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MODELLING OF INTERACTIONS BETWEEN CRACKING, SHRINKAGE AND CREEP WITHIN COUPLED HYGRO-MECHANICAL ANALYSES OF CEMENTITIOUS MATERIALS

Erkan Rumanus$^{\star 1}$**, Günther Meschke**[1]**, Jan Carmeliet**[2,3] **and Staf Roels**[2]

[1]Institute for Structural Mechanics
Department of Civil Engineering, Ruhr-Universität Bochum, Germany
e-mail: [erkan.rumanus, guenther.meschke]@rub.de, web page: http://www.sd.rub.de

[2]Laboratory of Building Physics, [3]Building Physics Group (TU Eindhoven)
Department of Civil Engineering, Katholieke Universiteit Leuven, Belgium
e-mail: [jan.carmeliet, staf.roels]@bwk.kuleuven.be, web page: http://www.kuleuven.be/bwf

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Summary. *A thermodynamically motivated multi-phase model for describing moisture flow in conjunction with cracking and creep is developed. The accelerated transport process in cracks is verified by measuring the moisture uptake due to capillary suction in brick samples. To capture the moisture dependent additional creep deformations (Pickett-Effect), the proposed model is extended by the microprestress-solidification theory*[1].

1 INTRODUCTION

Shrinkage deformations, shrinkage-induced cracks and creep are long-term phenomena in cementitious materials attributed to hygral stresses acting in the nano- and capillary pores. In this paper, a coupled hygro-mechanical model[2] is extended to long-term creep. It is used to examine the interactions between moisture transport, cracking and creep. Advanced measuring techniques, used to monitor the moisture uptake in cracked specimens, are employed to validate the capability of the proposed transport model.

2 LONG-TERM CREEP WITHIN A POROMECHANICAL MODEL

2.1 The creep law within the scope of the microprestress-solidification theory

The coupled constitutive properties of partially saturated porous media are described in the framework of poromechanics by defining a set of macroscopic state variables characterising the free energy function Ψ. By relating micro-macro quantities and considering the Maxwell symmetries, the identification of the coupling coefficients for describing the differential state equations can be derived[2]. The extension of the poromechanical model to capture long-term creep deformations is characterised by the consideration of the irreversible creep strain tensor $\boldsymbol{\varepsilon}^f$ and the corresponding viscous slip γ_f associated with relative motions within the micropores[1]. The creep deformations are described in terms

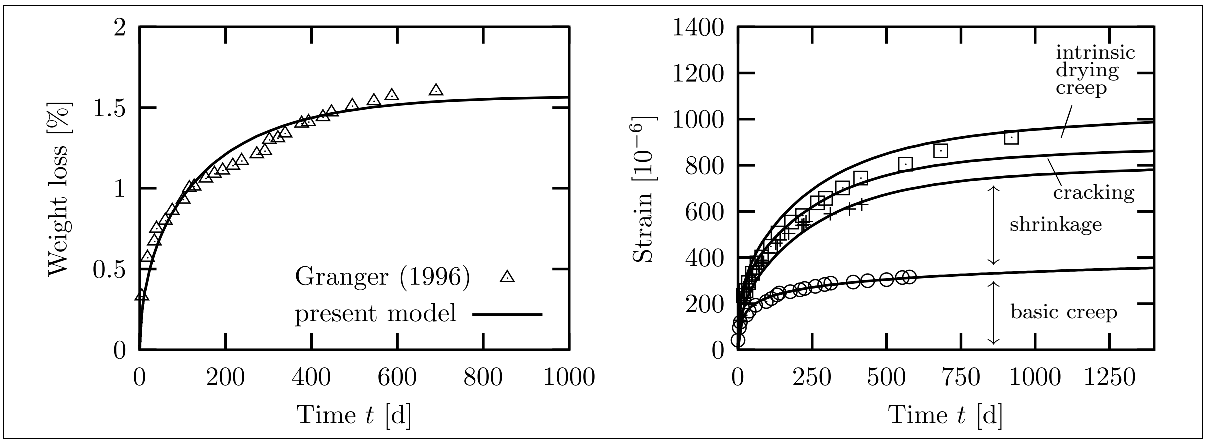

Figure 1: Evolution of weight loss and of the delayed deformations

of the (plastic) effective stress tensor[2] $\boldsymbol{\sigma}'$ and the microprestress S_f acting in the gelpores. In the original formulation of the microprestress-solidification theory[1,3], the dependency of the microprestress S_f on the moisture content is accounted for by the capillary pressure p_c representing macroscopically the disjoining pressure and the liquid pressures attributed to molecular adsorption and capillary condensation

$$S_f = S_f(\gamma_f, p_c) = -\partial\Psi/\partial\gamma_f = S_{f0} - H\gamma_f + \tilde{c}_1 p_c \ , \tag{1}$$

where S_{f0} denotes the initial value of the microprestress S_f, H is the constant relaxation coefficient and $\tilde{c}_1$ describes the moisture-microprestress coupling parameter. In the present formulation, in addition to the moisture dependent viscosity η_f, also the moisture dependent (plastic) effective stress tensor $\boldsymbol{\sigma}'$ affects the irreversible creep strains

$$\dot{\boldsymbol{\varepsilon}}^f = \frac{E}{\eta_f(S_f)}\,\boldsymbol{\mathcal{C}}^{-1} : \boldsymbol{\sigma}'. \tag{2}$$

In the following section it will be shown that within a poromechanical framework the dependency of S_f on the moisture content is not necessary.

2.2 Numerical verification of the creep law

For the validation of the proposed model, creep and shrinkage experiments based on cylindrical concrete specimens are reanalysed numerically using the finite element method. The measurements are performed on 28 days old specimens under isothermal conditions (20°C ± 1°C) at constant relative humidity (50 % ± 5 %). The evolution of the weight loss and the corresponding drying shrinkage deformations were measured. In order to quantify the drying creep strains a uniaxial load equal to 12 MPa was applied on two identical specimens, with one of the specimens being loaded under sealed conditions to obtain the basic creep strains[4]. The comparison of the numerical results with the experimental data is depicted in Figure 1. A satisfactory agreement can be observed for the whole duration of the measurements. The additional creep strains (drying creep) are identified from the numerical analysis. The two governing mechanisms, namely the *cracking effect* resulting from the microcracks at the surface and the *intrinsic drying creep* being the result of the moisture dependent creep strains (see equation (2)), are separated in Figure 1. The computed strains due to cracking increase gradually during the first days and remain almost constant at a value of $\sim$ 80 μm/m. A similar order of magnitude is also reported by other authors[4,5]. In the analysis the viscosity η_f is considered as moisture independent, i.e. it is assumed that the pore humidity does not affect the microprestress S_f ($\tilde{c}_1 = 0$). The parameter S_{f0} and H were calibrated according to the test data. This analysis shows that the coupling between the *intrinsic drying creep* strains and the moisture field can be solely captured by the (plastic) effective stresses $\boldsymbol{\sigma}'$ which represent (on a macroscopic level) the stresses acting on the skeleton by considering the state of damage.

3 TRANSPORT PROPERTIES IN CRACKED MEDIA

3.1 Measuring technique and experimental set-up

To analyse moisture transport in cracked media, free water uptake is monitored in cracked brick samples using X-ray radiography. In the X-ray apparatus the oven dry samples (wrapped with cling film to avoid evaporation drying during the experiment) are placed on a recipient which can be filled with water. First, an X-ray image of the oven-dry sample is taken. Then, water is poured into the recipient, so that the base of the specimen touches the free water plane. Images are now taken at subsequent time steps while the water is taken up by the sample. The evolution of the moisture front in the sample can then be visualised by subtracting the reference X-ray image (sample in dry state) from the images taken during the imbibition experiment. Advantage of the technique is that both the moisture profiles in the matrix and the height of the waterfront in the fracture can be quantified during the experiment[6].

3.2 Validation of the moisture transport through and in the vicinity of cracks

The interactions between tortuous cracks and transport mechanisms are governed by the diffusivity which is considerably increased in the crack compared to the intact material. To calibrate and validate phenomenologically the saturation dependent hydraulic permeability within cracks, water uptake experiments on dried brick samples with various predefined crack widths are reanalysed by means of the poromechanical model. The vertical cracks were located in the centre of the samples. Only samples with smooth crack topography and rather constant crack aperture are considered here. In Figure 2 the results of the finite element calculations obtained from the proposed poromechanical model are compared with the measurements. The evolution of the moisture content m_l is captured satisfactorily for both crack widths of $w = 0.01\,\mathrm{mm}$ and $w = 0.1\,\mathrm{mm}$. The corresponding heights of the waterfronts in Figure 2 illustrate the considerable influence of the crack width on the moisture transport. For the crack width $w = 0.01\,\mathrm{mm}$, moisture profiles obtained from the analyses are compared with the respective X-ray images. For different stages of the uptake experiment a reasonable agreement is observed.

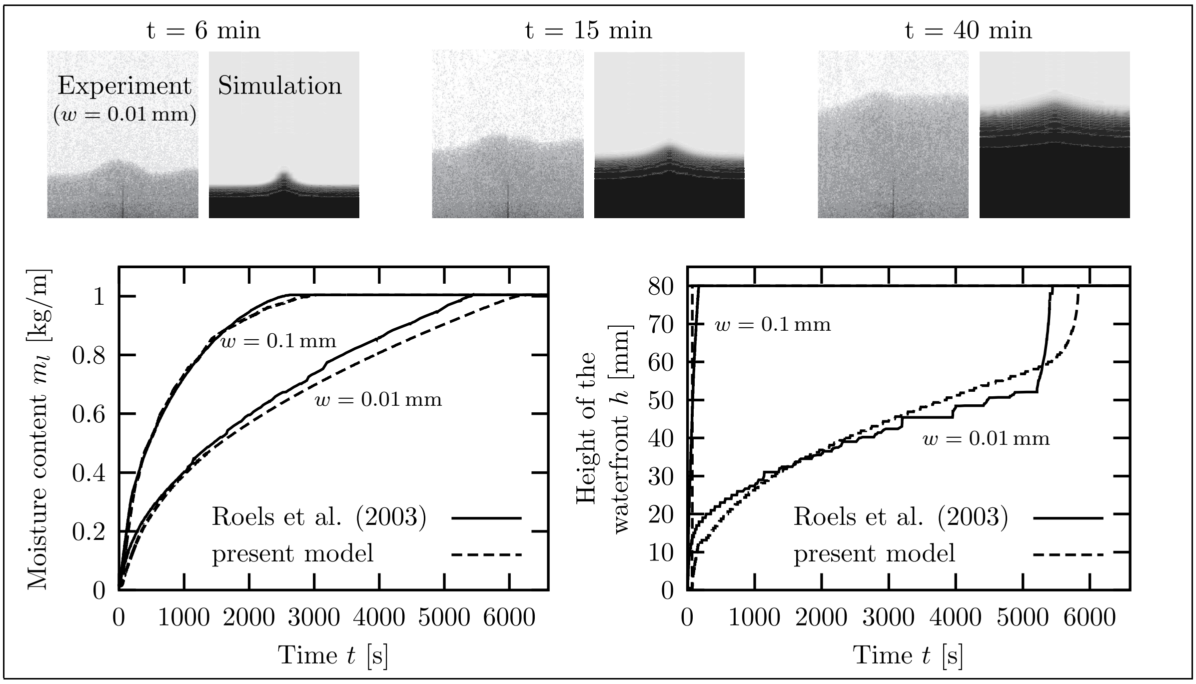

Figure 2: Validation of moisture uptake in fractured brick samples (crack width $w = 0.01/0.1$ mm)

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