Drying and Hygral Diffusion Coefficient of Concrete

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Abstract

Service life of many reinforced concrete structures is not sufficient. This fact leads to increasing economical and ecological problems. Crack formation due to shrinkage is one of the most frequent reasons for early repair measures and limited service life. The cover of reinforced concrete elements experiences for decades strong hygral gradients. These gradients are at the origin of high tensile stresses, which lead to strain softening and crack formation. Therefore it is essential for design and prediction of service life to know the time-dependent moisture distribution under given climatic conditions.

In the project described in this contribution, loss of three different types of concrete under drying conditions has been determined experimentally. Based on the drying data the moisture-dependent diffusion coefficient of concrete has been determined by inverse analysis. With the moisture diffusion coefficients as determined in this way, it is possible to predict moisture distributions in drying concrete structures exposed to different climatic conditions. This is the first step for realistic prediction of crack formation in concrete structures in practice. This method enables us also to optimise properties of concrete in order to prevent crack formation. Service life of concrete structures can be extended significantly in this way.

Keywords: Drying, hygral diffusion, concrete

Trocknen und hygrischer Diffusionskoeffizient des Betons

Zusammenfassung

Die Nutzungsdauer von vielen Stahlbetontragwerken ist nicht ausreichend. Dadurch entstehen in zunehmendem Maße ökonomische und ökologische Probleme. Rissbildung durch Schwinden ist eine der häufigsten Ursachen für frühzeitige Reparaturmaßnahmen und begrenzte Nutzungsdauer. Bei Stahlbetonbauteilen liegt der Überdeckungsbeton häufig Jahrzehnte unter hohen hygrischen Gradienten. Diese Gradienten verursachen hohe Zugspannungen, die zur Dehnungsentfestigung und zur Rissbildung führen. Aus diesem Grund ist es so wichtig, für die Bemessung und Vorhersage der Lebensdauer einer Stahlbetonkonstruktion die Zeit abhängige Feuchtigkeitsverteilung unter den gegebenen klimatischen Bedingungen zu kennen.

In dem hier beschriebenen Beitrag wurde der Wasserverlust von drei unterschiedlichen Betonarten unter trocknenden Bedingungen experimentell bestimmt. Der feuchtigkeitsabhängige hygrische Diffusionskoeffizient des Betons wurde mit Hilfe der inversen Analyse aus den Trocknungsdaten ermittelt. Mit den so ermittelten hygrischen Diffusionskoeffizienten ist es möglich, die Feuchtigkeitsverteilung trocknender Betonbauteile, die unterschiedlichen klimatischen Bedingungen ausgesetzt sind, zu berechnen. Dies ist ein erster Schritt für eine wirklichkeitsnahe Vorhersage der Rissbildung in Betontragwerken in der Praxis. Diese Methode ermöglicht es uns auch, die Eigenschaften des Betons so zu optimieren, dass Rissbildung vermieden werden kann. Die Nutzungsdauer von Betontragwerken kann auf diese Weise beträchtlich verlängert werden.

***Stichwörter:** Trocknen, Hygrische Diffusion, Beton*

1 Introduction

Young concrete with a water-cement ratio of 0.5 and higher is in hygral equilibrium with a relative humidity close to 100 %. Due to self-desiccation the relative humidity in the pore space of high strength concrete decreases rapidly to values below 90 %. If the surface of young concrete is exposed to an environment with an average relative humidity of 50 to 70 % after removal of the formwork, a long lasting drying process begins in order to establish hygral equilibrium between the pore space of concrete and the environment. The drying process leads to a hygral gradient in drying concrete elements, which lasts in structural elements of usual dimensions for decades. As a consequence concrete shrinks [1-4] and cracks are formed in the dry surface near zone. These shrinkage cracks often limit the service life of concrete structures. If the surface of pre-dried concrete gets in contact with liquids containing harmful dissolved chemical compounds such as chlorides or sulphates, deterioration of concrete structures is significantly accelerated. Cracks are preferential paths for transport of liquids deep into structural concrete elements [5]. Because of these serious durability problems it is important to be able to predict the time-dependent moisture distribution in structural concrete elements.

Several mechanisms contribute to the moisture movement during drying of concrete. At the moment it is not possible to take all the different transport processes separately and quantitatively into consideration [6-8]. It has been shown earlier, however, that drying of concrete can be considered to be a non-linear diffusion process [8]. The diffusion coefficient depends strongly on the water content [8, 10]. We can explain the decrease of the diffusion coefficient with decreasing water content qualitatively. At the beginning liquid water is sucked to the surface by capillary forces where it evaporates. This is an efficient mechanism. As drying continues less liquid water is transported but water vapour instead diffuses towards the surface. This second mechanism is comparatively less efficient [6]. In a phenomenological approach the corresponding humidity dependent composite apparent diffusion coefficient has to be determined from drying data by inverse analysis [11, 12].

In this contribution drying data obtained from three different types of concrete have been used to determine the phenomenological hygral diffusion coefficient. By means of the obtained results it is possible to estimate the diffusion coefficient for concrete with a water-cement ratio between 0.35 and 0.7. Using these values it is possible to predict the time-dependent moisture distribution in drying concrete elements. This information is useful and needed for a realistic service life prediction.

2 Theoretical Background

The diffusion of moisture W in a drying porous material such as concrete can be described by means of the following partial differential equation [13]:

$$\partial W / \partial t = div[D(W) grad W] \qquad (1)$$

Moisture content W comprises in this case all types of physically different mobile water in the porous material such as free water in coarse pores, water held in fine pores, and water adsorbed on the internal surface. If we consider drying of a prismatic specimen with four sealed surfaces eq. (1) can be simplified in order to describe a one-dimensional problem:

$$\partial W / \partial t = \frac{\partial}{\partial x}\left[D(W)\frac{\partial W}{\partial x}\right] \qquad (2)$$

Several expressions have been proposed to describe the humidity dependence of the diffusion coefficient (see for example [3]). We have adapted an exponential function as initially suggested among others by Kasi and Pihlajavaara [14]:

$$D(W) = a_0 + a_1 \exp(a_2 W) \qquad (3)$$

In some cases and in particular if we neglect the low humidity region, a_0 can be considered to be zero. D(W) has to be determined by inverse analysis from reliable drying data [12].

3 Experimental

Three types of concrete (I, II, and III) with different water-cement ratio have been prepared (W/C = 0.35, 0.50, and 0.70). The concrete composition is shown in Table 1. High sulphate resistant Portland cement has been used throughout. The size distribution of sand was between 0 and 4 mm and of coarse aggregates between 4 and 8 mm. After mixing for three minutes, workability and air content of the fresh concrete has been determined according to German standards. Then the mix was filled in cubic steel moulds and compacted twice for 45 seconds on a vibrating table. The cubes were first

Table 1: Composition of the three types of concrete

Concrete type	W/C	Cement kg/m^3	Water kg/m^3	Sand kg/m^3	Gravel kg/m^3	Air content %
I	0.35	426	149	962	787	2.7
II	0.50	348	174	962	787	1.8
III	0.70	280	196	962	787	1.4

Table 2: Saturated aqueous salt solutions to maintain constant RH at 20 °C

Dissolved salt	RH, %
$CaCl_2 \cdot 6H_2O$	31
$NaBr \cdot 2H_2O$	65
$(NH_4) \cdot 2SO_4$	81
$ZnSO_4 \cdot 7H_2O$	90
$Na_2SO_3 \cdot 7H_2O$	95
$CuSO_4 \cdot 5H_2O$	98

allowed to harden under a plastic foil in the laboratory for 24 hours. After demoulding the concrete cubes were stored under water until an age of 60 days. In this way water loss by self-desiccation could be compensated. From the hardened and water saturated concrete cubes cylinders with a diameter of 92 mm were drilled and from the cylinders slices with a thickness of 15 mm were cut with a diamond saw. These slices were finally placed in boxes in which the relative humidity was maintained constant by means of saturated salt solutions (see Table 2). From the equilibrium water content at different RH desorption isotherms could be determined and from the drying data between 100 % RH and 31 % RH the diffusion coefficients have been determined by inverse analysis.

4   Results and Discussion

The concrete slices with a diameter of 92 mm and a thickness of 15 mm have been placed in boxes in which the RH humidity was kept constant by means of saturated aqueous salt solutions. The water loss has been determined by weighing the specimens in regular intervals until constant weight had been achieved. Then the concrete discs were dried at 105 °C. In this way the water content after drying to a certain RH could be determined. This allows us to determine the desorption isotherm of the three types of concrete. All measurements have been carried out in triplicate and mean values will be shown in the following.

In Fig. 1 the three desorption isotherms are plotted. In the saturated state concrete with a water-cement ratio of 0.7 has the highest water content due to the high porosity of the cement-based matrix. But at values of RH between 95 % and 50 % capillary pores of hardened cement paste with a radius smaller than 20 nm are filled and below 45 % RH water adsorbed at the internal surface of the cement gel remains in the porous structure. Due to the higher cement content of mixes I and II in this range concrete with water-cement ratio of 0.35 has the highest water content followed by concrete type II.

The water content at 31 % RH can be related to the internal surface of hardened cement paste. As the cement content decreases from concrete type I to concrete type III, the amount of water adsorbed on the internal surface increases in the same order. From the measured values it can also be seen that the degree of hydration in concrete type I is lower as compared to the two other types of concrete.

The water loss of the samples placed in an environment with RH = 31 % is shown in Fig. 2 as an example. As can be seen it takes about 150 days for the small discs to reach hygral equilibrium under the given environmental conditions. Now the water loss is calculated by means of eq. (2). The parameters in eq. (3) are varied until good agreement with the experimental data is reached. From previous investigations it is known that a_0 in eq. (3) is very small. Therefore we have neglected this value in the present analysis. This simplification is justified if the usual range of RH as observed in European climate is of primary interest. If, however, values of RH smaller than 30 % have to be expected, a_0 must be determined as well by inverse analysis.

A typical result of the inverse analysis is shown in Fig. 3. Experimental results obtained on concrete samples with a water-cement ratio of 0.5 and drying in an environment with RH = 31 % have been used to determine the parameters a_1 and a_2 by inverse analysis. As can be seen very good agreement between the experimental data and the fitted curve has been achieved.
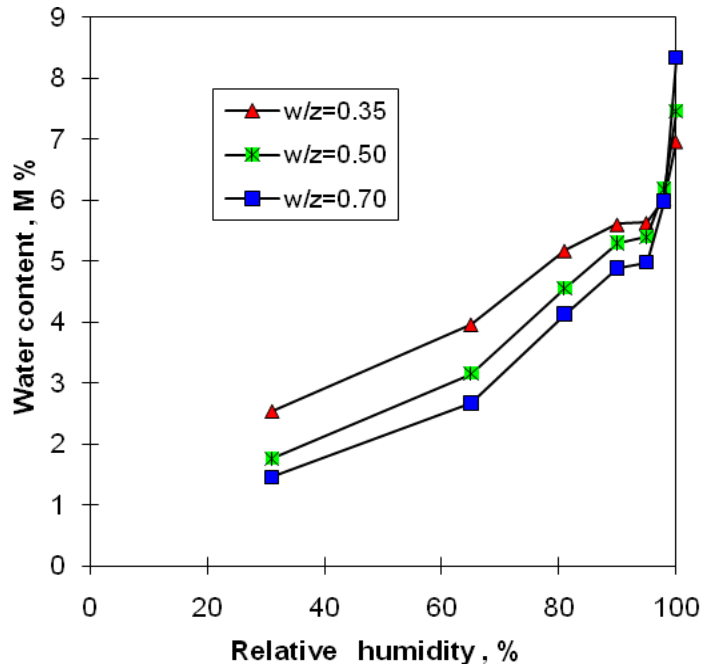
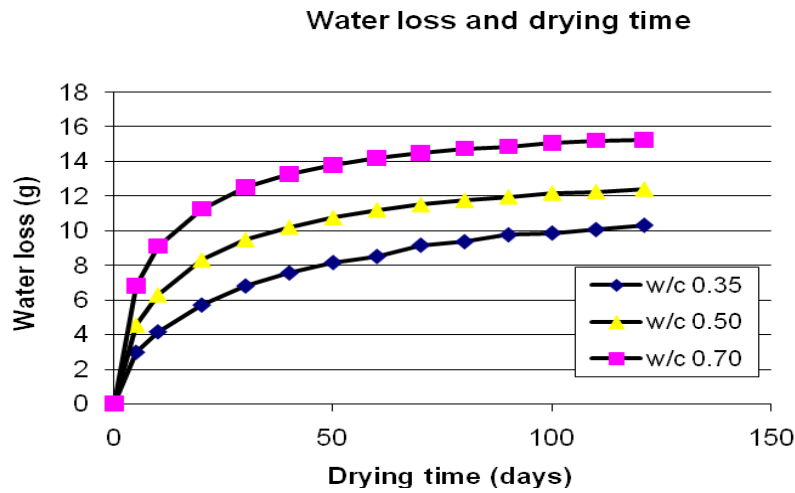**Figure 1:** Desorption isotherm of the three types of concrete under investigation

Water loss and drying time

Figure 2: Water loss of drying concrete samples as function of drying time

Parameters a_1 and a_2 as obtained by fitting the calculated moisture loss with experimental data are shown in Table 3. It turned out that the parameter a_2 is approximately independent on water-cement ratio: 3.6 ± 0.1. The influence of water-cement ratio is expressed by parameter a_1.

If the parameters of eq. (3) are known, the hygral diffusion coefficient can be calculated as function of water content. The moisture dependent hygral diffusion coefficient $D(W)$ of the three types of concrete under investigation is shown in Fig. 4. At high water content the hygral diffusion coefficient

of concrete with a water-cement ratio of 0.7 is more than four times higher than the corresponding value of concrete with water-cement ratio 0.35. The ratio between these two values decreases significantly with decreasing water content.

Water-cement ratio is not the only factor influencing the hygral diffusion coefficient. Cement type and cement content have a significant influence. A strong influence of the addition of mineral admixtures such as fly ash or silica fume has also been noticed. For this reason results presented in this contribution cannot be generalized. If crack formation
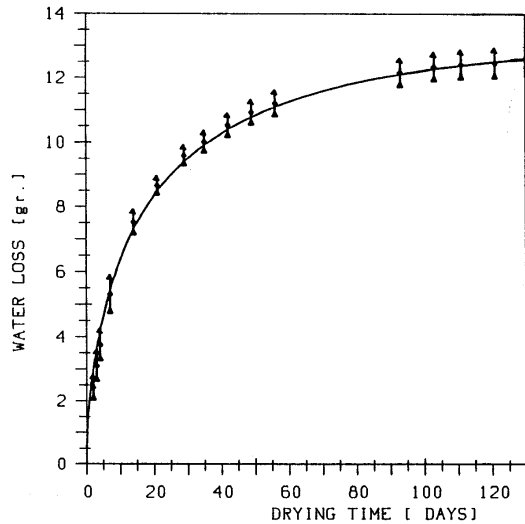
Figure 3: Measured data of water loss and fitted function

Table 3: Parameters a_1 und a_2 of the moisture dependent hygral diffusion coefficient D (W) determined by means of eq. (3) assuming $a_0 = 0$

W/C	a_1	a_2
0.35	0.0026	3.6
0.50	0.0055	3.5
0.70	0.0085	3.7

and service life of reinforced concrete structures is to be predicted in a meaningful and reliable way the specific hygral diffusion coefficient has to be determined in a similar way as described in this paper.

With the moisture dependent hygral diffusion coefficient, as shown in Fig. 4 or expressed with eq. (3) using the parameters of Table 3, the time-dependent moisture distribution can be calculated. If fracture

energy and strain softening of the same type of concrete are known or have been determined in parallel, crack formation can be predicted in a realistic way. This approach provides us with a solid basis for improving service life of reinforced concrete structures.

5 Conclusions

The moisture dependent hygral diffusion coefficient depends on the complex composition of concrete. Water-cement ratio is dominant but it is not the only influencing factor. For a reliable prediction of crack formation and service life of reinforced concrete structures realistic values of the moisture dependent diffusion coefficient are needed. It is recommended that for sensitive structures and structures in aggressive environment the moisture dependent diffusion coefficient is to be determined in a similar way as described in this contribution.

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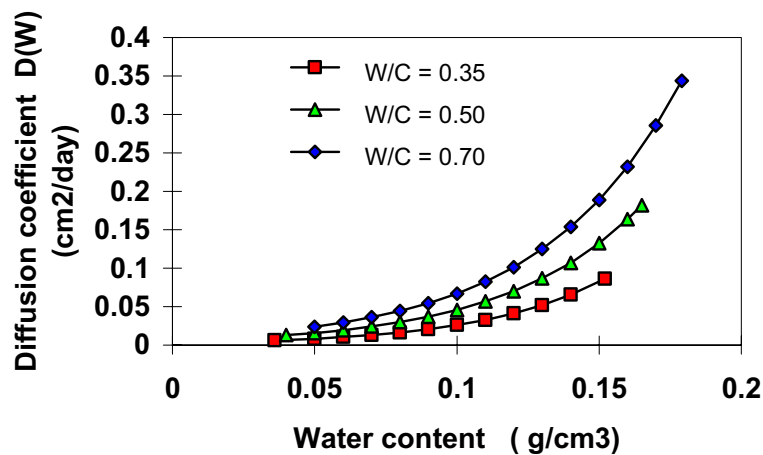
Figure 4: Moisture dependent hygral diffusion coefficient for three types of concrete

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