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Surface Shrinkage of Concrete: Evaluation and Modelling

Retrait superficiel du béton: évaluation et modélisation

Oberflächenschwinden des Betons: Ermittlung und Modellierung

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SUMMARY

The mechanical effects of drying shrinkage were investigated in the field and the laboratory, using theoretical, experimental and technological means. Direct stress measurements, by the stress release method, and their numerical analysis gave the stress profiles and the depth of damage for different configurations. Simulation of the drying effects by a stochastic model reproduced the same stress profiles. The explanation and evaluation of these effects should lead to appropriate precautions, for reinforcement protection and a better durability.

RÉSUMÉ

Les effets mécaniques dûs au retrait de dessiccation ont été étudiés, sur ouvrages réels et en laboratoire, associant des moyens théoriques, expérimentaux et technologiques. Des mesures directes de contraintes, par la méthode de libération, et leur analyse numérique ont permis de déterminer les profils de contraintes et la profondeur d'endommagement, pour différents configurations. Une simulation des effets du séchage par un modèle stochastique a reproduit les mêmes profils de contraintes. L'explication et l'évaluation de ces effets devraient faciliter la définition des précautions à prendre, pour la protection des armatures et une meilleure durabilité.

ZUSAMMENFASSUNG

Die Wirkung des Schwindens infolge Austrocknung wurde an Hand von Labor- und Bauwerksuntersuchungen erforscht. Dazu wurden drei verschiedene Studien durchgeführt; experimentelle, theoretische und technologische Studien. Direkte Spannungsmessungen mit flachen Druckmessdosen und ihre numerische Analyse haben die Bestimmung des Schwindens ermöglicht. Eine Simulation des Trocknungsvorganges durch ein stochastisches Modell hat die Ereignisse bestätigt. Durch die nun mögliche Erklärung und daraus resultierende Berechenbarkeit dieser Wirkung kann eine bessere Dauerhaftigkeit gewährleistet werden.

1. INTRODUCTION : EXTENSIVENESS OF CONCRETE SKIN CRACKING

In most concrete formulae, the water quantity necessary for the mix greatly exceeds that needed for the cement hydration. As soon as shuttering is removed, even in humid climates, a part of the water will migrate to the outside. This drying can attain a 5% loss of the total concrete weight and lead to considerable dimensional variations. Drying is never uniform and its effects have three components :

- . eigenstresses, due to very slow drying and resulting gradients ;
- . skin cracking of evolutive depth ;
- . apparent strains, usually known as drying shrinkage.

These depend on the geometry of the sample or structural element. By their intense superficial mechanical effects, both the removal of shuttering and the variation of air humidity are equivalent to a thermal shock. In general, the result is a pattern of very dense, shallow hair cracks which do not always jeopardize the durability of the material. However, under certain conditions, an extensive growth of this cracking can favour reinforcement corrosion, a very frequent type of pathology cases in concrete structures.

To better control this mechanism, it could be helpful to first evaluate the mechanical effects of shrinkage with the utmost possible accuracy.

2. A DOUBLE APPROACH BY EXPERIMENT AND MODELLING

Many authors [1], [2], have given a fair but rather qualitative description of these effects. By thermal analogy, shrinkage strains and eigenstresses cannot be properly calculated from measured water content distributions (fig. 1), owing to the lack of a sufficiently accurate "coefficient of hydric contraction". This can only be obtained on a test sample free from gradients and cracks, which are difficult to avoid, given the excessively slow drying process [3].

For a quantitative analysis of the mechanical effects, we needed an accurate method of direct stress measurement, leading to a more realistic constitutive model. It happens that such a method has already been developed by one of the authors [4], [5], for the assessment of structures. It now offers a suitable means for this quantitative approach.

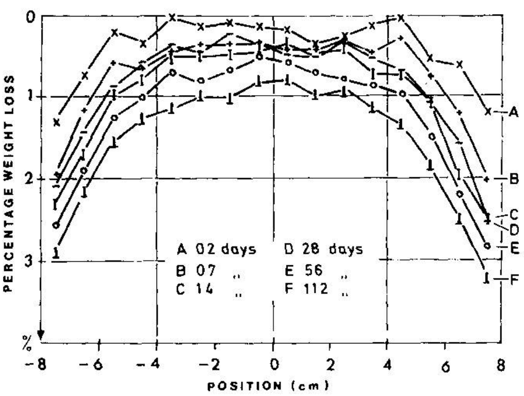

Fig. 1 : Time-dependent distribution curves of water content measured in a 10-cm-diameter, 16-cm long concrete core, laterally coated to represent uniaxial drying in a 16-cm thick infinite slab.

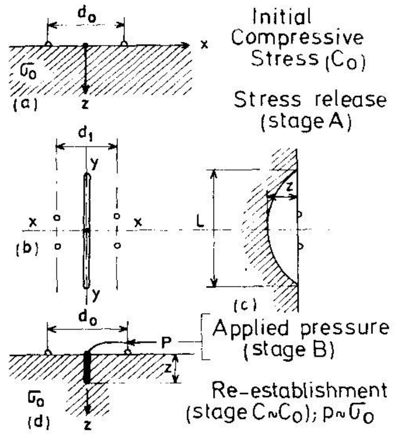

Fig. 2 : Different stages of direct stress measurements, by the release method.

3. DIRECT MEASUREMENT OF STRESS

3.1 - The release method

It is a local and partial release of stress, followed by a controlled pressure compensation [5]. In practice (fig. 2 and 3), a displacement reference field is first set up on the surface ; a tiny slot is then cut in a plane normal to the desired stress direction ; finally, a special very thin flat jack is introduced into the slot and used to restore the initial displacement field. The amount of cancelling pressure gives the absolute compressive stress normal to the slot. In the same way, with the same accuracy, tensile stresses are obtained by a corollary. The stress profile is traced by repeating the operation at closely successive depths of the same slot, then by treating the data numerically. In spite of the minute working scale, the error stays within 0.3 MPa. The depth operating range is 80^{mm}, giving an average stress till 32^{mm}. Measurement is "direct" in the sense that the same physical quantity is involved (pressure for stress) and that none of the material elastic properties are needed. These are even determined in the process. Stress components may sometimes be separated.

3.2 - Applications on site

The first operational field application of the release methode was on a 10-year-old tall concrete column with a box section [6]. It carries two half, simply supported spans of a bridge (equivalent to 2.5 MPa) and undergoes a slow, irregular foundation settlement. On four points of the section, absolute stress profiles were determined through the outside part of wall thicknesses (fig. 4). At all four points, contrary to what is expected from a compression member, high tensile stresses were measured close to the surface, falling sharply with depth.

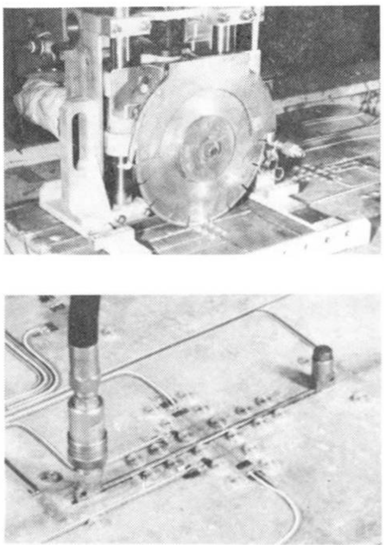

Fig. 3 : (top) Slot cutting machine with 0.1-mm adjustment ;
(bottom) A 0.1 µm-precision displacement measuring apparatus with a 4-mm thick flat jack in the slot.

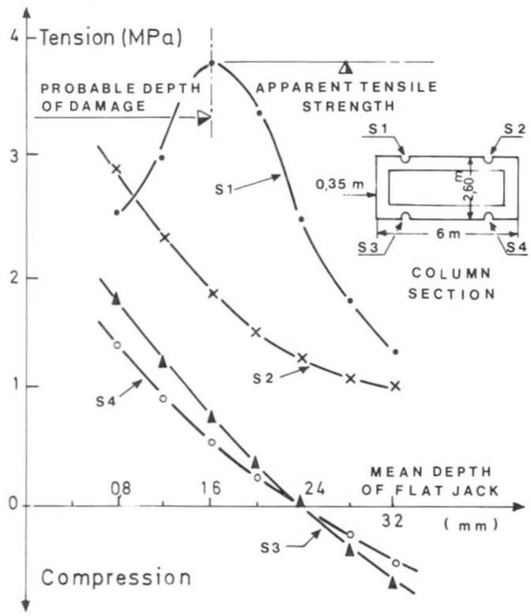

Fig. 4 : Compensating pressures, given by the release method, reflecting the actual stress profiles on a 10-year-old concrete column with a 2.5 MPa external compression. They show the still prevailing superficial tensions and sharp gradients of shrinkage. The relative vertical shift between the curves, illustrates the effect of flexure (confirmed later while completely cutting and shoring the column base).

Shrinkage effect is undoubtedly the cause, running deep with similar gradients and stabilizing beyond the range of measurement. At point S1, the stress curve breaks right below the usual tensile strength of concrete, announcing a softening of stress by superficial cracking. The measured stress at this depth is in fact an average over the area of the flat jack, hence the actual stress distribution should be more pronounced upwards.

Such applications helped to emit basic and realistic assumptions necessary to carry on the research.

4. LABORATORY TESTS AND A MODEL FOR ANALYSIS

Three plain concrete test slabs were casted, 80 x 40 cm, respectively 8, 10, 16 cm thick [7]. The first one had a uniform 12.5 MPa prestress at 7 days. In areas away from edges, stress distribution is assumed to depend exclusively on the distance from the surface.

The release method was used again in all slabs. The displacement field evolution, accurately measured as cutting proceeded, was combined with a specific compliance matrix (F.E.M. 3-D programme CESAR), to obtain a better defined stress profile as a function of depth. In this analysis model, elastic behaviour is assumed, as confirmed by the linear and reversible response of the displacement field to the flat jack pressure, at consecutive slot depths.

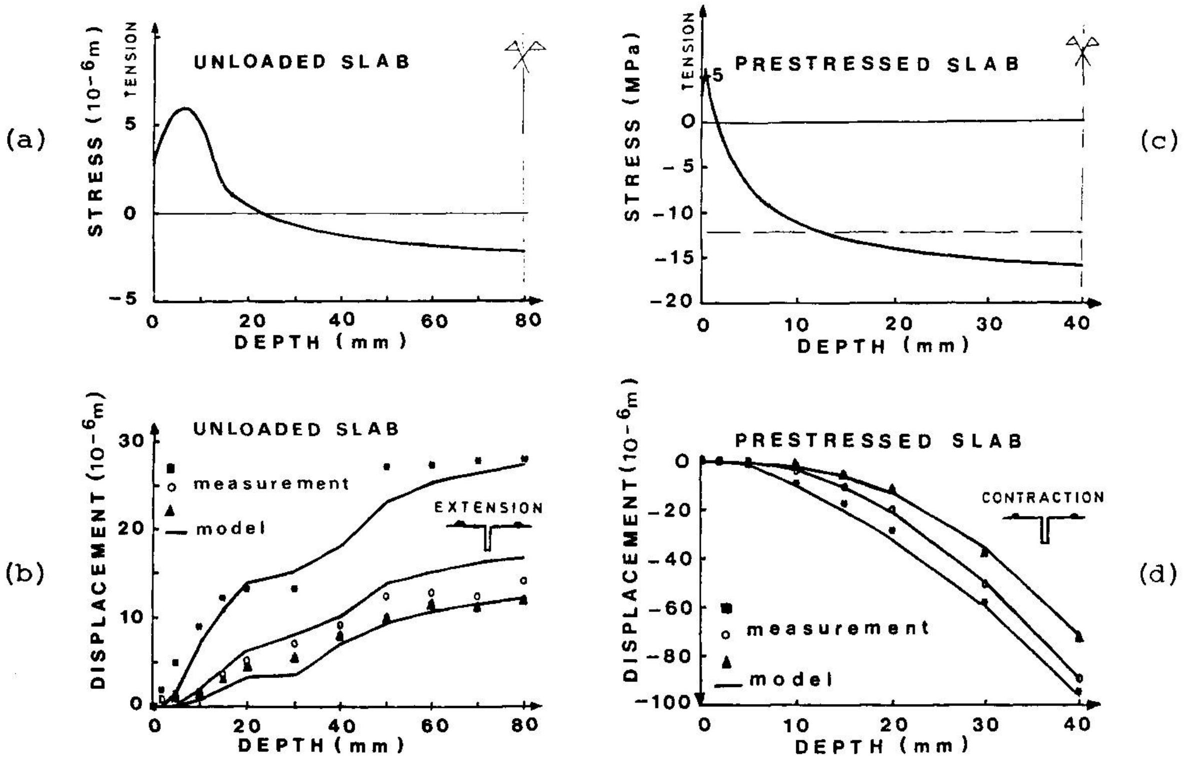

Fig. 5 : (a, c) Stress distribution, in non-loaded and prestressed configurations, estimated by the analysis model, completed by parametric optimization.

(b, d) Respective surface displacements comparing those actually measured by the release method (points), and those deduced from stress distributions (curves). In the two-step evolution observed in (b), the first discontinuity marks a stress fall to zero, the second, an opposite flexure effect of stress redistribution after partial release in a slab of limited cross-section.

5. RESULTS AND DISCUSSION : HIGH STRESSES, SOFTENING AND LOAD COUPLING

The resulting stress profiles and the comparison of measured and computed surface displacements are given in fig. 5. Considerable surface displacements were observed, depending heavily on the external loading configuration.

In the non-loaded slab (fig. 5b), the increasing depth-dependent extension reflects an intense superficial tension of several MPa's. A direct resolution by the above analysis model gave the general form of this tension which rises first with depth, passes by a maximum, then falls to compression, in the central part of the thickness, to sum up the internal forces over the cross-section to zero. The presence of a softening zone confirms earlier stress measurements on structural members with low compression loading (curve S1, fig. 4). The shrinkage stress profile may now be assimilated to a junction of two curves : (i) a parabola, covering the damaged depth, with its vertex on the tensile strength level and (ii) a central curve, proportional to the water content distribution.

Very close to the surface, the analysis model grows too delicate to apply owing to the extremely small compliance coefficients. The damaged depth then becomes the main parameter whose optimum value should fix the stress curve and give the best correlation between the theoretically deduced displacements and those actually measured by the release method (fig. 5b, d). The optimization process yielded a 4.0 and 6.4 mm damage, respectively for the 10 and 16 cm thick non-loaded slabs. It is 0.3 mm only for the prestressed slab. With these additional and consistent data, the stress profiles (fig. 5a, c) were obtained.

The main difficulty of the above approach naturally resides in the lack of a reliable constitutive law for concrete in tension. On this scale, the experimentally observed softening strongly depends on the size of discontinuities [8]. This size effect may be explicitly reproduced in Rossi's stochastic model [9]. Specific, perfect brittle, contact elements are inserted in an elastic F.E.M. model with tensile strength values placed at random according to an experimentally determined statistic distribution. In applying this model to the above example fig. 5 b, the stochastic mean stresses generate a shape similar to the experimental distribution (fig. 6).

At successive drying stages, the model shows a "condensation" process of main crack openings : as damage deepens, fewer cracks propagate giving more concentrated, hence wider, openings.

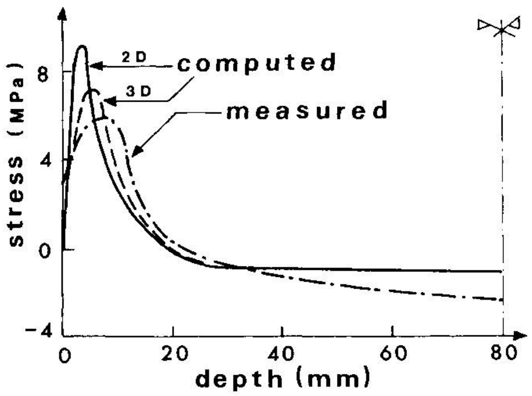

Fig. 6 : Depth-dependent mean stresses, computed by the stochastic model and compared to experimental values for the 16 cm thick test slab.

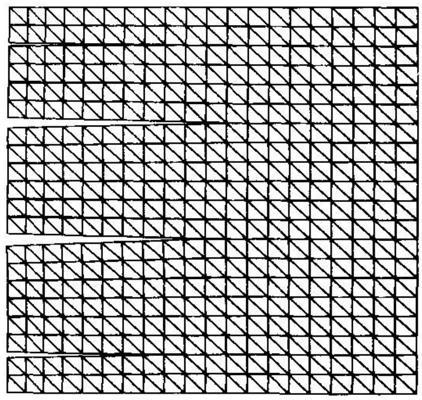

Fig. 7 : Crack pattern obtained by the stochastic model. Cracking depth varies from 5 to 11 mm but only a few cracks appear open.

Finally, in the prestressed slab, even a 12.5 MPa applied compression could not prevent a slight tension damage experimentally observed. However, this loading did favour an almost full development of the intrinsic drying strains. These reflect the water content distribution and proportionally induce the stress profile (fig. 5c) deduced through the release method.

6. CONCLUSIONS

1- The displacements, occuring on the concrete surface while cutting a slot, reflect the high tensile stresses due to drying shrinkage and enable their evaluation.
2- The observed displacement field response to stress release is significantly different according to whether concrete is prestressed or not. In both cases, the response to jack pressure confirmed the linear elastic relationship assumed between drying strains and stresses.
3- A closer scrutiny of the results shows potential tension exceeding the strength of the material through an appreciable depth (5-10 mm), and creating a damage or softening zone.
4- The quantitative analysis of the mechanical damage, actually suffered by the concrete skin layer, confirms the importance and facilitates the optimization of two re-bar parameters : cover and bond. This may contribute to a better control of durability problems linked with the drying of concrete.
5- The stress release method, developed in the LCPC, proved suitable for the analysis of drying effects. The method also enables the access to external load stresses acting on the structure, for a drying depth within the measurement range. For drying beyond this range, other operation ways are now being tested to attain the load stresses.

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REFERENCES

1. WITTMANN F.H., ROELFSTRA P.E., "Total Deformation of Loaded Drying Concrete", Cement and Concrete Research, Vol. 10, p. 601-610, 1980.
2. BAŽANT Z.P., RAFTSHOL W.J., "Effect of Cracking and Drying in Shrinkage Specimens", Cement and Concrete Research, Vol. 12, n° 2, 1982.
3. MENSI R., ACKER P., ATTOLOU A., "Séchage du béton : analyse et modélisation", Matériaux et Constructions, Vol. 21, p. 3-12, 1988.
4. ABDUNUR C., "Stress and Deformability in Concrete and Masonry", IABSE Symposium, Final Report, p. 123-130, Venezia, 1983.
5. ABDUNUR C., "Mesure de contraintes sur ouvrages d'art par une méthode de libération miniaturisée", Bulletin de Liaison des LPC, n° 138, p. 5-14, 1985.
6. ABDUNUR C., "Mesures directes de contraintes sur une pile du viaduc de Charmaix", Rapport LCPC, 1986.
7. MIAO B., "Effets mécaniques dus au retrait de dessiccation du béton", Thèse de l'ENPC, Paris, 1988.
8. Proc. CNRS-NSF Workshop "Localization, Damage and Size Effect", J. Mazars and Z.P. Bažant Ed., Elsevier Publ., 1989.
9. ROSSI P., PIAU J.M., "The Usefulness of Statistical Models to Describe Damage and Fracture in Concrete", in Workshop ref.8.
10. ACKER P., "Comportement mécanique du béton : apports de l'approche physico-chimique", Rapport de Recherche des LPC, n° 152, 1988.