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Numerical Analysis of the Moisture Behaviour of Building Elements

Analyse numérique de l'état hygrométrique des éléments de construction

Numerische Berechnungen zum Feuchteverhalten von Bauteilen

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SUMMARY

The effectiveness of moisture protection measures may be substantially improved if these are supported by numerically modelling the moisture behaviour of a given building element. For this, the known fundamental laws of moisture transport in porous materials have to be applied to real masonry structures. Then calculations of the moisture distribution may be used to analyze the influence of changing boundary conditions as well as the effectiveness of possible protection methods.

RÉSUMÉ

L'efficacité d'une mesure d'assèchement peut être améliorée considérablement à l'aide des calculs numériques sur l'état hygrométrique d'un élément de construction. Pour cela, il faut appliquer les lois fondamentales des mécaniques du transport d'humidité dans des matériaux poreux aux constructions réelles. De cette manière, il est possible de démontrer la cause d'une charge hygrométrique élevée aussi bien que l'influence des mesures d'assèchement sur l'état hygrométrique.

ZUSAMMENFASSUNG

Die Planung wirksamer Trockenlegungsmassnahmen kann mit Hilfe numerischer Berechnungen zum Feuchteverhalten unterstützt werden. Hierzu ist die für poröse Baustoffe gültige Feuchtebilanzgleichung auf Mauerwerk zu übertragen. Damit können Berechnungen zur Feuchteverteilung durchgeführt werden, die die Ursache der hohen Feuchtebelastung ebenso aufzeigen, wie den Einfluss zeitlich veränderlicher Feuchtebeanspruchungen am Bauwerk. Vor allem kann die Wirkungsweise möglicher Trockenlegungskonzepte nachvollzogen werden.

1. INTRODUCTION

In the repair and conservation of historical structures the protection of building elements against moisture is of importance because most types of degradation of natural stones, clay bricks, mortars and plasters occur in the presence of moisture.
Aside from rain and condensation of water vapor in many cases excess moisture is absorbed by the foundations of the building due to capillary rise of water.
In the past, numerous attempts to install or reinstall protection against moisture in outer walls failed, and occasionally even accelerated the degradation processes. These failures were mainly caused by a lack of knowledge of moisture behaviour and moisture movement in porous materials.
The selection of an effective moisture protection method, therefore, should be based on a careful analysis of the structure and its materials, the exposure conditions, and the mechanisms of moisture ingress, moisture movement and drying of the element.
With the help of the necessary material parameters the moisture balance of a structural element then may be modelled numerically for the prevailing boundary conditions. Also different protection techniques may be simulated by introducing locally modified material properties in a cross-section or by modified boundary conditions of a structural element. Based on these case studies effective moisture protection methods can be chosen.

2. MOISTURE BALANCE IN A STRUCTURAL ELEMENT

2.1 Moisture behaviour of porous materials

In an exterior wall moisture transport takes place through the porous material by diffusion of water vapor or at higher moisture concentrations by capillary flow in the liquid phase. Moreover, moisture flow may also be caused by a temperature gradient or by a hydrostatic pressure acting on the structural element. Assuming isothermal and isobaric conditions, the moisture balance of a porous material is described by eq. (1) [1,2]:

$$\frac{\partial \theta}{\partial t} = \nabla\left(\frac{D_v}{R_D T}\nabla p_v\right) + \nabla\left(D_{\theta l}\nabla\theta + K\nabla z\right) \tag{1}$$

In eq. (1), the material parameter D_v characterizes the flow of water vapor by diffusion due to a gradient of water vapor pressure ∇p_v. The last two terms in eq. 1 represent the moisture transport due to capillary effects in a porous material. Here, the gravity term characterized by the product of the capillary conductivity K and the height of the moisture front counteracts the driving force due to capillary pressure. The capillary rise of moisture can be expressed by the product of moisture diffusivity $D_{\theta l}$ and the gradient of the local moisture concentration $\nabla\theta$ [2]. All the material parameters are strongly influenced by the local moisture concentration θ and the ambient temperature T and

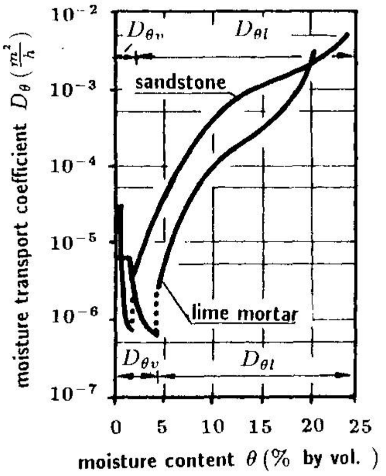

Fig. 1 Transport coefficient

they have to be determined experimentally. With the help of sorption isotherms the diffusion coefficient of water vapor D_v can be expressed for isothermal conditions as a function of the moisture concentration $D_{\theta v}=f(\theta,T)$.
Experimental and theoretical results showed, that due to their fine pore system for most building materials gravitational effects are negligible [1]. Then the gradient of moisture concentration $\nabla\theta$ is the driving force both for water vapor diffusivity and for capillary flow given in eq. 2:

$$\frac{\partial\theta}{\partial t} = \nabla\big((D_{\theta v} + D_{\theta l})\nabla\theta\big) \tag{2}$$

Although the mechanisms of capillarity and diffusion are effective in different ranges of moisture concentrations, the transport characteristics $D_{\theta v}$ and $D_{\theta l}$ may be superimposed as shown in Fig. 1 for two different materials, i.e. a sandstone and a mortar. As can be seen the shape of the curve is determined by the diffusion in the range of low moisture content and by the capillary flow for higher concentrations.

2.2 Moisture behaviour of masonry structures

Masonry exhibits an heterogeneous structure because it is composed of at least two very different materials, i.e. the masonry units either artificially made such as clay bricks or natural stone and a joining material such as hydraulic or lime mortar. In most cases the moisture behavior of these individual components of masonry differ considerably beceause of differences in their pore structure. In equilibrium with the relative humidity of the ambient air, the moisture concentration of a building material is determined by the adsorption of water vapor at the interior surfaces of the pores for an initially dry material or by desorption processes for wet materials. At higher relative humidities capillary condensation in very fine pores with radii of $r < 10^{-8}$ m may occur [1].
For a given equilibrium condition materials with a very fine pore structure and a large specific surface area, therefore, have a higher moisture content than materials with a coarse pore size distribution. If two materials with different porosity characteristics are in contact to one another as it is the case for masonry units and the mortar joint, the moisture distribution should exhibit a discontinuity across the interfacial zone.

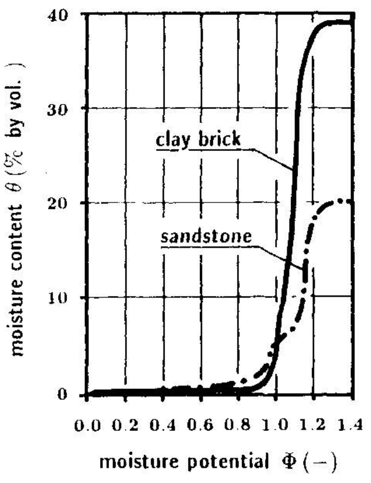

Fig. 2 Moisture potential

Therefore, eq. (2) is not applicable to describe the moisture balance of the inhomogeneous masonry structure Kießl [4] has introduced a moisture potential Φ to formulate the moisture transport through the pore system of different materials. Each building material is characterized by a specific curve as shown in Fig. 2, which relates the moisture content θ to the moisture potential Φ. In Fig. 2 these correlations are presented for a sandstone and a clay brick. For low moisture concentrations this relation is given by the sorption isotherm. Here, the moisture potential Φ increases with the relative humidity h from $0 < h < 100$ % r.h. to $0 < \Phi < 1$.

If the porous material is in contact with liquid water, capillary flow occurs in larger pores with radii in the range of 10^{-7} m < r < 10^{-3} m. Therefore, the moisture potential at a higher moisture content of the material can be described by the pore structure. For a corresponding analysis the cumulative pore volume and the pore size distribution is used, which was measured with the help of mercury intrusion porosimetry [1]. In Fig. 2 the shape of the cumulative pore volume characterizes the moisture potential for higher moisture concentrations of the material. Here, the moisture potential Φ rises from Φ =1.0 for pores with a radius of 10^{-7} m to Φ =1.4 for pores with a radius of 10^{-3} m according to eq. (3):

$$\Phi = 1.7 + 0.1 \log r \tag{3}$$

The upper value of the moisture potential Φ =1.4 does not represent a limit. Instead, this value is a result of the low volume of pores with a radius r > 10^{-3} m and the effect of gravitational forces which counteract capillary suction in larger pores.
With the help of this correlation between the moisture content θ and the moisture potential Φ shown in Fig. 2 the transport characteristics for diffusion and capillarity are expressed as a function of the moisture potential Φ. Then, the moisture balance of a masonry structure may be expressed by eq. (4):

$$\frac{\partial \Phi}{\partial t} = \nabla\big((D_{\Phi v} + D_{\Phi l})\nabla \Phi\big) \tag{4}$$

In Fig. 3 the superimposed transport characteristics $D_{\Phi v}$ and $D_{\Phi l}$ are given for a sandstone and a mortar. They demonstrate the extreme nonlinearity of this coefficient.

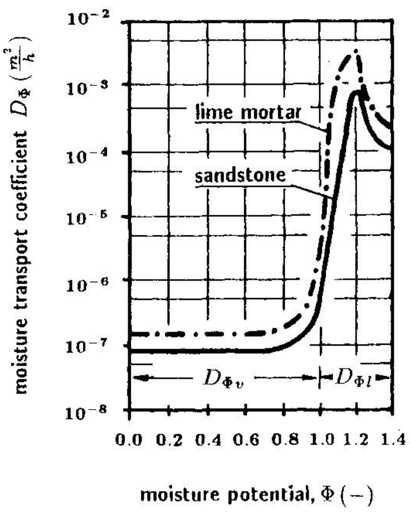

Fig. 3 Transport coefficients

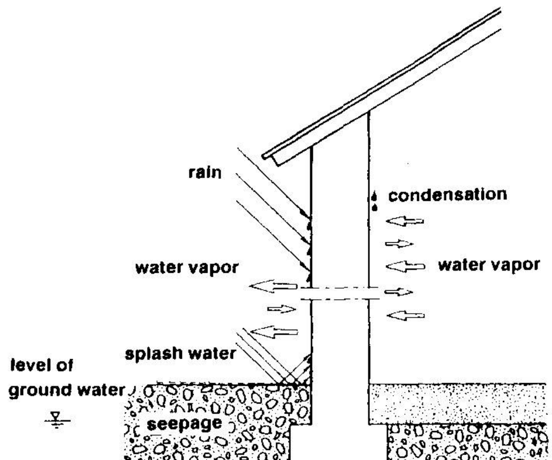

Fig. 4 Boundary conditions

3. NUMERICAL SIMULATION

The wetting and drying behaviour of structural elements is determined by the moisture transport and storage capacity in the materials of the structure as well as by the boundary conditions prevailing on the site. Water in the liquid phase will be absorbed by capillary suction. At the evaporation zone the desorption of water is also governed by the boundary conditions. The higher the temperature and the lower the relative humidity of the climate in the ambient atmosphere the better the drying conditions of a moist masonry structure. For known climatic conditions to which the structural element is exposed the moisture behaviour can be analyzed with the help of eq. (4). The transient field problem is solved with a finite element model.

3.1 Boundary conditions

Fig. 4 shows the analyzed system which represents the cross-section of an exterior wall with a height of 5 meters and a thickness of 0.8 meters. With the foundation immersed in ground water and the lower portion of the external wall in contact with wet soil, water will be taken up by capillary activity. In the upper section, the wall surface is exposed to the atmosphere. The relative humidity of the atmosphere and the exposure of the wall to liquid water may vary with time. At the interior surface of the wall evaporation may take place, e.g. at 55% rel. humidity in the ground floor and 90% in the basement, respectively. Fig. 4 also shows possible boundary conditions, such as driving rain, splash water,condensation of water vapor etc..
To simulate the moisture behaviour of real building elements, the cross-section of the external wall was divided in up to 7000 elements. This element arrangement allows to consider different types of building materials used in the structural element. Aside from natural stones, bricks and mortars also plasters inside and outside of the external wall as well coatings may be taken into account. Most important is the possibility to evaluate the effectiveness of moisture protection methods. These methods may alter the hygric behaviour of the building elements, e.g. due to chemical injection or other moisture barriers.

3.2 Results of numerical modelling

In the left part of Fig. 5 the distribution of the moisture potential within a wall, which is exposed to ground water, wet soil and surrounding air with a relative humidity of 55, 80, and 90 percent respectively, is shown. The moisture potential profiles represent the state of equilibrium starting from saturation at the bottom, where the wall is immersed in ground water. This equilibrium condition is equivalent to a moisture potential of $\Phi = 1.4$. At the upper part the distribution of the moisture potential is determined by the outer moisture condition at the evaporation zone. The difference between two adjacent profiles amounts to $\Phi = 0.05$. The numerical results demonstrate that at a level of 1 meter above the ground level the moisture potential indicates a high moisture content. In the left part of Fig. 5 also the quantity of up-take and loss of moisture is shown.
With the relation between the moisture potential and moisture concentration given in Fig. 2 the moisture distribution in the masonry structure can be calculated. For the presentation of the results, the degree of saturation of the material is represented by the scale in Fig. 5. Here the color shade changes from a light grey for dry materials to a dark grey for water saturated materials.
As shown by the distribution of the moisture potential this figure demonstrates the high moisture content in the masonry structure, even 1 meter above the ground level. It can be seen also, that the surface of the wall at the evaporation zone will be wet up to a height of half a meter above the ground level.

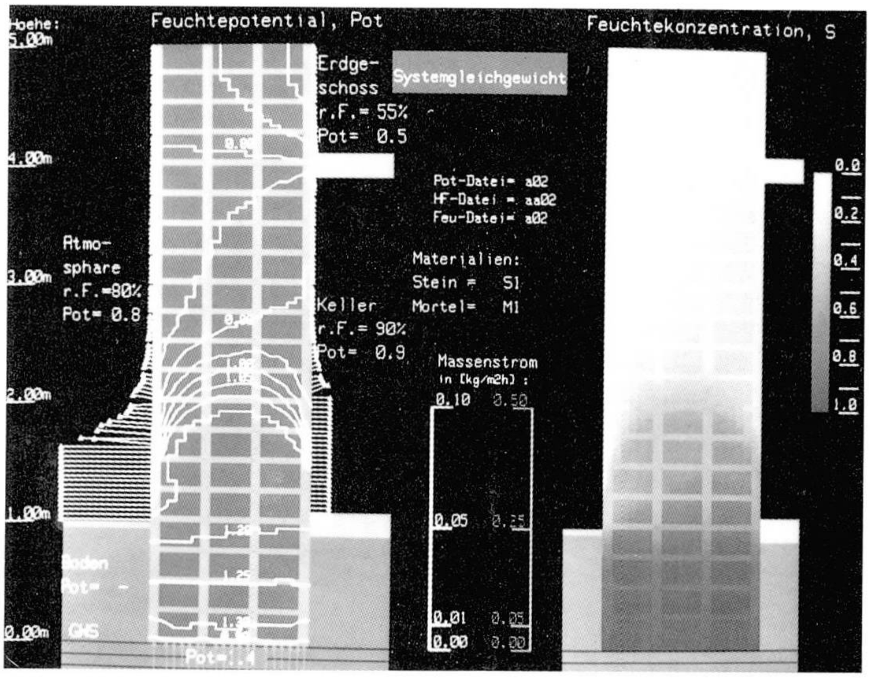

Fig. 5 Equilibrium moisture distribution

Further calculations of the equilibrium moisture distribution inside the structural element can demonstrate the effect of changing boundary conditions such as changing evaporation conditions as well as the effect of higher relative humidities inside and outside the building. Also the geometric situation of the structure can be varied. As an example, Fig.6 shows the effect of driving rain over a period of 4 days.
The distribution of moisture concentration demonstrates how the moisture front moves into the interior sections of the wall. The ingress of moisture is faster in the mortar joints than it is in the sandstone units. Therefore, the wetting of the sandstone units does not only take place in a horizontal direction but also from the mortar joints.
The numerical simulation of subsequent drying of the element shows the well known fact, that drying processes are much slower than the wetting of building structures.

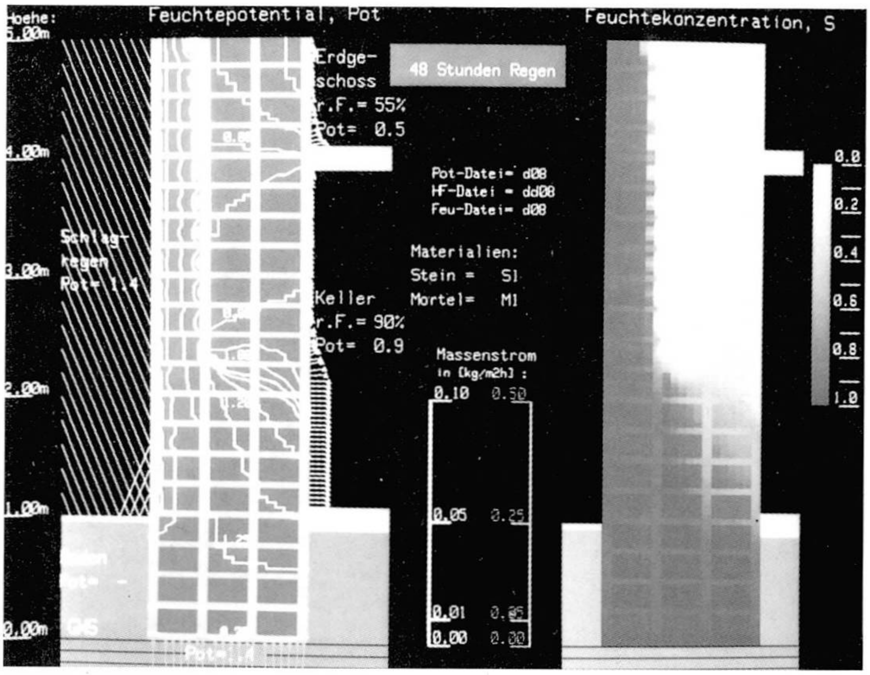

Fig. 6 Effect of 4 days of driving rain

Only in rare cases a wall will be exposed to 4 days of continuous driving rain. However, dirty facades of historic buildings are often cleaned by sprinkling of water on their surfaces for periods of several days. This may cause a moisture distribution similar to that shown in Fig. 6. If the masonry is effectly injected at the socle zone a further moisture transport from the soil into the structure is prevented and the

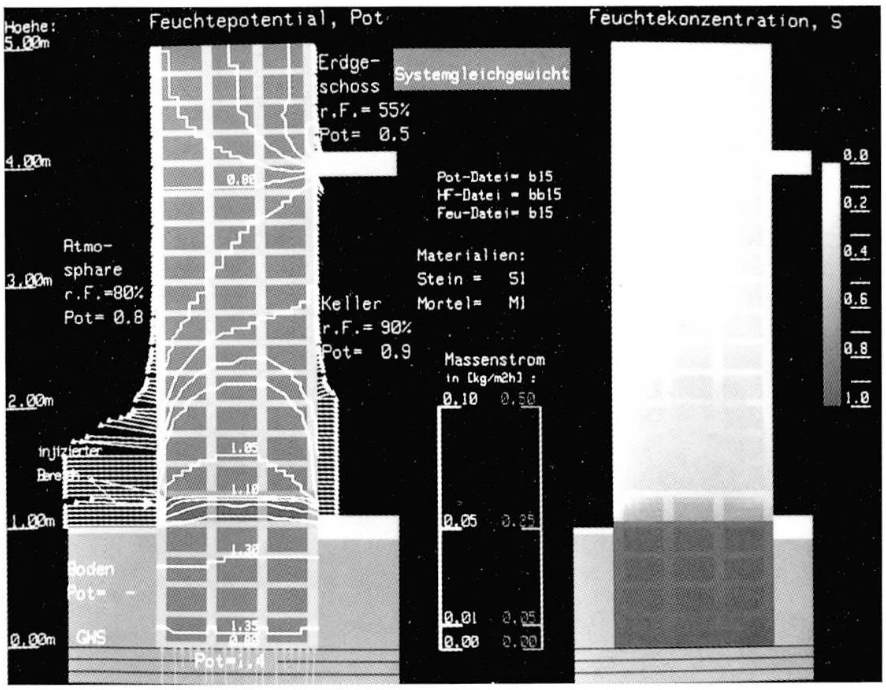

Fig. 7 Effect of an injection with reduced effectiveness

cross-section above the injected masonry section will dry. Most of the excess moisture is lost after a drying period of 3 months. In many cases it is difficult to carry out a complete injection, particularly when the moisture content in the pores of the building materials exceeds 50 percent of the saturation moisture content. Fig. 7 shows the moisture distribution after treatment of the socle zone with an injection which only fills the larger pores of the materials with a radius of r > 10^{-6} m.

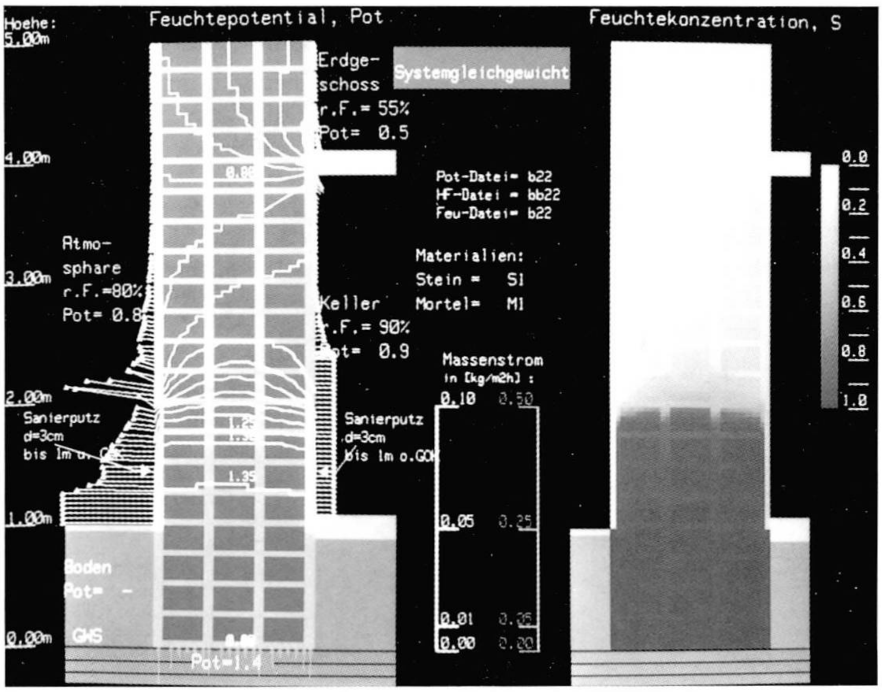

Fig. 8 Effect of an water repellent plaster

Of course, this method can also be used to simulate the effectiveness of other protection measures or a combination of several methods.
Although it is well known that water repellent plasters with very good drying behaviour cannot stop the capillary suction of the protected wall sections they are frequently used against rising dampness. As a result of the hydrophobic behaviour of such plasters, the moisture front remains inside the masonry structure behind the plaster. Hence, the surface of the plaster appears to be dry but numerical results shown in Fig. 8 proof that the moisture front inside the structure will rise drastically. The evaporation rate of the masonry is controlled by diffusion through the plaster. Therefore, the thicker the plaster and the lower the evaporation rate the higher the moisture front will rise inside the structure. These numerical results are also supported by field observations.

4. CONCLUSIONS

The wetting and drying behaviour of structural elements can be simulated with the help of numerical methods. These calculations require detailed information on materials properties such as sorption isotherms and various transport coefficients for the flow of water in the liquid and in the vapor phase. The calculations demonstrated that high moisture concentrations in building materials can arise from soustained contact with liquid water, e.g. due to driving rain or ground water. However, the equilibrium condition between capillary rise and evaporation limits the level of the moisture front. To model the moisture transport in masonry structures, the differences in moisture content of mortar and stone materials subjected to the same hygric conditions makes it necessary to define a common moisture potential as proposed by Kießl. The numerical simulation then allows to perform case studies of possible protection methods, thereby introducing locally modified material properties or partially modified boundary conditions. Different methods then may be compared with regard to effectiveness, effort and required drying time.
In this paper the infuence of temperature as well as the influence of salts often found in historic structures was negleted. These additional effects are presently incorporated into the numerical model.

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