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MOISTURE TRANSPORT OVER THE BRICK/MORTAR INTERFACE

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ABSTRACT

The moisture transport in brick, mortar that was cured separately, and combined brick/mortar samples was studied using NMR. The experimental results show that the mortar is less permeable if it is cured bonded to the brick instead of cured separately. Models of the moisture transport are usually formulated on the basis of a diffusion equation. Preliminary simulations of the moisture transport over brick/mortar interfaces roughly correspond with measured moisture contents.

1. INTRODUCTION

Moisture transport plays a dominant role in many deterioration mechanisms of traditional masonry constructions. This deterioration may exhibit itself in various forms, e.g., by decolouring of the surface (visual damage), cracking, chipping, or disintegration of brick and/or mortar (visual and mechanical damage).

Therefore a detailed knowledge of the moisture transport is essential to understand the various deterioration mechanisms. Previous research has often been focused on the moisture transport in single porous materials. However, in masonry brick and mortar are bonded and moisture can be transported over the interface. Preliminary experiments indicated that during the bonding process the hygric prop-

erties of mortar change significantly [1,2]. In this paper additional research will be presented together with some preliminary simulations.

2. MODEL

The mathematical formulation of the mass transfer in porous materials at a macroscopic level is usually based on diffusion equations. These were first established by Philip and de Vries [3]. A more fundamental description of these transfer equations was given later by Bear [4]. If the gravity is neglected the moisture transport for the one-dimensional isothermal absorption problem considered in this paper can be described by:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(D_{\theta} \frac{\partial \theta}{\partial x} \right) \quad (1)$$

In this equation θ [m^3m^{-3}] is the volumetric moisture content and D_{θ} [m^2s^{-1}] the moisture diffusivity describing the moisture flow. This moisture diffusivity is a function of the actual moisture content. For water absorption, D_{θ} is commonly approximated by an exponential form:

$$D_{\theta} = D_0 \exp(\beta\theta) \quad (2)$$

where D_0 and β are constants, that depend on the material. In the experiments cylindrical bars of initially dry material were allowed to freely absorb water through one end. Therefore the initial and boundary conditions are:

$$\begin{aligned} \theta &= \theta_0 \quad \text{for } x > 0, t = 0 \\ \theta &= \theta_{\text{cap.}} \quad \text{at } x = 0, t > 0 \end{aligned} \quad (3)$$

In these conditions $\theta_{\text{cap.}}$ is the capillary moisture content, that is the maximum moisture content under atmospheric conditions, and θ_0 is the initial (uniform) moisture content of the sample.

In case of absorption in a sample that consists of two different materials, there is a second boundary condition at the material/material interface. At this interface the

macroscopic capillary pressure, Ψ , will be continuous [5]:

$$\Psi_I = \Psi_{II} \quad (4)$$

where subscripts I and II indicate the two materials. For each material the moisture content is a function of the capillary pressure, so in general this condition will result in a jump of the moisture content at the interface:

$$\theta_{II} = f(\theta_I) \quad (5)$$

Over such a material/material interface the moisture flux will be continuous:

$$q_I = q_{II} \quad (6)$$
$$D_I(\theta_I) \frac{\partial \theta_I}{\partial x} = D_{II}(\theta_{II}) \frac{\partial \theta_{II}}{\partial x}$$

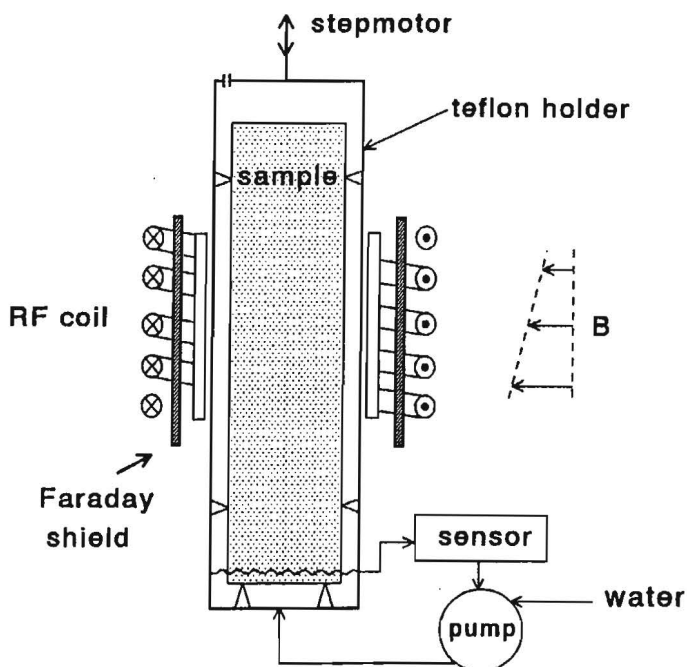
3. MOISTURE CONTENT MEASUREMENT

The experimental results presented in this paper are obtained using a nuclear magnetic resonance (NMR) method. This method offers the possibility to determine moisture content profiles non-destructively and with a high spatial resolution. In such a NMR experiment the magnetic moments of the hydrogen nuclei are manipulated by suitably chosen alternating radio frequency fields, resulting in a so called spin-echo signal. The amplitude of the spin-echo signal is proportional to the amount of hydrogen nuclei excited by the radio frequency field. The resonance condition for the nuclei is given by: $f = \gamma B_0$. Here f is the frequency of the alternating field, γ is the gyromagnetic ratio ($\gamma = 42.58$ MHz/T for ^1H) and B_0 is the externally applied magnetic field. Because of the resonance condition the method can be made sensitive to only hydrogen and therefore to water.

For the experiments described here, a home built NMR apparatus was used which operates at a frequency of 33 MHz. A well defined magnetic field gradient is applied, offering a one-dimensional resolution of 1.0 mm [6]. In the absorption

experiments a cylindrical bar with a diameter of 20 mm and a length ranging between 80 and 180 mm of initially dry material was allowed to freely absorb water through one end. The experimental set-up for measuring the absorption profiles during absorption is given in figure 1.

Figure 1
Experimental probe head for measuring moisture profiles during absorption. Using an electrical sensor and a pump the water level is maintained constant.



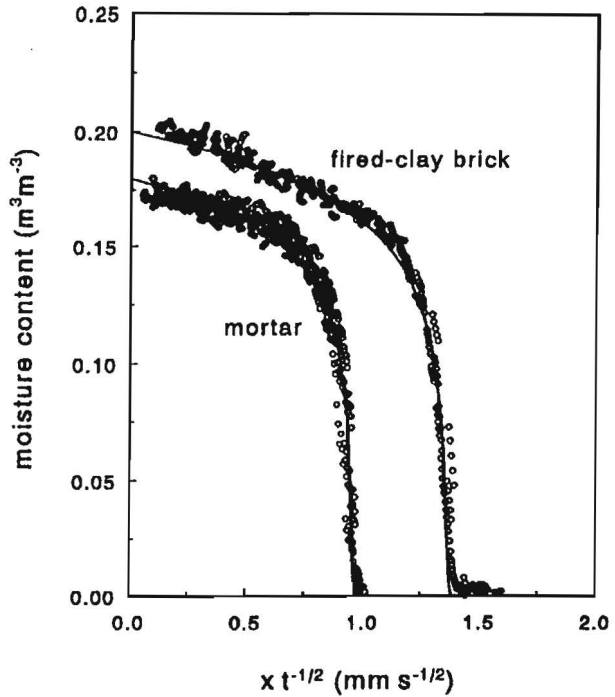
In this set-up the moisture distribution in a small region (1 to 2 mm) of the sample is measured simultaneously. After determination of such a partial profile, the sample is moved in the vertical direction over a few mm with the help of a step motor. This is repeated until a complete wetting moisture profile has been measured. Subsequent moisture profiles are measured by repeating the procedure mentioned above.

4. EXPERIMENTAL RESULTS

First, the moisture profiles during absorption were measured for fired-clay brick and mortar that was cured separately. In figure 2 these profiles are given after applying the well known Boltzmann transformation. As can be seen this transformation yields a distinct curve on which the data from the various profiles for that particular material collapse. Since the profiles collapse they are

related by a simple \sqrt{t} scaling. This indicates that the moisture diffusivity does not depend on the position and supports the modelling of the moisture transport during absorption by a diffusion equation [7]. In figure 2, computer simulations that are based on an exponential behaviour of the moisture diffusivity (equation 2) are added. It is obvious that these simulations give an adequate description of the observed moisture profiles.

Figure 2
 (o) Boltzmann transformation of the measured moisture profiles of fired-clay brick and mortar.
 (—) Boltzmann transformation of the simulated moisture profiles based on an exponential moisture diffusivity.



The brick/mortar samples that were used to perform the absorption experiments were prepared in two different manners. The first series of samples was made using moulds to allow 45 mm of mortar to cure on top of a 110 mm bar of fired-clay brick. The samples therefore differ from the mortar joints in practice, which have a thickness in the order of 12 mm. In figure 3a and 3b the absorption profiles measured in these brick/mortar samples are plotted. For the bonded mortar it is found that, after the Boltzmann transformation, the profiles do not collapse on a single curve, indicating that the moisture diffusivity is dependent upon the position. This variation of the hygric properties with position is probably caused by suction of water out of the mortar into the brick during the bonding process. As a result, particles will be transported to the mortar/brick

interface and the mortar becomes more compact near this interface [8]. From the experiments it was estimated that towards the brick/mortar interface the water penetration coefficient decreased by a factor 2 to 4. Because of the relatively large moisture diffusivity of the brick in comparison to that of the mortar, two situations can be distinguished. In figure 3a water is first absorbed

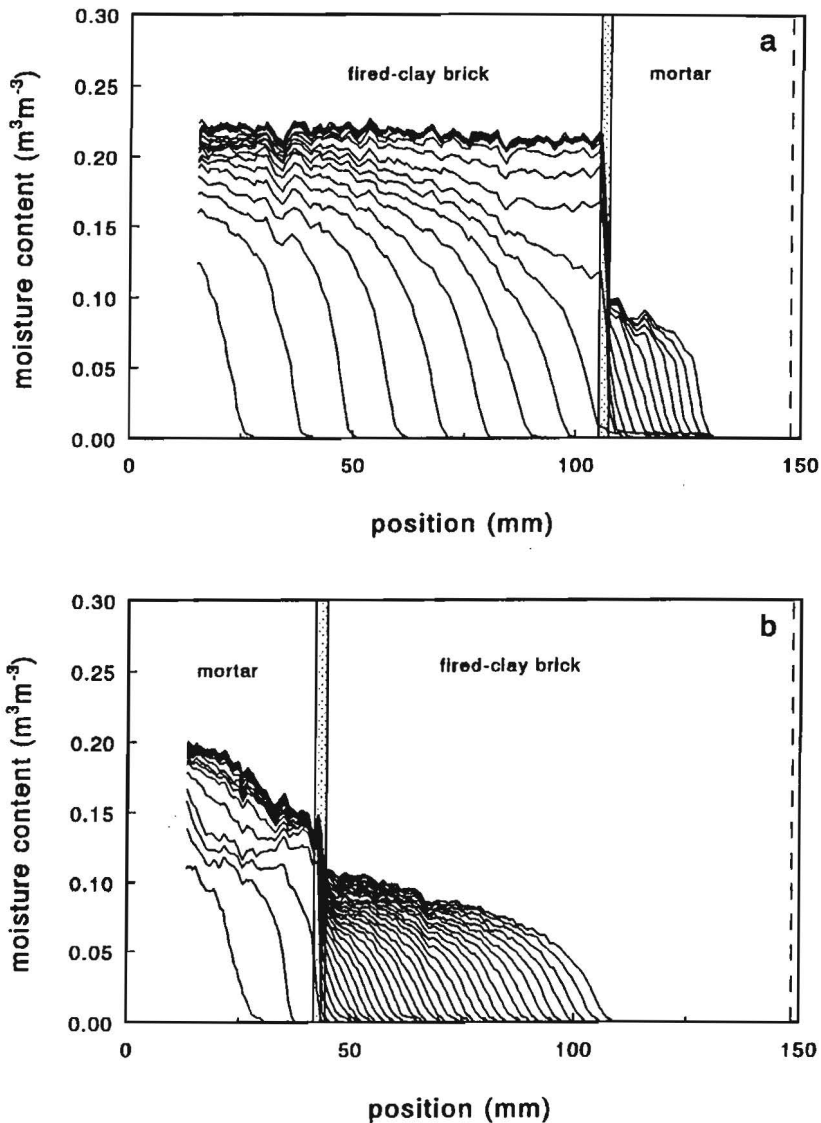


Figure 3 - Moisture profiles measured during the absorption of water in a sample of fired-clay brick and mortar. The experiment lasted 6 hours in the case of absorption from brick to mortar (a) and 24 hours in the case of absorption from mortar to brick (b). The shaded box indicates the interface area and the dashed line indicates the end of the sample.

in the brick before it reaches the brick/mortar interface. Since the mortar absorbs water rather slowly, the brick is fully saturated while the first profiles start to develop in the mortar. In figure 3b water is absorbed in the reverse direction. In this case the water is quickly absorbed by the brick once it reaches the interface and an almost stationary moisture profile develops in the mortar.

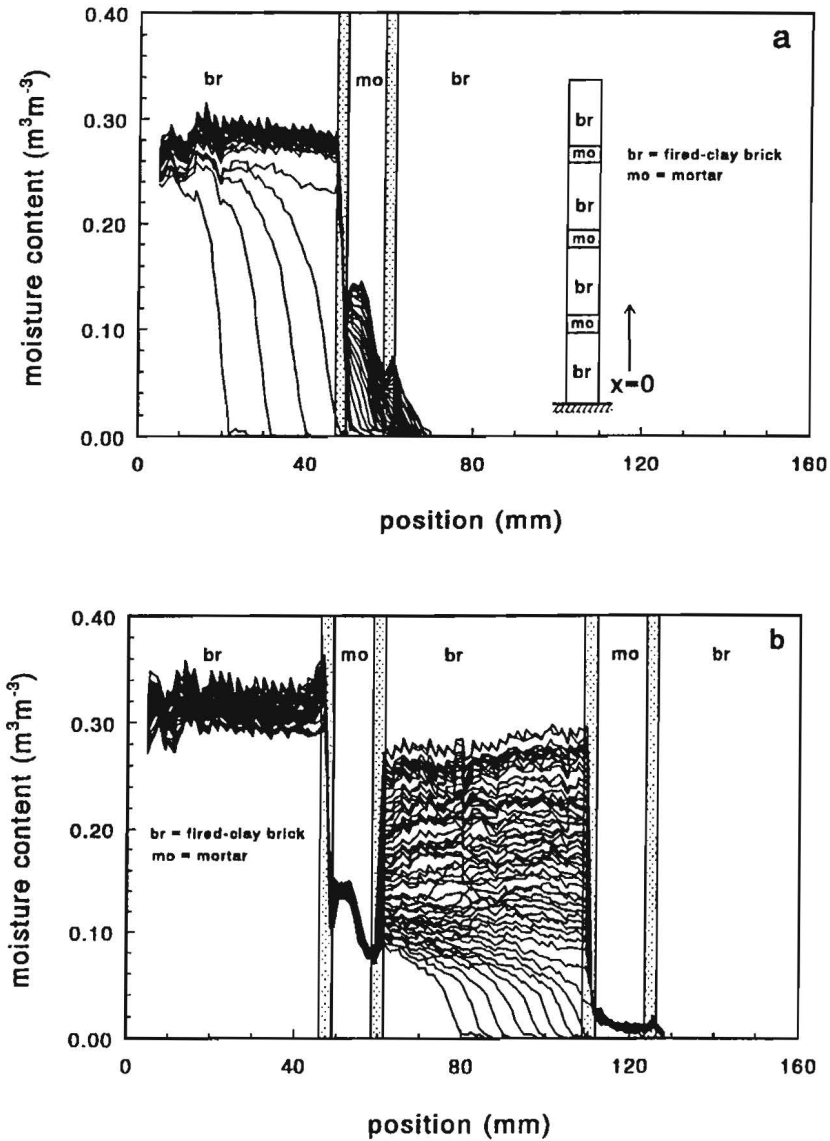


Figure 4 - Moisture profiles measured during the absorption of water in a masonry segment. The first 40 profiles were measured continuously during the first 4 hours of absorption (a) whereas the next profiles were measured at subsequent time intervals of 2 hours (b). The total experiment lasted 5 days.

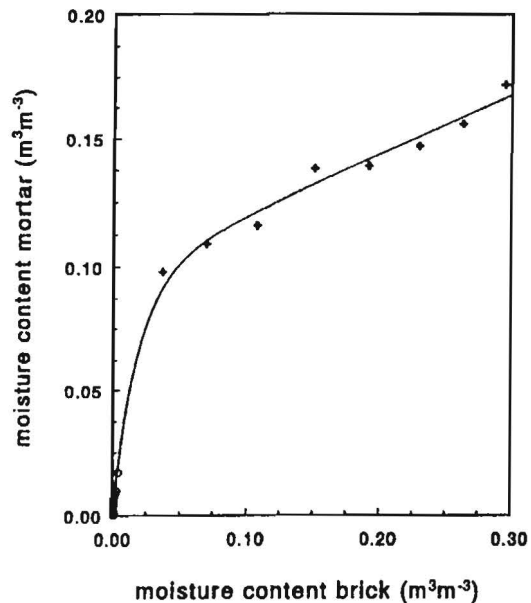
In addition, small masonry segments were made that contained four fired-clay bricks with 12 mm mortar in between. (The mortar was the same, but the bricks were different from those in Fig. 3.) The cylindrical bars needed for the absorption experiments were drilled out of these segments, after the segments were allowed to harden for at least 28 days.

Figures 4a and 4b show that the water absorption in these samples is slowed down once the first interface is reached. The mortar layer transports the moisture to the second brick layer, which absorbs the water at a reduced rate, governed by the permeability of the mortar. Once a flat profile has developed in the second brick layer, the moisture content in the second brick layer starts to increase until saturation is reached. This process took about 5 days in this experiment. Figure 4b reveals that the second mortar layer hardly absorbs water, even at full saturation of the second brick layer.

5. NUMERICAL SIMULATION OF THE MOISTURE TRANSPORT

The numerical simulation is performed on basis of equations (1), (5) and (6). The relation between the moisture content of the fired-clay brick and the mortar at this interface is deduced from the macroscopic capillary pressure and the hygroscopic curves of both materials. This relation is

Figure 5
Relation between the moisture content of the brick and the mortar that is deduced from (+) the macroscopic capillary pressure and (o) the hygroscopic curves of the brick and the mortar.



plotted in figure 5. The one-dimensional simulation is done by using standard procedures from the NAG-library. In these simulations it has been assumed that the moisture diffusivity in the mortar can still be approximated by a single exponential behaviour. However, in case of the second mortar layer a different moisture diffusivity was used ($D_{\theta_{II}} < D_{\theta_I}$). In figure 6 the simulated moisture profiles are plotted for subsequent time intervals of 2 hours. The simulated profiles plotted in this figure roughly correspond to the measured profiles plotted in figure 4, indicating that the simplified model may very well serve as a tool to predict moisture transport in brick/mortar samples.

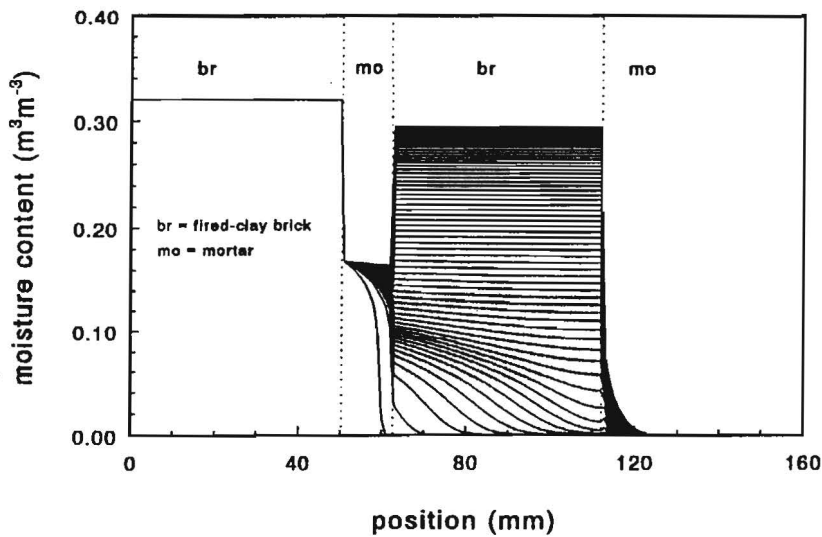


Figure 6 - Simulated moisture content profiles at subsequent time intervals of 2 hours. In total 120 hours are simulated.

6. CONCLUSIONS

The moisture transport in porous materials can be modelled by a diffusion equation. For water absorption, the moisture diffusivity that is used in these models can be approximated by a single exponential function of the moisture content, as was deduced from measured moisture profiles. With NMR these moisture profiles can be determined quantitatively, one-dimensionally, and in a non-destructive way. In case of mortar bonded to brick, the hygric properties of mortar change significantly compared to mortar samples

cured separately. More research is needed to identify the parameters that determine the hydraulic contact of the final cured brick/mortar interface.

The simplified model presented in this paper may serve as a tool to predict moisture transport in brick/mortar samples. However, different moisture diffusivities were used for the mortar layers in one sample. As our absorption experiment lasted 5 days, during which the second mortar layer did not seem to reach full saturation, long-term experiments should be performed to give a satisfactory explanation of the observed phenomena.

7. ACKNOWLEDGEMENTS

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