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COUPLED HEAT- AND MASS TRANSFER IN PRESTRESSED CONCRETE ELEMENTS

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Abstract

Simulation of the coupled heat- and mass transfer in thick-walled concrete elements requires detailed knowledge of the corresponding thermal and hygral transfer coefficients. These are themselves dependent on the local values of temperature and moisture content. These coefficients can be obtained experimentally, but heat and mass transfer can be influenced by other phenomena as well. One effect is the development of leaks, which can influence the transfer of water vapour. Leaks can be a consequence of thermal stresses, and the amount of moisture escaping along such paths is difficult to determine in advance. We have measured moisture distributions in a prestressed concrete vessel under thermal gradients, and compared the results with numerical calculations.

1 INTRODUCTION

A realistic simulation of spatial temperature and moisture distributions in thick-walled concrete elements under thermal and hygral gradients must be based on experimentally determined transfer parameters. Coefficients, such as thermal and hygral diffusivities, are generally functions of temperature and moisture content. We have measured thermal and hygral transport parameters, and used them in a phenomenological model of simultaneous heat and mass transfer.

In order to compare the numerical predictions of temperature and moisture distributions in thick-walled concrete elements under thermal and hygral gradients as a function of time, two models of a prestressed reactor vessel were built. These concrete structures contain various gauges for temperature and moisture detection. The first model was presented in a previous contribution [1], and is shown again in fig. 1 for convenience. The concrete used was made with crushed basalt aggregates and a water-cement ratio of 0.45. Blast furnace slag cement blended with fly ash was used.

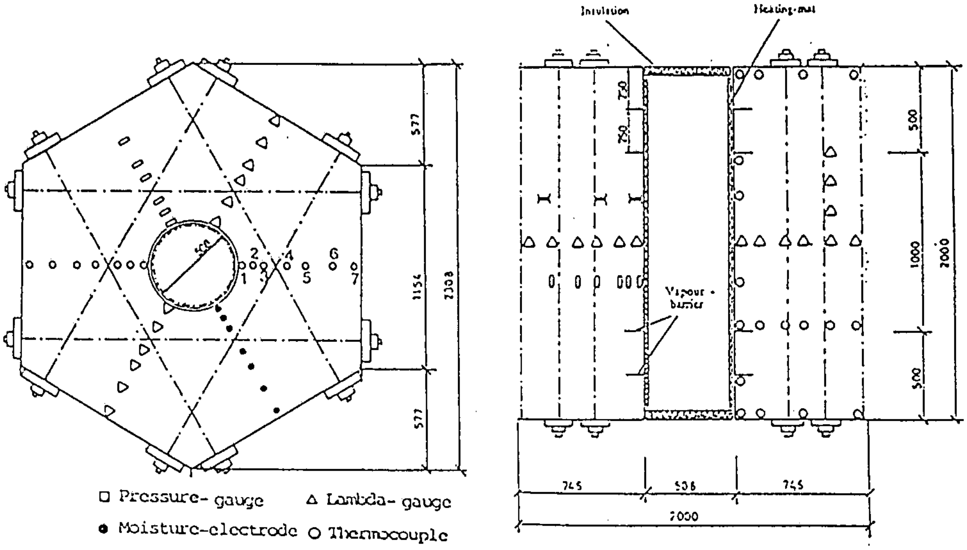

Figure 1: Model of a prestressed reactor vessel with measuring devices. a) Sectional view. b) Plan view.

The inner steel liner can be heated to a constant temperature of up to 300°C, and in this way a radial temperature gradient can be created and maintained constant in the centre section of the concrete vessel. In the following, we will restrict the discussion to the steady temperature state.

The detection of moisture in the concrete vessel is achieved by employing capacitors as humidity-sensors. These consist of a cylindrical steel grid frame filled with mortar. The electrical capacity of a sensor depends on temperature as well as on humidity. These dependencies have been accounted for through an experimentally obtained calibration surface, as described in [2].

2 TRANSPORT MECHANISMS

2.1 Moisture diffusion

The transfer of heat and moisture in concrete can be described by the phenomenological diffusion equation $-J_X = D \cdot \nabla X$. The flux J_X of the quantity X, corresponding to heat or moisture content, is controlled by its own gradient as the driving force:

$$\begin{aligned} -J_T &= D_{TT} \cdot \nabla T + D_{TW} \cdot \nabla W + K_T \cdot \nabla P \\ -J_W &= D_{WW} \cdot \nabla W + D_{WT} \cdot \nabla T + K_W \cdot \nabla P \end{aligned} \tag{1}$$

Here, the coupling parameters D_{TW} and D_{WT} have been added to account for the transfer of heat and moisture content under a gradient of the other quantity. The steam pressure transfer coefficients K have also been introduced.

The thermal transfer coefficients applicable to the model vessel have been described earlier [1], as well as the numerical simulation of the temperature distribution with a heated inner liner. The hygral diffusion coefficients D_{WW} were determined by drying experiments [2].

As the concrete vessel is subjected to simultaneous thermal and hygral gradients, the coupling coefficients of the equations (1) may contribute to the transfer process. We have conducted a parameter study using experimental values of the thermal and hygral diffusivities.

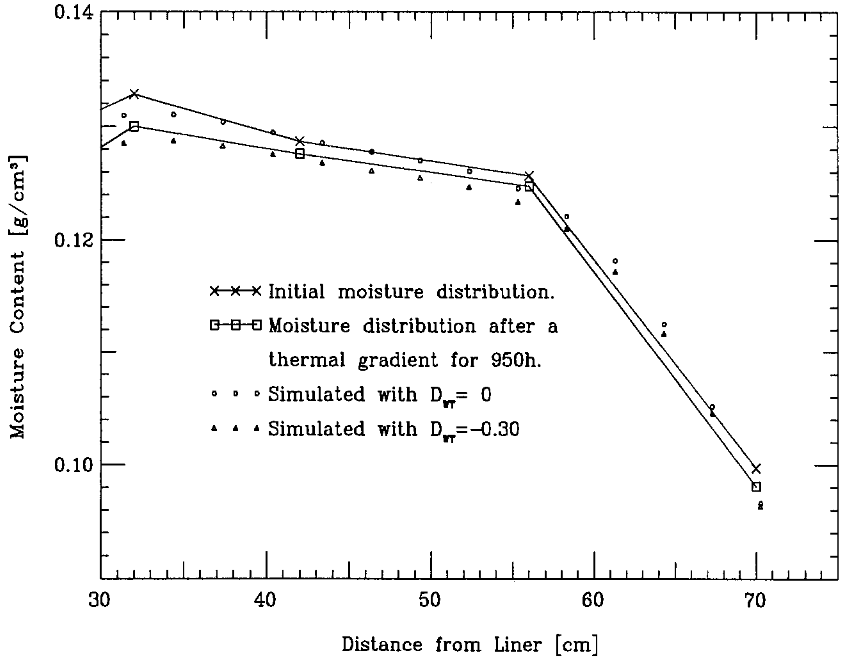

Figure 2: Parameter study of the influence of the coupling coefficient D_{WT} at a liner temperature of 70°C.

As can be seen from fig. 2, the influence of the coupling coefficient on the moisture content is small in the outer zone of the concrete vessel. This indicates that the uncoupled diffusion equation is a suitable description where moderate thermal gradients exist.

In order to simulate the moisture distribution near the inner liner, one would need to experimentally determine the proper coupling coefficients separately.

2.2 Permeability and steam pressure

Close to the inner steel liner, a temperature of about 70°C has been reached. This leads to pressure-induced moisture transfer, which can be described in terms of permeability. A model of the thermodynamical properties of moisture must take into consideration both components in the pore-volume of concrete (i.e. water and air). The following equation holds for the mass of each of the two components [3]:

$$M^{(\kappa)} = \phi \sum_{\beta} S_\beta \rho_\beta X_\beta^{(\kappa)} \tag{2}$$

Here, the index β specifies the phase (liquid or gas) of the κ'th component. The saturation (the fraction of the pore volume occupied by the phase β) is S_β, and the porosity is ϕ. The density of the phase β is ρ_β.

The flux of each phase can be described by Darcy's law, written here in terms of the phase β when neglecting gravitational effects:

$$-J_\beta^{(\kappa)} = k \cdot k_{r,\beta} \frac{\rho_\beta}{\eta_\beta} X_\beta^{(\kappa)} \nabla P_\beta \tag{3}$$

The value used in our simulation for the absolute permeability k was $k_{liquid} = 1.0 \cdot 10^{-18}\mathrm{m}^2$. Further details on the transport parameters can be found in [3].

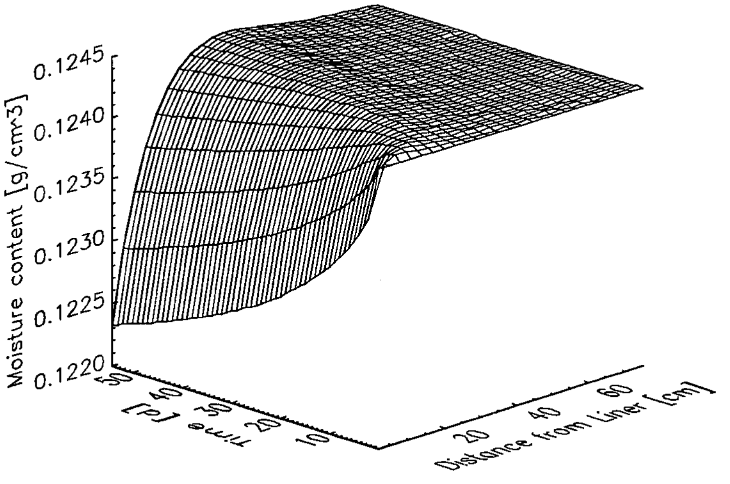

Figure 3: Distribution of the moisture content in the concrete vessel as a function of time and distance from the inner liner. The liner temperature was 70°C.

A numerical simulation of the moisture distribution starting from a uniform moisture content of 95% at 20°C was carried out using the above equations. This was done by applying the computer code TOUGH [4]. Fig. 3 shows the moisture content in the prestressed concrete vessel as a function of time and the distance from the liner. Here, the liner temperature was 70°C.

From fig. 3 it can be seen that the moisture content decreases with time close to the liner, although no moisture can escape through or along the liner in the numerical model. The moisture is transferred towards more remote and cooler parts of the vessel, according to the set of equations (3).

Experimentally, an absolute pressure lower than the theoretical value has been measured. This might be due to leaks at the liner-concrete interface. Such a path for moisture transfer can be implemented in the above calculations as a non-zero permeability of the steel liner. With a minute permeability of $k_{liner} = 1.0 \cdot 10^{-30}\mathrm{m}^2$, a slow drop in pressure near the liner results. The presence of leaks partially deflates the steam pressure. This is shown in fig. 4, and the computed values match experimental findings.

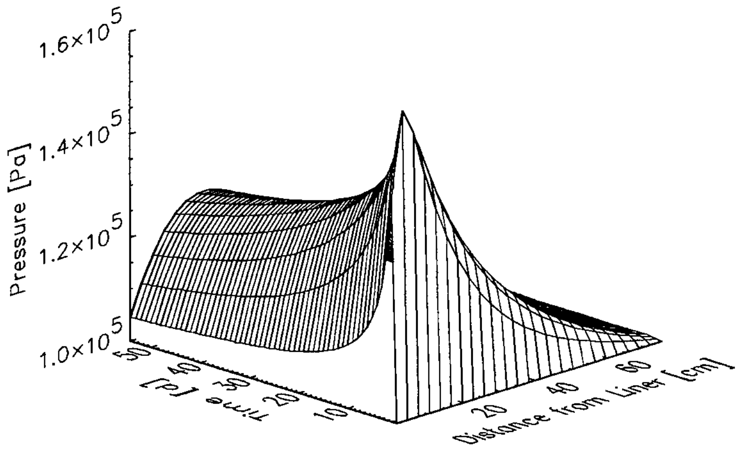

Figure 4: Pressure distribution in the concrete vessel as simulated with a small leak near the steel liner. The liner temperature was 70°C.

The shape of the moisture distribution in the thick-walled concrete vessel after some time of heating (inversely U-shaped, as combined from figs. 2 and 3), is due to several effects. The concrete close to the liner has had time to dry during previous heating cycles, as shown above. The outer zones had dried for 790 days already, with a thermal gradient on the surface during several periods of continous heating. Here, the phenomenological diffusion equation yields a good description of the dominating moisture transfer mechanism when using experimentally obtained temperature dependent diffusion coefficients. The concrete of the inner section is nearly saturated, as moisture has moved there from the zones close to the liner.

3 CONCLUSIONS

- Thermal and hygral diffusion coefficients depend on temperature and moisture content. At moderate temperatures, experimentally determined values allow us to predict heat and mass transfer.
- If the liner reaches temperatures of about 70°C or higher, an internal pressure is built up. This leads to a strong moisture displacement away from the hot liner, and saturates the inner parts of the concrete wall. This phenomenon obviously cannot be described by means of diffusion equations.

ACKNOWLEDGEMENT

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