drying shrinkage is taken into account (D + S), the resulting damage is overestimated. Non-linearities appear very quickly, decreasing stiffness as well as peak strength. However this state is not representative of the phenomenon, the creep will reduce the stresses within the sample and at the same time reduce the damage, which will give a stronger behaviour (D + S + TC). Finally, within the material, the desaturation of the pores will lead to capillary phenomenon, which will lead to an increase in the overall strength. The case (D + S + TC + CP) takes this phenomenon into account. The overall behaviour appears to be better represented, however, an underestimation of the initial stiffness is still observed.

3.4 Crack opening fields

To illustrate the crack openning routine based on postprocessing the damage, one can look at the cracking map obtained after 70 days of desiccation (figure 8). There are no other stresses than those imposed by drying.

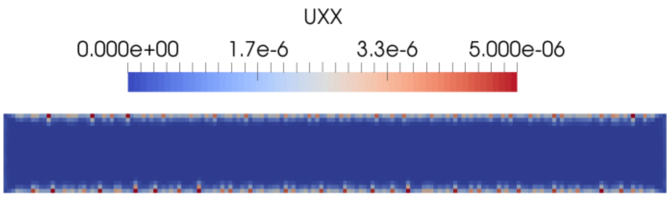

Figure 8. Crack map due to drying shrinkage [m]

With regard to the distribution of the cracks, it is noted that they are distributed around the circumference of the sample. This is easily justified by the fact that these areas are most affected by the hydric gradient. As for the order of the openings, they do not exceed ten microm. This cracking is diffuse on the edges of the specimen and remains superficial.

4. CONCLUSION

The drying phenomenon of cementitious materials is of major importance for understanding and forecasting long-term behaviour. Whether in terms of mechanical strength, behaviour (more or less britlle) or even transfer properties (fluid flux by permeation evolved with the cube of the crack opening), an impact of drying is observed experimentally. Although relative to all structures, drying is not much studied. The results found in the literature are sometimes inconsistent but can be explained by the different phenomena involved. Indeed, in this process three main phenomenon can be distinguished: the capillary pressure which stiffens the structure, the microcracking induced by the gradient of moisture and finally the strains incompatibilities.

The numerical approach presented in this paper is based on a four steps procedure which is concerned firstly with characterizing the water state of the material. This subsequently allows to quantify the delayed strains in order to then assume the internal state of stresses generated by drying shrinkage. These stresses are then took as initial value of the mechanical computation to finally obtain the cracking pattern. They can be characterized regarding transfer phenomena by a external model not presented in this paper. The results presented here show that, as experimentally observed, the drying behaviour is strongly impacted by the drying shrinkage. Taking into account the phenomenon of capillary

pressure and creep make it possible to approach a more realistic behaviour. In the modelling protocole there is no regard concerning strains incompatibilies. Some authors have proposed models to take this phenomenon into account but it is not widespread and it is still difficult to calibrate models' parameters.
Finally, the model presented allows to simulate the behaviour of large structure under drying from the hydric characterization to the hydric transfer. It has the advantage to be based on a model regularized in fracture energy which makes it suitable for large scale modelling.

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