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AN INSIGHT IN THE REDUCTION OF DRYING SHRINKAGE OF CONCRETE DUE TO SKIN MICRO-CRACKING

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Abstract
An evaluation of the potential structural drying creep of concrete (defined as the reduction of drying shrinkage due to skin micro-cracking) is proposed based on the analysis of experimental curves of drying shrinkage as a function of the weight loss. Assumptions concerning the closure of the micro-cracks are proposed to analyse the experimental curves. Finally, to confirm the hypotheses presented, a modelling of the drying shrinkage test with a probabilistic approach of concrete fracture is performed. Interesting information concerning the skin micro-cracking is derived and discussed.

1 Introduction

Even if drying creep represents an important part of the delayed behaviour of ordinary concrete, its physico-chemical origins are hardly known. Meanwhile, it is now admitted that drying creep is the sum of at least two components (ConCreep4, 1986), an intrinsic drying creep with its own mechanisms (see e.g. the ideas proposed by Bazant), and a structural drying creep resulting from a micro-cracking effect due to the non-uniformity of the free drying shrinkage in the concrete specimen. But the contribution of the two components is still a mater of research (Bazant, 1994; Granger, 1994). In this paper, we propose to determine the amplitude of the micro-cracking effect by analysing the curves showing the variation of the drying shrinkage as a function of the loss of weight. This method will permit us to give an upper bound (cracks don't close) or a lower bound (cracks are closing completely) of the potential structural drying creep. After presenting some experimental results obtained on six concretes from a recent study (Granger, 1995), we propose some hypotheses that we try to validate in the last part by using a finite element code allowing to take explicitly into account the fragile behaviour of concrete in tension.

2 Experimental results

The six curves of drying shrinkage as a function of the weight loss presented on fig. 1 were obtained in the following way. After demolding, the samples were protected from drying by using two self adhesive aluminum sheets and kept at 20°C during 28 days to ensure a good and uniform maturing of the concretes tested. At the age of 28 days, the samples were uncovered and placed in a room at 20°C and 50% RH. The measurements were performed on a 16 cm diameter specimen, the drying shrinkage was measured on a 100 cm long specimen according to RILEM 's recommendations and the weight loss was measured on a 15 cm long specimen, easier to move. The measurements were performed with a mean of 1 per week.

3 Interpretation of the experimental results

We assume in this paper (1) that the drying shrinkage of concrete $\varepsilon_{rd}(x,t)$ is locally proportional (ConCreep4, 1986) to the variation of water content w (kg/m^3) :

$$\varepsilon_{rd}(x,t) = \kappa\left(w_0 - w(x,t)\right) \tag{1}$$

Then, if the behaviour of concrete were purely ageing viscoelastic (no cracking), the integration of (2) on a section of the specimen (sections

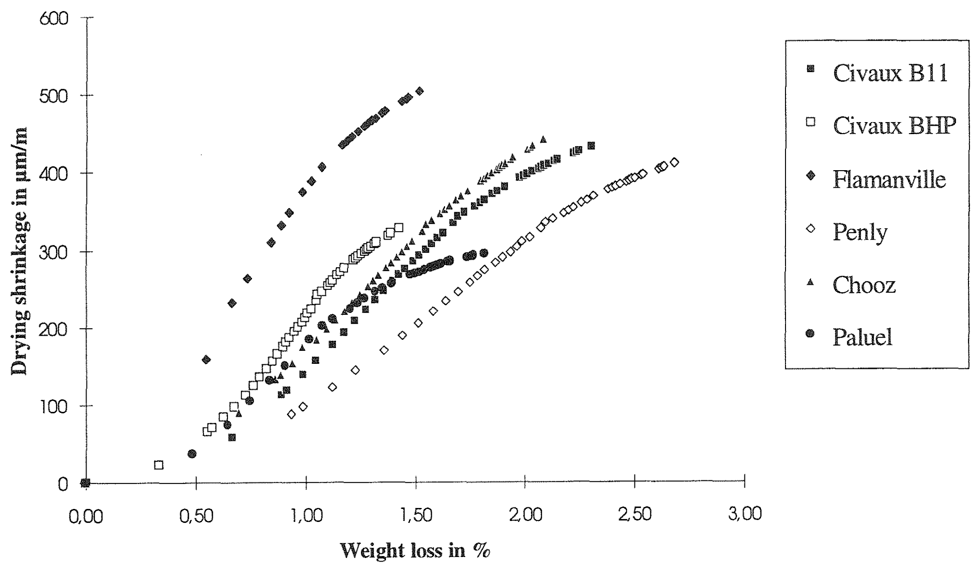


Fig. 1. Drying shrinkage *vs* weight loss for 6 French nuclear containment

remain planes and $\iint_S \sigma.dS = 0$) shows that the overall drying shrinkage strain would be proportional (3) to the weight loss of concrete $(\Delta P/P_0)$:

$$\varepsilon_{rd}(t) = \int_{\tau=0}^{t} J(t,\tau)\frac{d\sigma}{d\tau}d\tau + \varepsilon_{rd}(x,t) \tag{2}$$

$$\varepsilon_{rd}(t) = K\frac{\Delta P}{P_0} \text{ with } K = \kappa\rho \tag{3}$$

where ρ is the concrete density. Thus, the difference between the calculated elastic behaviour and the experimental measurements is equal to the potential structural drying creep of concrete. It is only potential because it would require, to be requisitioned at the beginning of the drying process, an important compressive stress equal to $\sigma(x \in \partial\Omega, t = 0^+) = E\kappa(w_0 - w(x,t))$ with E, the Young's modulus of concrete.

First of all, the curve $\varepsilon_{rd} = F(\Delta P/P_0)$ is clearly non linear. Its very low slope at the beginning of drying can be interpreted as the sign of the well known skin micro-cracking. Then, its slope increases and remains constant during the central part of the curve and finally diminishes again in the long run which could be interpreted as a non complete or non perfect closure of the concrete cracks. Meanwhile, the value of K is not easily determined with simple experimental procedures and two opposite radical hypotheses concerning the possible closure of the micro-cracks can be proposed (Bazant, 1994; Granger, 1994).

- Hypothesis H1. The slope of the curve, in its central linear part, K' permits to get the value of K_{H1}, intrinsic to the material. This corresponds to the idea that the cracks are not very deep an are entirely opened very quickly after the beginning of drying. Thus, the shrinkage strain is rapidly controlled by the loss of weight of the central part of the specimen (4). Then, (2) must now be integrated on S', defined as the uncracked part of S. Since we have now $\iint_{S'} \sigma . dS' = 0$, (5) has to replace (3) where $(\Delta P'/P_0')$ is the weight loss of S'.

$$\Delta P' \cong \Delta P \tag{4}$$

$$\varepsilon_{rd}(t) = K_{H1}\frac{\Delta P'}{P_0'} \cong \left[K_{H1}\frac{P_0}{P_0'}\right]\cdot\frac{\Delta P}{P_0} = \left[K_{H1}\frac{S}{S'}\right]\cdot\frac{\Delta P}{P_0} \quad \Rightarrow \quad K_{H1} = K'\frac{S'}{S} \tag{5}$$

Finally, an approximate value of S'/S is obtained in writing that the value of $(\Delta P/P_0)_0$ (fig. 2) is obtained with a water content equal to w_{atm}=w(h=0.5) on (S-S') and w_0 on S'.

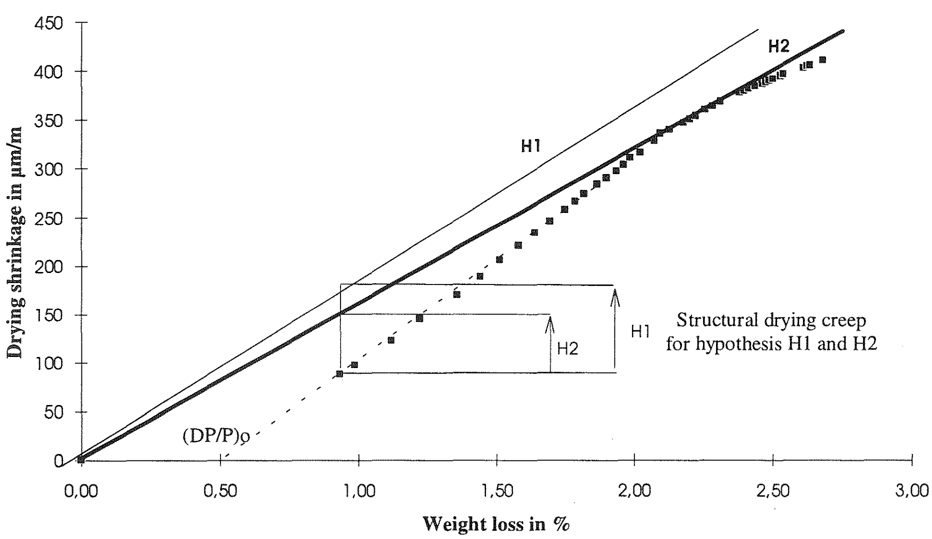


Fig. 2. Modelling of Penly's concrete according to hypotheses H1 and H2

$$\frac{\Delta P}{P_0} = 0.5\% = \frac{(S - S')(w_0 - w_{atm})}{\rho S} \quad \Rightarrow \quad \frac{S'}{S} = 0.84 \tag{4}$$

with ρ=2270 kg/m^3 and w_0=132.7 kg/m^3 and w_{atm}=62.1 kg/m^3 for this particular case.

- Hypothesis H2. The cracks close entirely. Thus, the intrinsic curve $\varepsilon_{rd} = K_{H2} \frac{\Delta P}{P_0}$ is tangent to the experimental curve (fig. 2).

In each case, the difference between the experimental curve and the potential drying shrinkage is equal to the potential structural drying creep. For H1, it is increasing up to 100.10^{-6} and remains almost constant with time whereas for H2, it is increasing up to 65.10^{-6} and then slightly decreasing to zero. Thus, the two hypotheses permit only to give an upper bound (cracks don't close) or a lower bound (cracks close completely) of the real structural drying creep (which could likely be between the two hypotheses).

4 Modelling - Analysis of the results with the probabilistic model

To confirm the physico-chemical ideas introduced previously, we have used the *modèle probabiliste* developed by Rossi in LCPC (Rossi, 1992) based on a probabilistic distribution of the material characteristics (Young's modulus E, tensile strength f_t) on the finite element mesh and assuming that the entire macroscopic behaviour can be described with a local elastic-fragile behaviour. This model has recently been "*coupled*" (Ulm, 1995) with a non linear calculation of the water content of the concrete due to drying with some conventional decoupling hypotheses between the diffusion process (resulting from a previous calculation (ConCreep4, 1986; Granger, 1994) in non linear diffusion : $\dot{w} = \mathrm{div}(D(w) \cdot \mathrm{grad}(w))$) and the mechanical behaviour of concrete. This is a classical but crude simplification that limits the generality of the work presented. Meanwhile, this will permit to understand better the reduction of drying shrinkage due to skin micro-cracking and to get some very interesting information concerning the spacing, depth, thickness and development of the cracks.

The mesh used is presented on fig. 3. The first zone is meshed with 8 nodes quadrilaterals where the concrete presents an elastic behaviour; the central part of the concrete specimen has been meshed with 6 nodes triangles (perfectly elastic) but interfaced with contact elements presenting a fragile behaviour in tension. As soon as the normal stress (resp. the shear stress) is greater than the local tensile strength (resp. shear strength), the

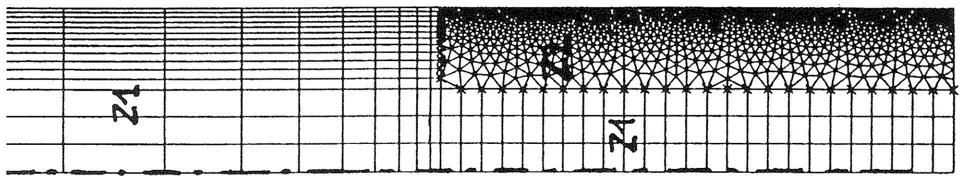
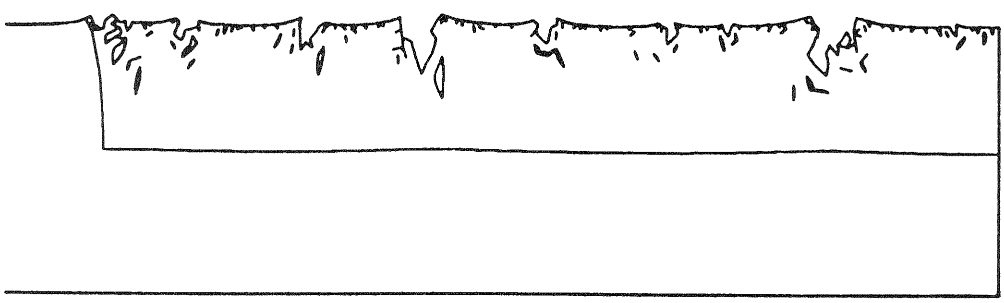
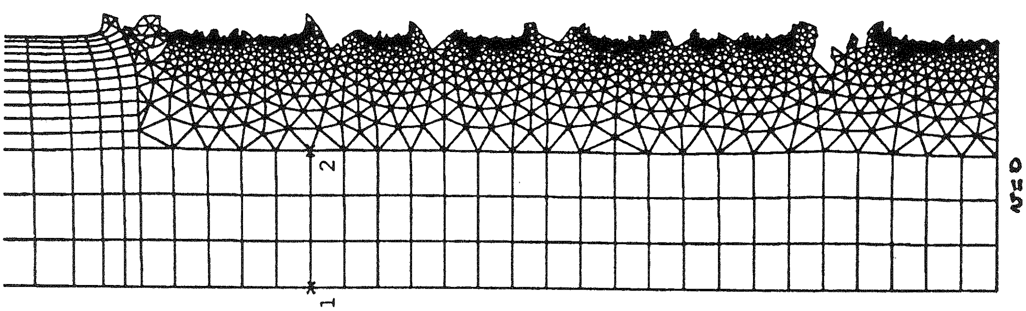


Fig. 3. Mesh used for the probabilistic calculations



(a)



(b)

Fig. 4. a) Visualisation of the cracks (depth, spacing) at the maximum opening of the tertiary cracks
b) Place of the points used to calculate the drying shrinkage

contact element opens allowing to model explicitly a crack. Finally, the interaction between the two lips of a crack, when it closes, is modelled with a Coulomb friction law.

- In the first calculation (C1), we model the drying shrinkage test (without loading). The observation of the skin cracks of the concrete allows to distinguish 4 phases (fig. 4.a and 4.b). At the beginning of drying, when the water content drops suddenly at the concrete's skin, a very large number of <u>primary cracks</u> appear with a very small opening. Then most of these cracks tend to close whereas a small number of them, <u>secondary cracks</u>, tend to open every 2.5 cm. On a third phase, certain secondary cracks close and a small number of them, <u>tertiary cracks</u>, (fig. 7) tend to open every 10 cm and reach a maximum thickness of 25μm and a depth around 2 cm. Finally, in the last phase, at the end of the drying process, the tertiary cracks tend to close very slowly but not completely.

- In a second calculation (C2), the drying specimen is loaded at 15 MPa. It is thus logical that the crack opening is reduced; it is what is observed on fig. 5 where only "primary" cracks occur.

Finally, in both cases, comparison of the calculated strain (measured in the elastic zone where it has been established that the sections remain planes) as a function of the weight loss is presented on fig. 6.

The comparison between experimental results (fig. 2) and simulations (fig. 6) shows that the probabilistic model gives an answer closer to hypothesis H2 than to hypothesis H1 since the structural drying creep seems to decrease with time after reaching a peak. Meanwhile, the cracks don't seem to close completely.

Furthermore, the simulations exaggerate the structural effect at the beginning of drying since the peak of the structural drying creep is reached for a higher weight loss (between 1.5 and 2% in the simulations as opposed to less than 1% in the experimental data). According to us, this is partly due to the fact that the calculation is performed in 2D axysimetric where cracking is only horizontal whereas the real cracks should be isotropic. Thus it is certain that the vertical cracks that are normally produced would reduce the horizontal cracks. Furthermore, the level run observed experimentally at the end of the drying process is reached sooner in the experimental results than in the numerical simulations. This could be explained by a non perfect description of the crack closure.

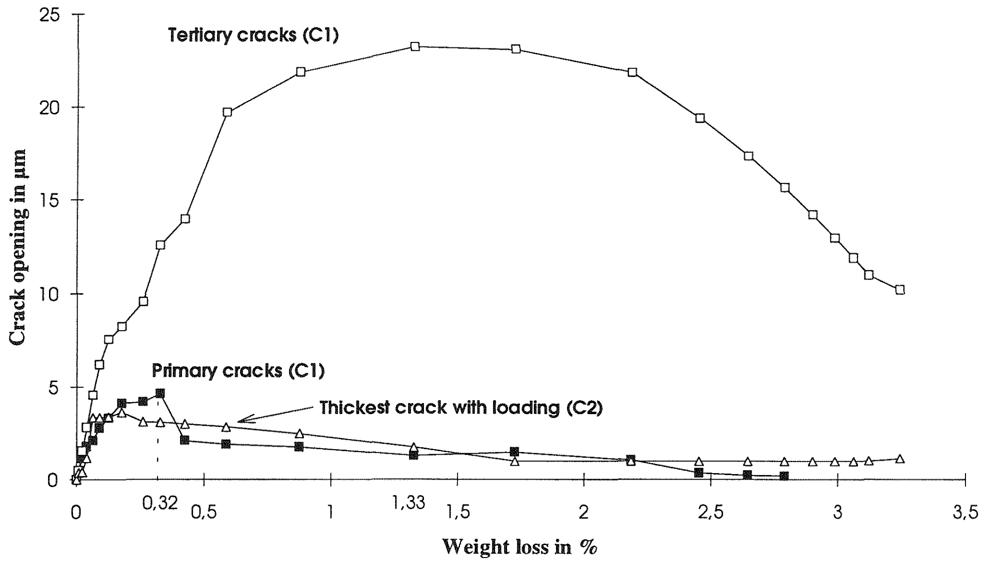


Fig. 5. Crack opening function of the weight loss in the two cases tested

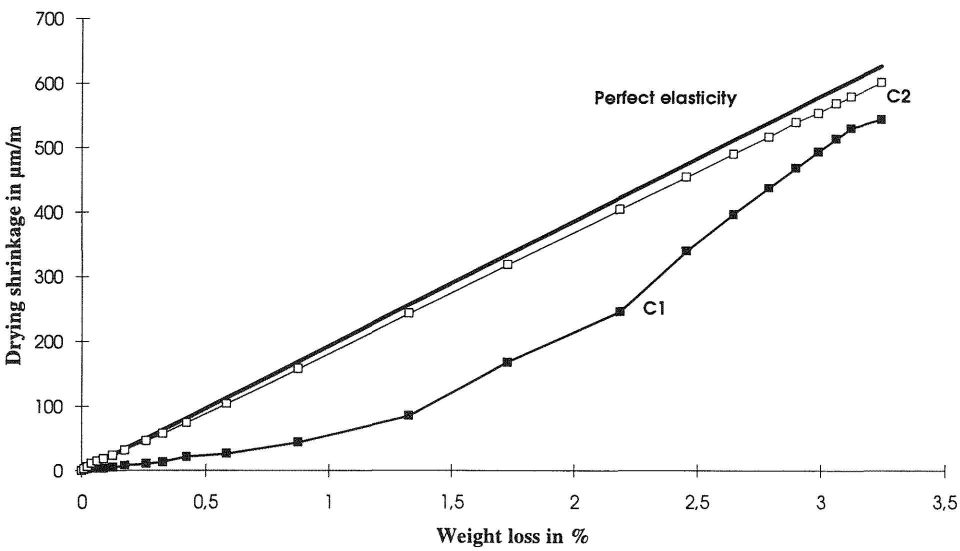


Fig. 6. Drying shrinkage as a function of the weight loss; comparison between experimental results and simulations C1 and C2

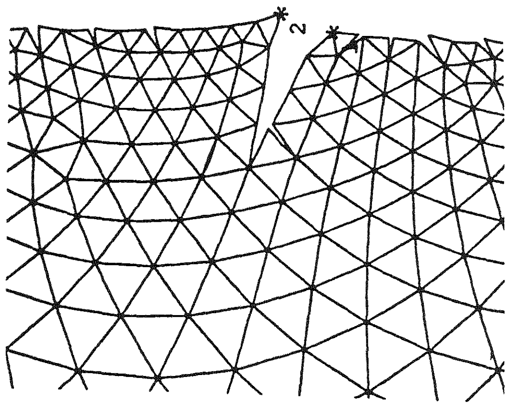


Fig. 7. Zoom on a tertiary micro-crack

5 Conclusion

A decoupling hypothesis between the drying process of concrete and its mechanical behaviour and a linear relationship between drying shrinkage and water content has permitted to give interesting information concerning the skin micro-cracking of drying concrete.
Two opposite assumptions have been presented to interprete the curves of drying shrinkage as a function of the weight loss. Both conclude on the existence of a structural drying creep, increasing with time for hypothesis H1 (cracks don't close) and around 65.10^{-6} and decreasing to zero for hypothesis H2 (cracks are closing completely). The numerical simulations performed with the *modèle probabiliste* seem to show that the structural drying creep reaches a peak and then decreases with time but without reaching a zero value. The reality would then remain between H1 and H2. Finally, a 3D calculation, in the future, will certainly give some more precise information.

Nota Bene
The *modèle probabiliste* is part of the CESAR-LCPC finite element code developed by P. Rossi since 1983. More recently, the coupling with the temperature and the water content has been realised by F. J. Ulm and A. Elouard.

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