Hygrothermal Properties and Behaviour of Concrete

Hartwig M. Künzel, Andreas H. Holm, Martin Krus

Fraunhofer Institute for Building Physics, P.O.Box 1152, 83601 Holzkirchen, Germany

Dr.-Ing Hartwig M. Künzel

Hartwig M. Künzel is department head at the Fraunhofer-Institut Bauphysik (IBP), the leading building research establishment in Germany. His department specializes in hygrothermal simulation, laboratory and field testing. The heat and moisture transport model WUFI® was developed during his PhD-thesis defended at the University of Stuttgart in 1994. He has been actively involved in many international projects (e.g. IEA Annex 14 & 24), standard committees (ASHRAE, CEN) and continuous education seminars. Dr. Künzel has published over 200 scientific articles in trade journals and text books.

Dr.-Ing Andreas Holm

Andreas H. Holm is head of department "Indoor Environment and Climatic Impacts" at the Fraunhofer-Institut Bauphysik (IBP). He studied physics at the TU Munich as well as at the Universities in São Paulo and Porto. In 2001 he finished his PhD work with the title "Determination of the uncertainty of hygrothermal calculations with a stochastic approach". He has been actively involved in many international projects (e.g. IEA Annex 41), standard committees (ASHRAE, CEN) and continuous education seminars. Since 2002 he lectures to civil engineering and architectural students at Applied University of Rosenheim, the Bundeswehr-Universität München and at the Stuttgart University. Andreas Holm has published over 100 scientific articles in journals, conference proceedings and text books.

Dr.-Ing. Martin Krus

Martin Krus, working for the Faunhofer Institute Bauphysik since 1985, is head of the working group “Physics of Surfaces and Biohygrothermics” and head of the test laboratories "moisture, mortar, radiation, emission protection”. He is assistant professor at the Technical University of Stuttgart and at the University of Applied Sciences in Rosenheim.

Abstract

Concrete has become irreplaceable for modern building structures while at the same time the number of existing concrete constructions requiring conservation or retrofit measures is continuously rising. It can be shown that moisture is a key factor when service performance and durability issues are concerned. Therefore, the moisture behaviour of concrete is investigated both by hygrothermal simulation and field tests. Additionally the material properties of concrete necessary for the calculations are determined and evaluated. The results show an abnormal behaviour compared to other building materials when water absorption is involved. There appears to be a self-sealing effect which causes liquid penetration to stop at some distance from the surface when concrete is exposed to rain or ground water for some time. Since this effect causes deviations between experiment and simulation, a tentative solution for the application of hygrothermal models is proposed: concrete components are divided in two layers: one where liquid transport is included and the other where vapour diffusion is the only moisture transport mechanism.

key words: concrete, moisture behaviour, hygrothermal simulation

Kurzfassung

Feuchteverhalten und hygrothermische Eigenschaften von Beton

Beton ist aus modernen Baukonstruktionen nicht mehr wegzudenken. Gleichzeitig steigt jedoch die Anzahl der Gebäude mit sanierungsbedürftigen Betonbauteilen stetig an. Dabei zeigt sich, dass die Feuchte für die Gebrauchstauglichkeit und die Dauerhaftigkeit von Baustoffen eine entscheidende Rolle spielt. Deshalb wird das Feuchteverhalten von Beton durch Freilandversuche und hygrothermische Simulationsrechnungen genauer untersucht. Als Grundlage für die Berechnungen werden auch die erforderlichen hygrothermischen Materialkennwerte bestimmt. Die Auswertung zeigt für Beton ein, im Vergleich zu anderen Baustoffen, abweichendes Verhalten beim Kapillartransport. Nach längerer Schlagregenexposition oder in Kontakt mit Grundwasser scheint bei Beton eine Art Selbstabdichtungseffekt einzusetzen, der den Flüssigtransport in einer gewissen Entfernung von der Oberfläche unterbindet. Da dieser Effekt zu einer Verschlechterung der Übereinstimmung von Rechnung und Messung führt, wird versuchsweise folgende Vorgehensweise bei der hygrothermischen Simulation vorgeschlagen: Das Betonbauteil wird in zwei Schichten unterteilt, wobei in der Wasser beaufschlagten Schicht mit Kapillartransport gerechnet wird, während in der anderen Schicht ausschließlich Dampfdiffusionsvorgänge berücksichtigt werden.

Stichwörter: Beton, Feuchteverhalten, hygrothermische Simulation

1. Introduction

Reinforced concrete has become the most important construction material worldwide. Concrete is used for the infrastructure (roads, bridges, tunnels, etc.), for industrial installations (e.g. power plants, production sites, storage tanks) for sanitary engineering as well as for all kinds of high- and low-rise buildings. Its mechanical properties depending on composition and curing conditions have been studied extensively. However, much less is known about its moisture transport properties which have been studied in a less rigorous manner by field observations and laboratory experiments.
This paper explains why the moisture behaviour of concrete is relevant for the hygrothermal performance and the durability of building components and what it takes to predict its behaviour in building practice by numerical simulation. To this end material property tests as well as experimental and mathematical investigations under natural exposure conditions on typical concrete samples have been carried out. The implementation of these investigations and their results are reported and some practical conclusions concerning the hygrothermal modelling of concrete are attempted.

2. Importance of moisture transfer in concrete

It is evident that the moisture transport characteristics of concrete, which is employed as first line of defence (without additional water-proofing layers) for damp-proof basements or flat roofs, represent a major performance issue. It is less obvious that the same transport characteristics may also adversely affect the thermal performance and the durability of a building. Since moisture transfer is always coupled with heat transfer, especially when vapour diffusion and drying processes are involved, it is preferable to talk about hygrothermal transfer because strictly isothermal moisture transfer hardly ever exists. The following examples are given to illustrate the importance of hygrothermal transfer in concrete for its expected function and service life of building envelope components.

2.1 Concrete acting as moisture source

When concrete is poured it contains a substantial amount of water, of which only a certain part (dependent on the water-cement ratio) will be consumed by hydration. The rest will be dissipated during and after the construction process by evaporation. After the enclosure of the building the evaporable water which is still in the concrete – commonly called construction moisture – will be released continuously to the interior spaces or adjacent building envelope layers until local equilibrium conditions are reached. The construction moisture from concrete or masonry structures is one of the main reasons for moisture damage (e.g. delaminating paint or gypsum plaster) and mould growth in modern buildings. It is therefore wise to deal with it by making sure it can dry out safely, i.e. without pushing the moisture content of sensitive materials (e.g. gypsum, organic insulation, wood based products) over their critical limits.
While construction moisture of concrete may take many years to dry, it will eventually disappear. However, when concrete is used for water-proofing of basements beneath the ground water table, it will act as a permanent moisture source. Water-impermeable concrete may be impermeable to liquid water – a requirement which is not always met in practice – but it is not impermeable to water vapour. A study in [1] comes to the conclusion that the long-term vapour diffusion flux through a water-impermeable concrete basement wall under steady-state conditions amounts to 5 g/(m²d), provided moisture evaporation from the wall's interior surface is unobstructed (i.e. the wall is not covered by other material layers). This quantity is not negligible compared to the normal moisture production in residential buildings (caused by occupants' activities like cooking, cleaning, showering) of usually less than 24 g/(m³d) [2]. Assuming a surface to volume ratio (A/V: A comprising walls and floor slab) in the basement of 0.9, the contribution of the vapour flux through the concrete envelope components is 4.5 g/(m³d) adding almost 20% to the interior moisture load. While more recent studies [3] indicate that the steady state moisture release from a water-impermeable concrete wall is probably lower than the number suggested in [1], all experts agree that it is not zero. The situation may become critical

when interior insulation is applied to such a basement wall. Since most interior insulation systems are equipped with a vapour retarder on the inside, the moisture released by the water-impermeable concrete gets trapped and may accumulate in the insulation material.

2.2 Concrete acting as vapour retarder or air barrier

Since concrete is less vapour permeable than most other load bearing mineral building materials (e.g. brick, lightweight concrete block, AAC, CSB, etc.) it acts like a vapour retarding layer. Any moist material applied to a concrete structure (e.g. screed) should not be expected to dry out through the concrete. This would be a very slow process. For the same reason, a vapour retarder is generally necessary on the other side when an interior insulation – especially with vapour-open materials – is installed because otherwise, penetrating indoor humidity would condense on the concrete wall's surface. In contrast to masonry walls which have to be made airtight by an interior plaster or exterior rendering, a cast-in-place concrete wall is usually airtight in itself without any additional finishing layer.

2.3 Moisture related durability issues of concrete

Apart from frost damage caused by water saturation under freezing conditions plain concrete is not sensitive to moisture. But concrete usually contains reinforcing steel which becomes susceptible to high humidity conditions once the concrete cover has carbonated. When the protection through the alkaline environment has gone corrosion starts and may lead to structural failure. A study by [4] indicates that even carbonated concrete offers some protection against steel corrosion. While black steel starts to corrode when the ambient humidity exceeds 60% RH, no corrosion progress was detected when the steel was covered by carbonated concrete up to a threshold of 80% RH. This means, any retrofit measure that helps to keep the relative humidity at the reinforcement in a carbonated concrete component below 80% RH, can solve the durability problem without special treatment like sanding and coating of the corroded rebars. The application of an exterior insulation system is an example of such a solution which has been confirmed by field tests and hygrothermal simulations in [5].

2.4 Moisture transfer prediction – a prerequisite for durable design

Since there is no doubt that moisture transfer has an important influence on performance and service life of concrete building components, the prediction of the hygrothermal behaviour becomes a prerequisite for a damage free and durable design. In the past these predictions were largely based on experiments, practical experience and simplified calculation tools, like the dew-point method [6]. Today there is a variety of hygrothermal simulation models available to the public. The model selected for the investigation in this paper is the hygrothermal simulation tool WUFI® [7], which has been validated by comparison with numerous filed tests and benchmark examples. It complies with the requirements of EN 15026 [8] the European Standard for hygrothermal performance assessment of building components.

There is an increasing necessity to apply renovation measures to historic structures and building components (some made of concrete) employing a wide variety of procedures and materials. In this context, problems have to be addressed regarding moisture behaviour and the related transport processes occurring after the renovation. That is the reason why the WTA has produces three guidelines describing the fundamentals, inputs and application of hygrothermal simulation tools [9, 10] as well as the evaluation of the results, e.g. by assessing the risk of mould growth [11]. The WTA guideline 6-2 [10] is the predecessor of the European Standard EN 15026 [8] which proves that the WTA has contributed substantially in pushing forward new technologies not only in the field of renovation and preservation but also in general building science.

3. Hygrothermal Material Properties

The investigations carried out within the framework of this study can be divided into two phases. Phase I includes the preparation of the concrete samples and the determination of the material parameters. Phase II deals with the determination of the moisture behaviour of concrete under natural exposure conditions which is described in Section 4. It involves the simulation of moisture transfer in concrete and the evaluation of the calculated results in comparison with laboratory and field measurements.

3.1 Preparation of samples

The fresh concrete is cast in cubes of 20 x 20 x 20 cm^3 and, after removal of the mould, is stored for 3 months under constant conditions in a climatic chamber at 23°C and 80% relative humidity. Subsequently, the samples are cut and conditioned for the various experiments. The absorption and desorption experiments are carried out on crushed samples of concrete with a maximum granulate diameter of approx. 20 mm, while the resistance to water vapour diffusion is determined on rectangular 20 mm thick slices with a surface area of 10 x 15 cm^2. The samples for determining the liquid transport coefficients and for outdoor weathering have a cross section of 5 x 5 cm^2 and a length of 15 cm, and their flanks are sealed with an epoxy resin so that the moisture transfer can only take place in the longitudinal dimension. Before starting the experiments, all samples are dried at 70°C in dry air until their mass is constant. Table 1 shows the composition of the concrete samples examined.

Table 1 Composition of the examined concrete C20/25 (B25)

Specifications		CEM I 32,5 R, PZ 35 F
Particle-size distribution curve		AB16
Cement content [kg/m³]		314
Water content [kg/m³]		186
Aggregate content [kg/m³]	0-4 mm	810
	4-8 mm	362
	8-16 mm	629
Water-cement ratio		0.6

3.2 Determination of the material parameters

The material properties and functions required to assess the moisture behaviour and to perform hygrothermal simulations are:

- Bulk density ρ [kg/m³], which serves to convert the specific heat by mass to the specific heat by volume.
- Specific heat capacity c [kJ/(kgK)], approx. 0.85 kJ/(kgK) for mineral materials like concrete.
- Thermal conductivity λ [W/(mK)] of the dry material (for concrete approx. 1.6 W/(mK)), a moisture-dependent heat conductivity is optional.
- Porosity ε [m³/m³], which determines the maximum water content w_{max} (by multiplication by ρ_{water} = 1000 kg/m³).
- Moisture storage, i.e. sorption res. suction isotherms w = f(φ) [kg/m³] that give the equilibrium moisture content of materials as function of relative humidity in both the hygroscopic and the capillary water (over-hygroscopic) range.
- Vapour diffusion resistance factor μ [-]. The μ-factor indicates how many times the diffusion resistance of the material is higher than that of stagnant air. The μ-factor may be dependent on moisture content of the material res. the ambient air humidity.
- Liquid diffusivity D_w [m²/s] both for water uptake and redistribution res. drying of materials as a function of moisture content.

Table 2 Basic hygrothermal parameters of the concrete investigated

Bulk density [kg/m³]	2300
Porosity [%]	13.5
Capillary saturation [kg/m³] Porosity determined from cap. sat. [%]	155 15.5

The bulk density ρ is a standard material property. The overall porosity of the dry material is determined by helium pycnometry. The capillary moisture content is determined by submerging the material in water until moisture saturation is achieved. These parameters, each determined for three concrete samples with the composition according to Table 1, are listed in Table 2. Porosity amounts to 13.5%, capillary saturation to 155 kg/m³ which would indicate a total porosity of 15.5% unless liquid water is compressed to a smaller specific volume which seems unlikely.

This result is surprising because the helium molecule is smaller than the water molecule and therefore the porosity measured with helium should be greater than the capillary saturation, provided that the solid matrix remains unaltered. However, when water enters the concrete pore structure, the water molecules seem to have access to pore spaces that are inaccessible to the inert helium molecules. One explanation for this may be, that the bipolar water molecules creep between the polar mineral gel-layers, increasing the distances between them and thus creating additional pore space. This additional pore space is lost when the material dries. The consequences for the macroscopic matrix are known as hygric dilatation (swelling and shrinkage) resulting from changing moisture conditions.

Moisture storage

To determine the absorption isotherm, dry samples are stored in climate chambers at 23°C with different relative humidity conditions (33, 50, 65, 75, 85 and 93 %) until constant weight is achieved in each case. The desorption isotherm is determined in the reverse order, starting with saturated samples which will release moisture when stored in the climatic chambers. The resulting sorption isotherms are shown in Fig. 1. Up to 80% RH the hysteresis (difference between absorption and desorption isotherm) is small. Over 80% RH it becomes more pronounced, however this may partly be due to an insufficient testing period, i.e. the sorption equilibrium has not been reached yet. For the hygrothermal simulations the average between the measured ab- and desorption values is used (solid line in Fig. 1). Since a high degree of saturation (approx. 100 kg/m³) is already reached at 93% RH, the sorption curve is extrapolated to the capillary water content (155 kg/m³) at 100% RH without performing additional pressure plate tests.

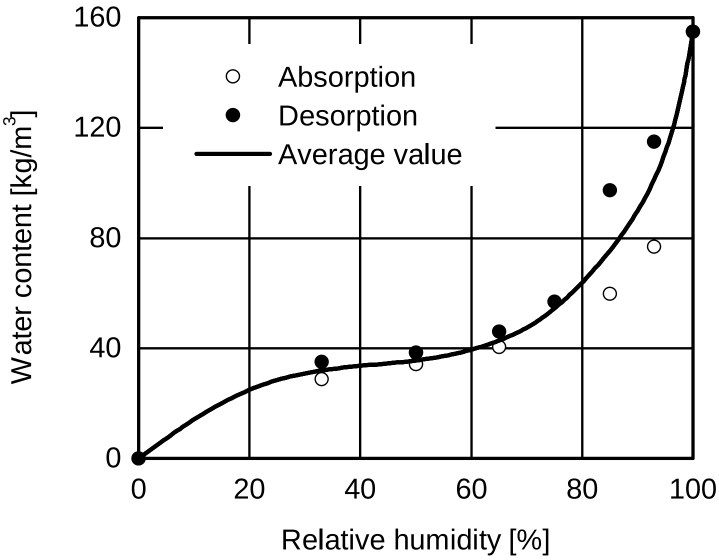

Fig. 1: Results of ab- and desorption tests performed on the investigated concrete samples including the average sorption isotherm which will serve as input for the simulations.

Vapour diffusion

In Europe the vapour transport properties of building materials are usually characterized by the vapour diffusion resistance factor (μ-factor) which is a dimensionless value comparing the vapour diffusion resistance of the porous material with that of stagnant air ($\mu_{air} = 1$). Since the μ-factor may be a function of ambient relative humidity, diffusion tests are performed under different humidity gradients. EN ISO 12572 [12] describes a dry-cup test (0% / 50%) and a wet-cup test (50% / 93%) where the diffusion flux is determined under steady-state conditions at 23°C. Applying theses tests to 20 mm thick slices of concrete also shows whether the vapour diffusion properties of concrete depended on the ambient humidity or not.

In Fig. 2, the dry-cup and the wet-cup μ-factors are presented as a function of the distance from the top surface of the original cubes. There is a resistance stratification which increases towards the bottom of the mould. This is probably due to the sedimentation of fine particles in the mould which results in smaller pore sizes at the bottom. For all layers, the μ factor in the wet range (wet-cup) is greater than in the dry range (dry-cup) by approx. 25 %. This unusual result – most materials show a lower vapour diffusion resistance in the wet-cup test – will be dealt with later on. Since it had been assumed that carbonation has a significant influence on the diffusion properties of concrete, the cup tests were repeated two years later when complete carbonation of the test specimens (20 mm thick slices) could be expected. The comparison with the initial results (see Fig. 2) taken directly after the end of the curing process (4 month after production because the cup tests last several weeks until steady-state conditions are achieved) shows almost no difference. Hence it seems that carbonation does not alter the vapour diffusion properties of concrete noticeably.

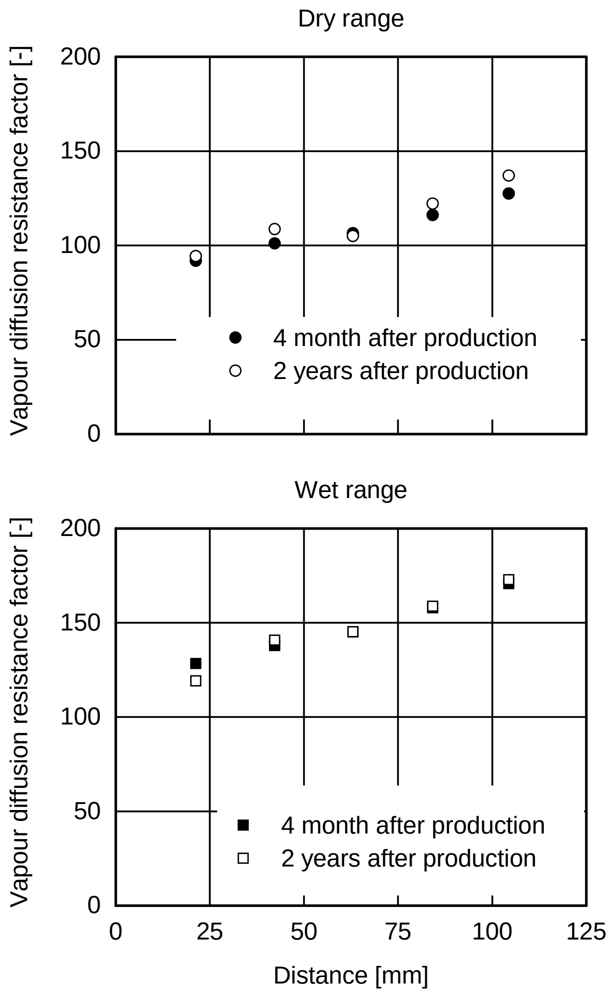

Fig. 2: Results of the dry-cup (top) and wet-cup (bottom) tests of 20 mm thick concrete slices taken from different positions in the original moulded cubes (x-axis indicates the original distance of the specimens from the cube's upper surface before it had been cut to prepare the specimens). The tests were repeated 2 years later to check the effect of carbonation.

Back to the humidity dependent vapour diffusion resistance of concrete: because most porous materials show a drop in diffusion resistance with higher humidity due to the onset of surface diffusion more cup tests were carried out to verify the unusual findings presented in Fig. 2. This time, additional RH ranges (RH difference between both sides of the specimen) which are not listed in EN ISO 12572 were selected. The results which are presented in Fig.3 show a maximum resistance around 65% RH. From this point the resistance drops by approximately 30% towards the dry range and a little less towards more humid conditions. However, since the position related scatter of the results is of the same order as the humidity dependence, it is suggested to use a constant μ-factor of 150 for hygrothermal simulations. This value is chosen because it is listed for normal concrete in DIN 4108-4 and EN 12524 while also fitting the results in Fig. 3.

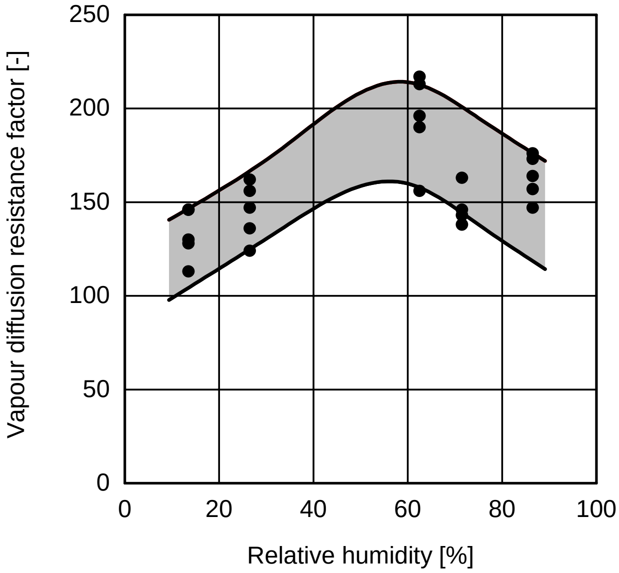

Fig. 3: Diffusion resistance factor of the different concrete specimens (reason for scatter see Fig. 2) plotted over mean ambient relative humidity (mean between the RH on both sides of the specimen).

Liquid transport

The liquid or capillary transport coefficients (also called liquid diffusivities) are derived from transient NMR-scans both for the suction and for the redistribution process according to the description in [13]. During this sophisticated laboratory test dry specimens of concrete with a cross-section of 50 x 50 mm² are brought at one side in contact with water. While water is absorbed the moisture content distribution is recorded periodically with a nuclear magnetic resonator (NMR). When enough scans have been taken for the determination of the "transport coefficient for water absorption", the water source is removed, and the transient redistribution in the specimen is recorded periodically again. This is done until sufficient data is available to determine the "transport coefficient for liquid redistribution". The resulting transport coefficients are plotted as a function of local water content in Fig. 4. As for most porous materials the liquid transport coefficients increase exponentially (logarithmic scale at y-axis) with moisture content.

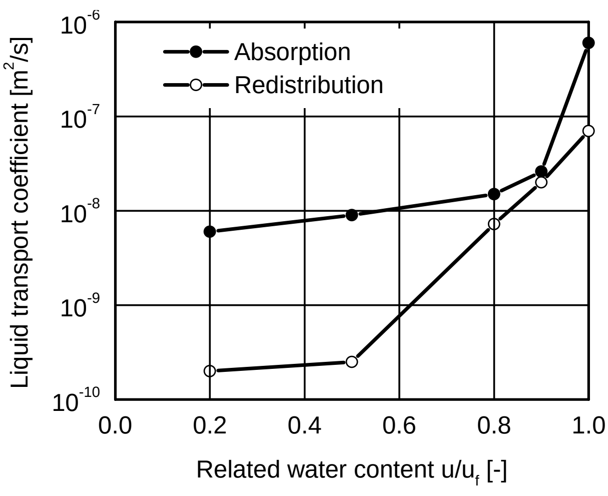

Fig.4: Transport coefficients for water absorption and redistribution determined from transient moisture content profiles. The water content at the x-axis is related to capillary saturation.

4. Moisture behaviour of concrete under natural exposure conditions

When concrete is exposed to natural weather, its moisture content depends on the wind-driven rain load and the drying conditions which are governed by solar radiation as well as outdoor air temperature and humidity. This situation, which is usually characterized by high moisture content fluctuations, has been successfully simulated with WUFI® – i.e. the calculated and measured moisture contents are in good agreement – for sandstone façades [7] and unrendered (no stucco finish) brick masonry with and without water repellent impregnation [14]. Similar investigations are repeated here with samples made from the same concrete which was used to determine the hygrothermal material parameters.

4.1 Field tests and hygrothermal simulations

The field tests are perfromed to check whether the moisture behaviour of concrete is in line with that of other porous rain screen materials. To do this, total water content and moisture distribution of prismatic specimens (5 x 5 x 15 cm³) are recorded over a weathering period of two years through periodic weighing and NMR moisture-profile measurements. On installation in the west façade of an unheated test hall (see Figure 5) at the beginning of May, the test samples had an equilibrium moisture content corresponding to 65% relative humidity. Except for the exterior surface which is exposed to natural weather, all surfaces of the prismatic specimens were sealed with epoxy resin to ensure a 1D situation and to protect them against condensation of indoor humidity.
From the time of installation onwards, internal and external temperature and air humidity conditions as well as the solar radiation and wind-driven rain hitting the façade are registered. These climate data, together with the material parameters determined earlier, serve as inputs for the hygrothermal simulations.

The measured water content fluctuations and moisture profiles (determined by NMR-scanning) are plotted in comparison with the hygrothermal simulation results in Fig. 6. The temporal variation of the total moisture content (average water content over the entire thickness of the specimen) is plotted in the top graph of Fig. 6. The measurements (circles) and the simulation results (solid line), which coincide quite well, show a rise in the moisture content of the concrete specimen due to driving rain interrupted by brief drying periods. The bottom graph of Fig. 6 shows the moisture profiles observed in the façade prisms at two different points in time during the first months of exposure. Again, there is a good agreement between measurements and calculations.

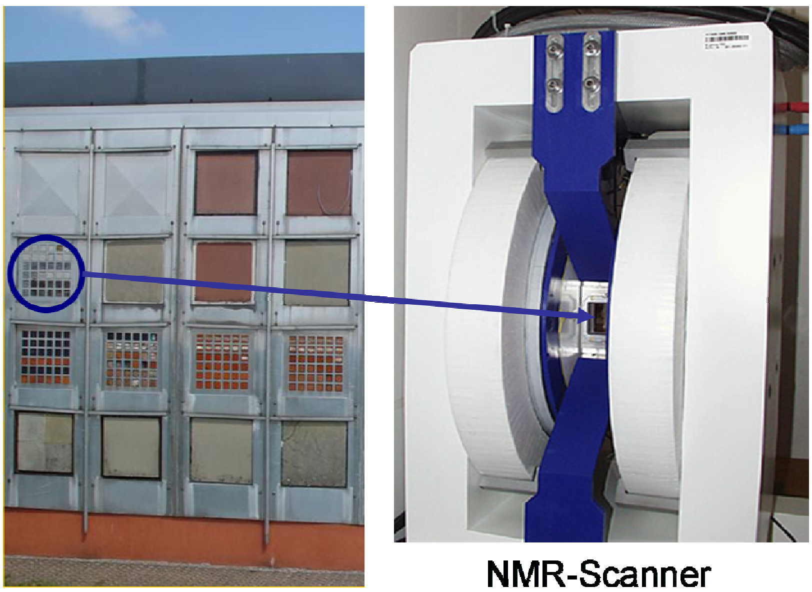

Fig. 5: Photographs of the concrete specimens exposed at the west oriented façade of a 4 m high test hall (left) and of the NMR-scanner which was used to determine the moisture profiles of the exposed specimens at certain points in time.

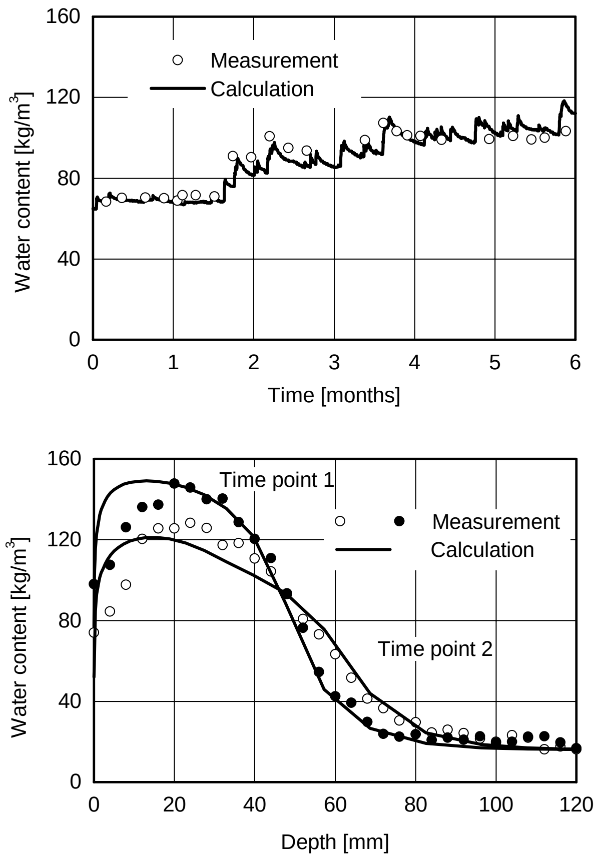

Fig. 6: Measured and calculated water contents of a prismatic concrete specimen exposed at the left hand side to natural weather during the first six months of the observation period.
Top: Total water content determined by weighing and calculation. Bottom: Measured (NMR-scanning) and calculated moisture profiles.

If the observation is continued beyond the first six months, however, the calculated temporal variation of the total water content starts to deviate from the experimental one (Fig. 7). In fact, the concrete specimen seems to have reached a steady state despite the changing boundary conditions. This impression is confirmed by looking at the NMR-scans which have been taken after six months (Fig. 8). These moisture profiles almost coincide, showing a more or less constant moisture gradient between the saturated 30 mm thick exterior surface layer and the interior dry layer. It looks as if the moisture distribution in the specimen was "frozen".

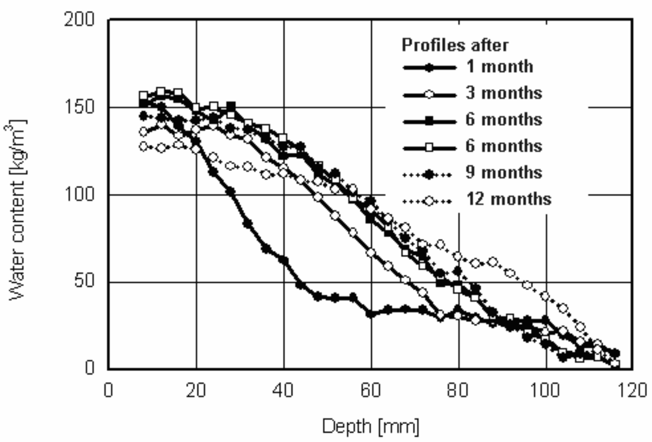

Fig. 8: Moisture profiles measured with the help of NMR at various times during the entire exposure period of the concrete specimen.

A similar behaviour has been detected in the case of other types of concrete too. In order to find the reasons for this rather unusual behaviour of concrete after an exposure period of several months some additional laboratory tests were performed for clarification.

4.2 Investigation of the "frozen" moisture profiles by water absorption tests

In order to find out whether the apparently unchangeable moisture profiles are just a response of the concrete to the particular exterior climate fluctuations during the test period, the observed specimen was taken from the natural weathering test and its formerly exposed surface was submerged in water. The development of the moisture profiles, which were measured periodically with the help of the NMR-scanner during this water absorption test, is presented in Fig. 9. While the exterior layer of the concrete specimen fills with water, there is no change in the middle part of the specimen even after 450 hours in water. The constant moisture gradient observed during field exposure is still there, again like being "frozen" at room temperature.

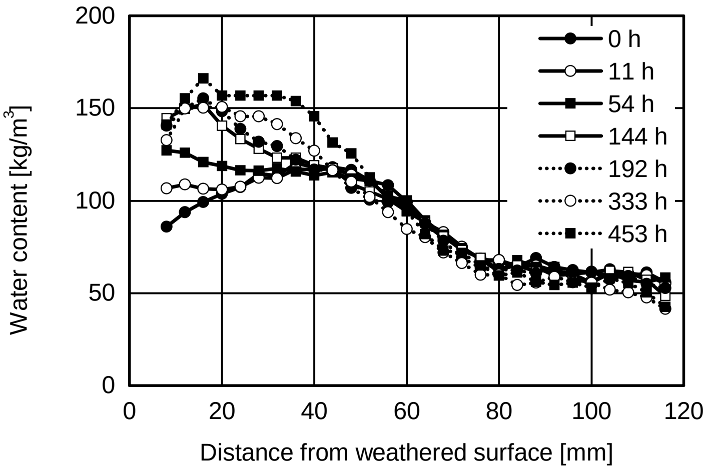

Fig. 9: Moisture profiles of the concrete specimen after the two-year weathering period determined by NMR-scanning during a laboratory water absorption test (formerly exposed side in contact with water).

However, when the specimen was turned around – i.e. the seal from the interior side was taken off and the concrete surface brought into contact with water – substantially more water was absorbed. The NMR-scans recorded during this "inverse" water absorption are displayed in Fig. 10. It took only about 50 hours and the whole specimen was saturated from the backside. This shows that there had been a capillary block which had formed during the exposure to natural weather.

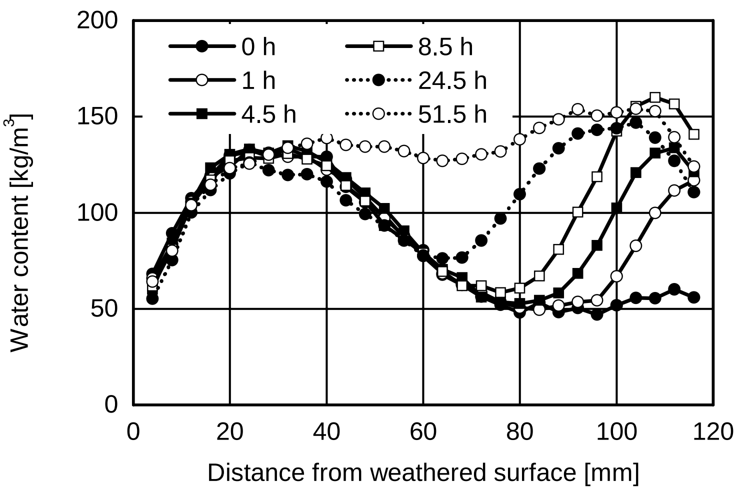

Fig. 10: Moisture profiles of the concrete specimen after the water absorption test in Fig. 9 by bringing the opposite side into contact with water.

A similar effect was observed during long-term water absorption tests carried out on water-impermeable concrete samples in the laboratory by Beddoe & Springenschmid [15]. They called this phenomena self-sealing effect of concrete and proposed a model where the cross-section of a concrete slab is subdivided into at least two zones: The zone in contact with water is assumed to have a thickness of less than 70 mm. Then there is a zone which they call drying zone which has a thickness of approximately 80 mm. This zone is comparable with the zone of the “frozen” moisture gradient in our investigations. In this zone moisture transport seems to be confined to vapour diffusion, i.e. the capillary transport mechanism is blocked.

5. Summary and Conclusions

The moisture behaviour of concrete plays an important part for the structural integrity and durability of modern constructions. Despite their relevance, studies dealing with moisture behaviour of concrete and the determination of its hygrothermal properties are scarce and experience with heat and moisture simulations of concrete envelope components is still limited. The presented investigations pinpoints some abnormalities of concrete when it comes to liquid water absorption while vapour sorption and diffusion processes appear to be similar to those in other building materials.
Since hygrothermal simulations have become standard practice in building design, it is important to further explore the moisture behaviour of concrete in dependence of composition, age res. state of carbonation and curing conditions. Especially the reasons why liquid transport is obstructed under certain situations should be more thoroughly investigated. For the time being it is preferable to concentrate on vapour sorption and diffusion processes when concrete is involved. If capillary water uptake is inevitable, because the considered building envelope assembly is exposed to wind-driven rain or ground water, the concrete component should be subdivided into two layers: one where liquid transport is possible and the other one where moisture transport is limited to vapour diffusion (i.e. liquid diffusivities are set to zero). However, more simulations and detailed moisture measurements are needed in order to validate the existing models and to gain experience concerning the long-term moisture characteristics of different types of concrete.

6. Literature

[1] Cziesielski, E. & Fechner, O.: *Wassertransport durch WU-Betonbauteile.* Bauphysik Kalender 2 (2002), S. 865-886.

[2] Künzel, H.M.: *Raumluftfeuchte in Wohngebäuden – Randbedingung für die Feuchteschutzbeurteilung.* wksb 51 (2006), H. 56, S. 31-41.

[3] Friedrich. M.: *Feuchtetransport bei WU-Beton – Stand des Wissens. Bauphysikalische Aspekte von Baukonstruktionen im Grundwasser.* Tagungsbd. 18. Hanseatische Sanierungstage (Hrsg H. Venzmer), Beuth-Verlag Berlin 2007, S. 111-128.

[4] Cziesielski, E.: *Energiegerechte Sanierung von Korrosionsschäden bei Stahlbetongebäuden.* Bauphysik 13 (1991), H. 5, S. 138-143.

[5] Marquardt, H.: *Korrosionshemmung in Beton-Außenwänden mit nachträglicher Wärmedämmung unter verschiedenen Klimabedingungen.* Bauphysik Kalender 3 (2003), S. 571-593.

[6] ASHRAE Handbook of Fundamentals, chapter 23: *Thermal and Moisture Control in Insulated Assemblies – Fundamentals.* Atlanta 2005.

[7] Künzel H.M.: *Simultaneous Heat and Moisture Transport in Building Components. - One- and two-dimensional calculation using simple parameters.* IRB 1995, http://docserver.fhg.de/ibp/1995/kuenzel/001.pdf.

[8] EN 15026: *Hygrothermal performance of building components and building elements – Assessment of moisture transfer by numerical simulation.* April 2007.

[9] WTA-Merkblatt 6-1-01/D: *Leitfaden für hygrothermische Simulationsberechnungen.* Mai 2002.

[10] WTA-Merkblatt 6-2-01/D & E: *Simulation wärme- und feuchtetechnischer Prozesse / Simulation of Heat and Moisture Transfer.* Mai 2002 / Oct. 2004.

[11] WTA-Merkblatt 6-3-05/D: *Rechn. Prognose des Schimmelpilzwachstumsrisikos.* Dez. 2005.

[12] EN ISO 12572: *Hygrothermal performance of building materials and products – Determination of water vapour transmission properties.* June 2001.

[13] Krus, M.: *Feuchtetransport- and Speicherkoeffizienten poröser mineralischer Baustoffe. Theoretische Grundlagen and neue Messtechniken.* Dissertation, University of Stuttgart 1995.

[14] Künzel, H.M. & Kießl, K.: *Drying of brick walls after impregnation.* Bauinstandsetzen 2 (1996), No. 2, pp. 87-100.

[15] Beddoe, R & Springenschmid, R.: *Feuchtetransport durch Bauteile aus Beton.* Beton- und Stahlbetonbau 94 (1999), H. 4, S. 158-166.