

# Long-term moisture transport in high performance concrete

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## ABSTRACT

Moisture is decisive for a large number of binding and transport processes in high performance concrete affecting the durability, shrinkage and performance in various environments. An experimental study on the moisture transport properties of 20 concrete mixes was made during seven years, with type of binder, additives and water-binder ratio as parameters. An upside-down glass cup method was used to obtain the steady-state flow through concrete discs.

The moisture diffusion coefficient decreases with a lower water-binder ratio, increasing amount of silica fume, especially when combined with fly ash and it continues to decrease also after four years for w/B lower than 0.40. The moisture diffusion coefficient is much less moisture dependent for HPC than for normal concrete, which means that steady-state moisture profiles through HPC structures will be almost linear. Long-term moisture profiles in submerged HPC will be affected by self-desiccation for a very long time because of the extremely small moisture flow.

## RÉSUMÉ

L'humidité a une influence prépondérante sur un grand nombre de processus d'interaction et de transport qui affectent de manière directe la durabilité, le retrait et le comportement des bétons à haute performance (BHP) soumis à différents types de conditions d'exposition. Une étude expérimentale sur les propriétés de transport d'humidité de 20 mélanges de béton a été effectuée durant une période de sept ans. Les variables étudiées concernaient le type de ciment et d'ajouts ainsi que le rapport eau/liant. Une procédure spéciale a été utilisée de manière à être en mesure de réaliser les essais de transfert d'humidité en régime permanent.

Les résultats des essais indiquent que le coefficient de diffusion d'humidité diminue avec une réduction du rapport eau/liant, une augmentation de la teneur en fumée de silice, tout particulièrement lorsque celle-ci est utilisée avec des cendres volantes. Pour des bétons de rapports eau/liant inférieurs à 0,40, la réduction du coefficient d'humidité se poursuit toujours même après 4 ans d'hydratation. Le coefficient de diffusion d'humidité des BHP semble être beaucoup moins sensible à la teneur en eau que celui des bétons ordinaires ce qui signifie que les profils d'humidité en régime permanent sont presque linéaires. Les profils d'humidité à long terme dans BHP submergés seront fortement affectés par l'autodesiccation.

## 1. INTRODUCTION

Moisture is decisive for a large number of binding and transport processes in concrete and, consequently, a significant parameter when predicting the durability and service-life of concrete structures [1]. Data on moisture sorption isotherms for various concrete compositions are frequent in literature, see e.g. [2-5]. Good data on moisture transport properties, however, are scarce especially for HPC since measurements are difficult and time-consuming.

This study was a part of a national durability project [6] where some 40 types of concrete specimens were exposed to seawater at the field station in Träslövsläge at the west coast of Sweden. The concrete compositions included three types of Swedish and Danish cements, two pozzolanic additives (silica fume and fly ash), different water-binder ratios (from 0.25 to 0.75) and air contents (from 1% to 6%). This part quantifies the moisture transport properties of several high performance concretes under conditions where HPC is exposed to water, i.e. in wet conditions.

### Editorial Note

Prof. Lars-Olof Nilsson is a RILEM Senior Member. He participates in RILEM TC 178-TMC 'Testing and modelling chloride penetration in concrete'.

## 2. THEORETICAL BACKGROUND

### 2.1 Moisture in HPC; the sorption isotherm

The moisture conditions in concrete in general may be well understood from the sorption isotherms, that show the relationship between the amount of physically bound moisture and the state of moisture, expressed as relative humidity, RH. The RH in concrete is the pore humidity and is, usually, defined as

$$RH = \frac{\nu}{\nu_s(T)} \quad [-] \quad (1)$$

where  $\nu$  is the water vapour content of the air [kg/m<sup>3</sup>] and  $\nu_s$  is the temperature dependent vapour content at saturation.

Even though RH is traditionally defined as the relative humidity of the air in the pores, and considering that most pores in HPC normally are closed to being saturated, the RH therefore gives an excellent measure of the state of moisture in the pore system. An accurate description, however, must take into account the influence of the concentration of ions, mainly alkalis, in the pore water, that will give an RH lower than 100% in saturated concrete.

The amount of moisture in concrete, the “evaporable water”, can be expressed in several ways. The “moisture content”  $w_e$  [kg/m<sup>3</sup>] is the weight of moisture per volume of concrete and the “moisture ratio”  $u$  [kg/kg] is the weight of moisture per dry weight of concrete. The

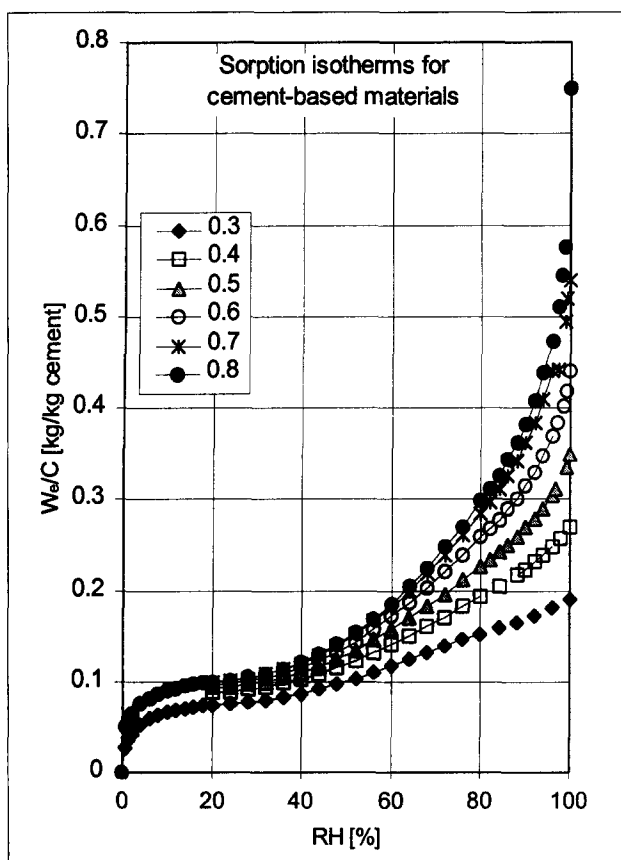


Fig. 1 - Moisture desorption isotherms for cement-based materials with w/C = 0.3 - 0.8, OPC [1].

“degree of capillary saturation”  $S_{cap}$  [-] is the portion of capillary pores that are filled with water. Capillary pores are the voids that can be filled by capillary suction, *i.e.* without any positive pressure being applied.  $S_{cap}$  is determined as the moisture ratio  $u$  of a sample divided by the moisture ratio  $u_{cap}$  of the same sample after capillary saturation,  $S_{cap} = u/u_{cap}$  [7].

The relationship between the amount of moisture and the state of moisture is the sorption isotherm that says a lot on the pore size distribution in a certain size interval. In Fig. 1, theoretical sorption isotherms are shown for various Portland cement concrete mixtures, and expressed as the amount of moisture per weight of cement.

Fig. 2 illustrates for two different concrete mixtures the three different ways to express sorption isotherms.

From the top part of Fig. 2 it is obvious that the amount of gel water is somewhat higher for a concrete with a higher water-cement ratio w/C and that the capillary water, corresponding to higher relative humidity, is much higher when expressed as moisture content per weight of cement. Because of the higher cement content in an HPC the total amount of moisture expressed per volume of concrete is higher for RH up to roughly 70-80%, cf. the central part of Fig. 2. Above approximately 80% RH, the moisture content per volume of concrete is of course higher for the mixture with the higher w/B because of its higher porosity. The degree of capillary saturation  $S_{cap}$ , however, is always higher for an HPC at any given RH, as can be seen from the bottom part of Fig. 2. Consequently, a much larger portion of the pore system is saturated.

### 2.2 Self-desiccation

The chemical fixation of water will decrease the internal “free” moisture content and partly empty the larger pores. Because of the “flat” sorption isotherm for HPC, *i.e.* a small slope due to absence of larger pores, the relative importance of self-desiccation will increase with a reduction of the w/C, see Fig. 3. Additionally, a clear distinction has been found between SRPC and OPC, partly because of the difference in the alkalinity of the pore solution and partly because of the difference in the slope of the sorption isotherm, *i.e.* a difference in pore size distribution.

### 2.3 Moisture transport in concrete

Traditionally, moisture transport mechanisms in porous materials are regarded as being vapour flow or liquid flow, where a division between different mechanisms is required. For HPC it is obvious that the pure liquid flow is negligible and, because of the large degree of saturation, pure vapour diffusion in air in the pores is only a part of the total flow. A significant portion of the transport paths for moisture should be diffusion of moisture through the gel, to some extent in series with diffu-

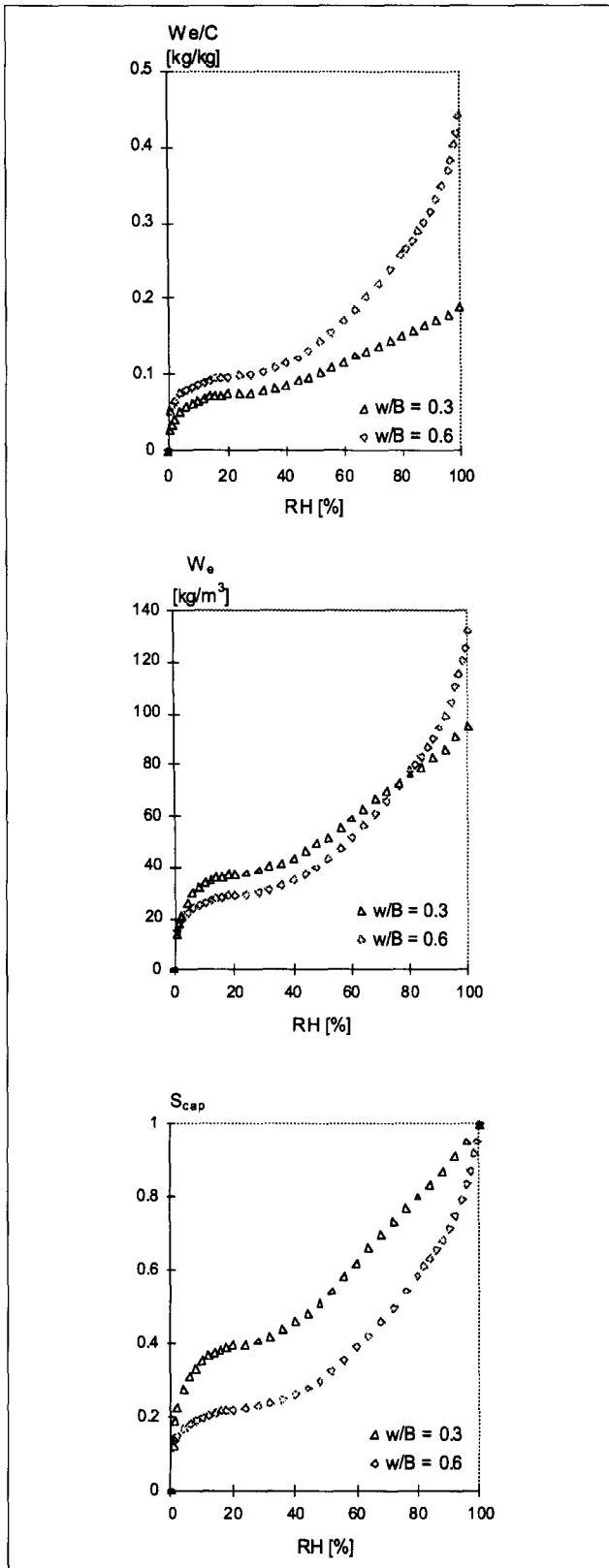


Fig. 2 - Theoretical desorption isotherms for a "normal" concrete ( $w/C=0.6$ ) and a high performance concrete ( $w/C=0.3$ ), expressed in three different ways. Based on Fig. 1.

sion in air, depending on the surrounding conditions. Wetter conditions should give less diffusion in air but more diffusion through the gel.

The potential for moisture flow should be determined in isothermal conditions in order to limit the transport of water induced by temperature gradients.

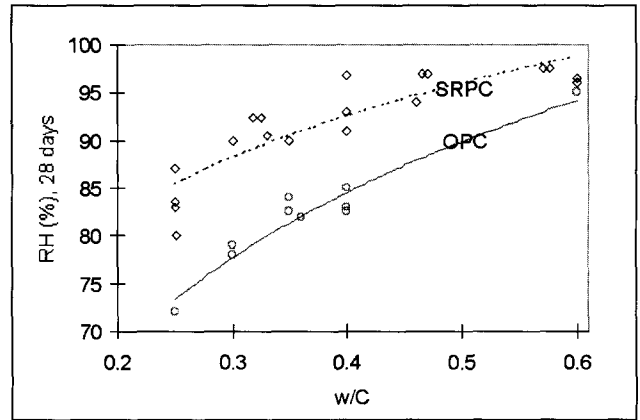


Fig. 3 - Self-desiccation for plain Portland cement concretes as a function of water-binder ratio, expressed as RH in the pore system after 28 days. Based on data from [8].

Since there are unique relationships between the state of moisture  $\varphi$  (RH), the moisture content  $w$  and the water vapour content  $\nu$ , any one of these parameters can be utilized to describe the total moisture flow  $J$  [ $\text{kg}/\text{m}^2\cdot\text{s}$ ], combining all types of moisture flow, see Equation (2).

$$J = -k_{RH} \frac{\partial \varphi}{\partial x} = -D_w \frac{\partial w}{\partial x} = -\delta_v \frac{\partial \nu}{\partial x} \quad (2)$$

The relationships between these moisture transport coefficients are obviously simple, see Equation (3).

$$\delta_v = k_{RH} \frac{\partial \varphi}{\partial \nu} = k_{RH} \cdot \nu_s$$

$$D_w = \delta_v \frac{\nu_s}{\frac{\partial w}{\partial \varphi}} \quad (3)$$

where  $\frac{\partial w}{\partial \varphi}$  is the slope of the sorption isotherm, called the "moisture capacity".

Between the "diffusion coefficient"  $\delta_v$  and the moisture transport coefficient  $k_{RH}$  there is a plain proportionality with the vapour content at saturation as the proportionality constant, similar to the relation between the vapour content and the relative humidity. The moisture diffusivity  $D_w$ , however, has a non-linear relationship to the other flow properties, depending on the slope of the sorption isotherm. That slope is small in an RH-interval around 20-70% but much higher at lower and higher RH, at least for concrete with  $w/C$  above 0.4, cf. Fig. 2. In this work the moisture diffusion coefficient  $\delta$  has been chosen as a measure of the moisture transport properties since that is what could be directly measured.

The moisture diffusion coefficient  $\delta$  is not a constant but highly moisture dependent parameter,  $\delta(\varphi)$ , especially for concrete with  $w/C$  of 0.5 and higher, cf. Fig. 4.

As can be seen in Fig. 4, the relative proportion of moisture transport occurring as liquid flow tends to increase with an increase of RH. This is particularly true for mixtures prepared at high  $w/C$ . For the 0.4  $w/C$  concrete, the moisture dependency seems to be very small,

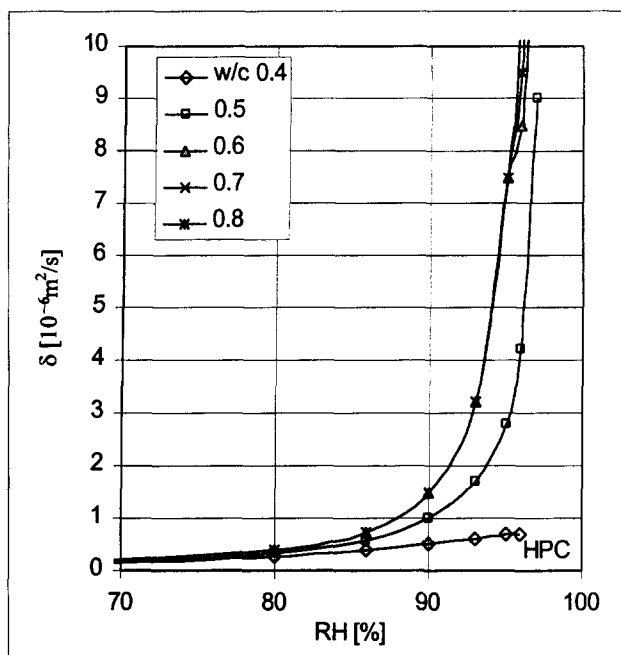


Fig. 4 - Moisture diffusion coefficient  $\delta(\varphi)$  for concretes with different w/C. Data from [9].

indicating that a larger portion of moisture diffusion through the gel and that type of transport mechanism is only weakly influenced by the state of moisture in the material, i.e. has a small moisture dependency.

Because of self-desiccation, the interesting RH inter-

Binder	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>3</sub> A	C <sub>4</sub> AF	CaO
Degerhamn SRPC	59	17	2	15	64.9
Slite OPC	59	14	8	6	61.1
Aalborg SRPC	55	15	11	9	66.8
Fly ash					4.1
Silica fume					1.5

val for moisture transport in marine HPC concrete is from some 70% RH and up to more or less complete saturation, corresponding to RH above approximately 94%, depending on the w/B and the alkalinity of the pore solution.

### 3. EXPERIMENTAL PROGRAM

#### 3.1 Specimen preparation

A study of moisture transport properties was made for 20 concrete mixes. Test variables included type of binder, type and replacement of mineral additive, water-binder ratio and air content. The maximum size of the coarse aggregate was 16 mm. The mix proportions are given in Table 1A and the mineralogical and chemical composition of the binders are given in Table 1B.

100 mm thick slabs were cast and wet cured for 14 days. 100 mm diameter cores were drilled and cut into 18 mm thick slices as discs for moisture transport measurements. Some slices were cut into smaller pieces for determination of sorption isotherms.

#### 3.2 Measurements

Sorption isotherms were determined for each concrete mix by storing small, a size of a few millimetres, originally wet, samples in climate boxes. The temperature of the environment was regulated by the control of the room. The RH in each box was controlled by saturated salt solutions (LiCl, MgCl<sub>2</sub>, K<sub>2</sub>CO<sub>3</sub>, NaBr, KCl, KNO<sub>3</sub>, K<sub>2</sub>SO<sub>4</sub>) and a fan that stirred the enclosed air. The weight of the samples was determined regularly until equilibrium was reached, after more than three months for some of the mixes. The point of equilibrium was not easy to detect only by weight changes, since a small, continuous weight loss are determined if the experiments continue for a year [3]. However, an independent check by directly measuring the RH of samples showed a correct RH already after less than three months. The results are given in Tables 2 and 3.

The steady-state moisture flow coefficients

Mix No.	Type of binder	Binder kg/m <sup>3</sup>	Aggregate kg/m <sup>3</sup>	w/B	Air content %
1-35	100%Anl. <sup>1)</sup>	450	1695	0.35	6.0
1-40		420	1692	0.40	6.2
1-50		370	1689	0.50	6.4
2-35	100%Slite <sup>2)</sup>	450	1695	0.35	5.7
2-40		420	1692	0.40	6.2
2-50		390	1646	0.50	5.8
3-35	95%Anl.+5%SF <sup>3)</sup>	450	1687	0.35	5.8
3-40		420	1685	0.40	6.1
3-50		370	1683	0.50	6.0
10-40	78.5%DK <sup>4)</sup> +17%FA <sup>5)</sup> +4.5%SF	420	1680	0.40	6.1
12-35	85%Anl.+10%FA+5%SF	450	1682	0.35	6.4
H1	95%Anl.+5%SF	500	1823	0.30	0.8
H2	90%Anl.+10%SF	500	1814	0.30	1.1
H3	100%Anl.	492	1845	0.30	3.6
H4	95%Anl.+5%SF	420	1685	0.40	5.9
H5	95%Anl.+5%SF	551.2	1812	0.25	1.3
H6	95%Anl.+5%FA	517.9	1800	0.30	2.8
H7	95%Anl.+5%SF	500	1823	0.30	1.3
H8	80%Anl.+20%FA	616.3	1629	0.30	3.0
H9	100%Anl.	500	1832	0.30	2.9

1) Swedish Degerhamn SRPC, 2) Swedish Slite OPC, 3) Silica fume, 4) Danish Aalborg SRPC, 5) Fly ash

**Table 2 - Data for sorption isotherms for concrete H1 to H9, expressed as degree of capillary saturation,  $S_{cap}$ , and as the capillary porosity  $P_{cap}$  that is filled above 75 % RH**

RH [%]	H1	H2	H3	H4	H5	H6	H7	H8	H9
11	0.249	0.273	0.230	0.179	0.279	0.232	0.262	0.218	0.253
33	0.465	0.516	0.477	0.332	0.519	0.457	0.480	0.443	0.479
42	0.539	0.594	0.492	0.423	0.575	0.481	0.545	0.525	0.493
59	0.658	0.724	0.592	0.558	0.695	0.603	0.658	0.628	0.663
75	0.759	0.809	0.692	0.664	0.771	0.701	0.771	0.710	0.752
85	0.829	0.877	0.747	0.739	0.865	0.800	0.839	0.791	0.742
95	0.898	0.914	0.880	0.844	0.893	0.869	0.885	0.881	0.869
97	0.900	0.918	0.845	0.828	0.882	0.847	0.898	0.855	0.806
$P_{cap}$ [%] (>75%RH)	2.4	1.9	2.9	4.7	2.1	3.1	2.4	2.8	2.6

were determined in experiments using an “upside-down cup”. This is a special version of cup methods described in ISO12572: 2001 [10]. 18 mm thick specimens were placed as lids on glass cups containing water with an asphalt tape as a seal. The cups were stored upside-down in a climate room at +20°C 85% RH for more than a year. Then the climate was changed to +20°C 65% RH. An example of a cup is shown in Fig. 5. Consequently, the top surface was exposed to 100% RH (water) and the bottom surface to 85 and 65% RH respectively. In this way there is no air gap between the sample and the water, as in traditional cup methods, see e.g. [11].

The moisture flow was measured by determining the weight loss as a function of time. As seen in Fig. 6, steady-state conditions were not quite reached during the first year. Consequently, the moisture transport properties in the RH interval 85-100% were not evaluated.

After reaching steady-state conditions the average moisture flow coefficient was calculated from the flow and the boundary conditions according to Equation (2). The results are shown in Tables 4 and 5.

**Table 3 - Data for sorption isotherms for concrete 1-35 to 12-35, expressed as degree of capillary saturation,  $S_{cap}$ , and as the capillary porosity  $P_{cap}$  that is filled above 75 % RH**

RH [%]	1-35	1-40	1-50	2-35	2-40	2-50	3-35	3-40	3-50	10-40	12-35
11	0.230	0.209	0.157	0.239	0.226	0.202	0.231	0.225	0.172	0.197	0.204
33	0.425	0.356	0.284	-	0.327	0.307	0.427	0.375	0.291	0.398	0.437
42	0.466	0.429	0.349	0.441	0.424	0.361	0.481	0.439	0.367	0.479	0.438
59	0.611	0.530	0.436	0.567	0.535	0.464	0.617	0.599	0.483	0.600	0.570
75	0.719	0.698	0.596	0.690	0.660	0.601	0.704	0.698	0.672	0.711	0.655
85	0.778	0.775	0.646	0.752	0.728	0.702	0.788	0.763	0.748	0.781	0.698
95	0.818	0.789	0.729	0.839	0.797	0.771	0.860	0.839	0.796	0.866	0.863
97	0.866	0.844	0.789	0.881	0.886	0.809	0.887	0.876	0.884	0.852	0.788
$P_{cap}$ [%] (>75%RH)	3.2	3.2	5.3	4.1	4.4	5.5	3.3	3.7	4.5	3.4	4.2

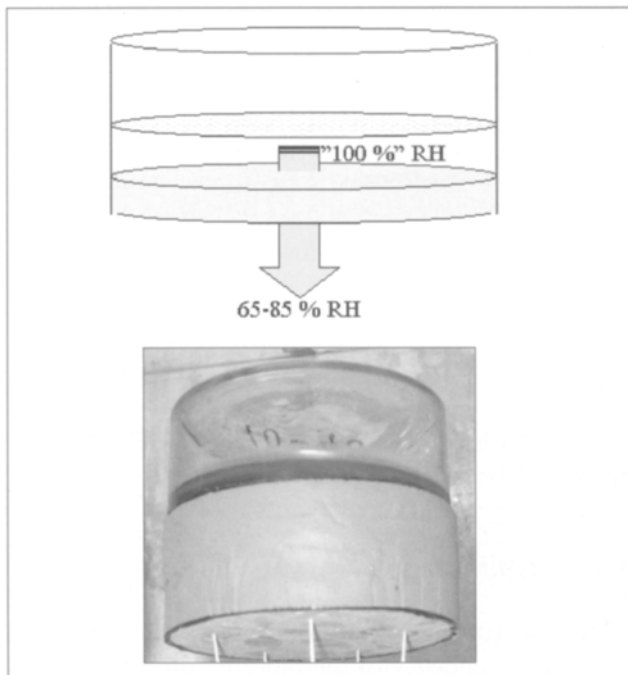


Fig. 5 - An “upside down cup” creating a moisture gradient over a thin concrete disc.

## 4. RESULTS AND DISCUSSION

### 4.1 Sorption isotherms

The sorption isotherms are shown in Fig. 7 for the 20 concrete mixes. Since the samples were originally wet before exposure, each sample lost water, i.e. the sorption

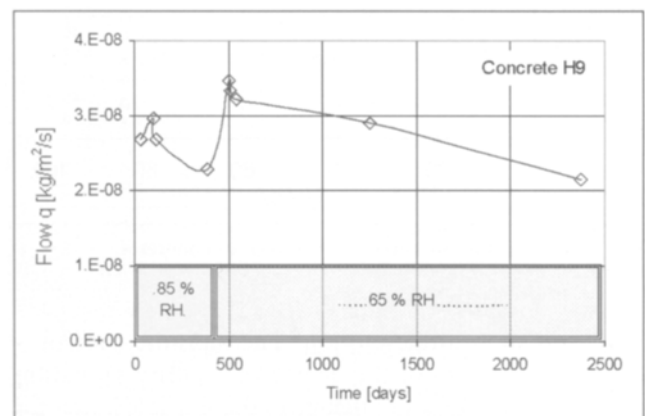


Fig. 6 - An example of the measured moisture flow out of the cups for concrete H9. Note that the climate was changed from 85 to 65% RH after approximately one year.

**Table 4 - Average moisture diffusion coefficients  $\delta(65,100)$  [ $10^{-7}m^2/s$ ] in the RH interval 65 to 100% RH at 3.5 and 6.6 years for concrete H1-H9**

Mix	H1	H2	H3	H4	H5	H6	H7	H8	H9
3.5 y	0.29	0.22	0.97	1.20	0.22	0.66	0.28	0.25	0.86
6.6 y	0.23	0.17	0.74	0.98	0.17	0.49	0.22	0.18	0.64

**Table 5 - Average moisture diffusion coefficients  $\delta(65,100)$  [ $10^{-7}m^2/s$ ] in the RH interval 65 to 100 % RH at 3.5 and 6.6 years for concrete 1-35 to 12-35**

Mix	1-35	1-40	1-50	2-35	2-40	2-50	3-35	3-40	3-50	10-40	12-35
3.5 y	1.69	2.08	2.10	1.47	2.19	2.09	1.19	1.21	1.28	0.37	0.51
6.6 y	1.36	1.73	1.98	1.19	1.67	1.75	0.83	1.01	1.27	0.29	0.38

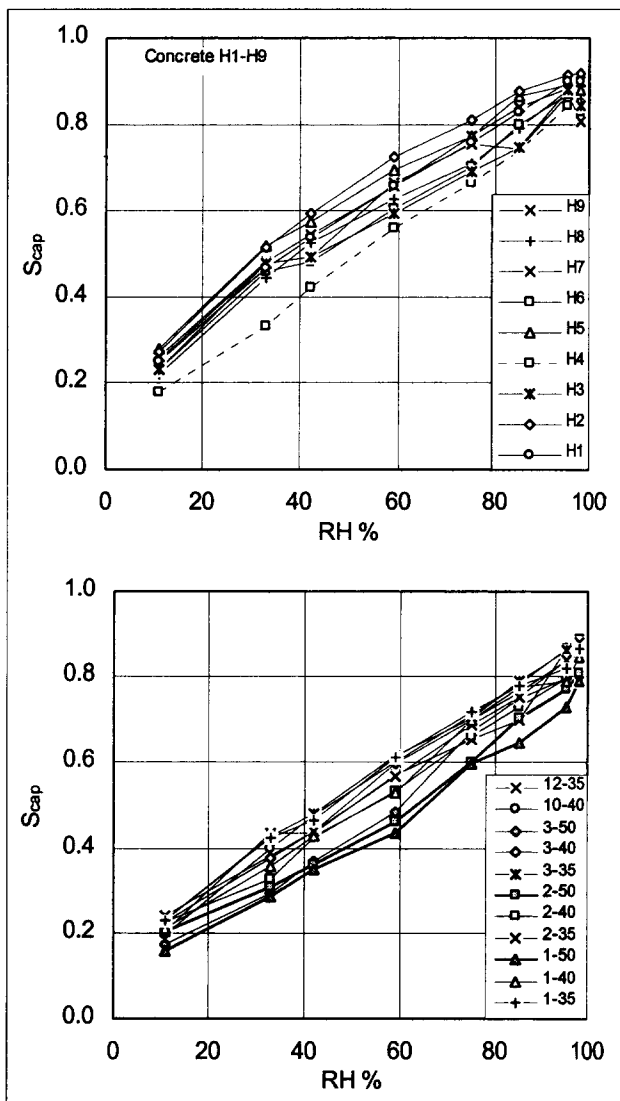


Fig. 7 - Desorption isotherms for the various concretes.

isotherms are from desorption. The moisture content is expressed in terms of the degree of capillary saturation since that is the measure that gives the smallest scatter for small concrete samples containing stones because the samples are not representative.

The sorption isotherms coincide fairly well with the

theoretical sorption isotherm in Fig. 2 for w/C 0.3. Concrete H1-H9 has a  $S_{cap}$  around 0.5-0.6 at 50 % RH, with the lowest value for concrete H4 having a w/B of 0.40, which corresponds to theory. Concrete H2 has the highest  $S_{cap}$ , which should be an effect of the higher silica fume content. Concretes 1-35 to 12-35 have lower  $S_{cap}$ , some as low as 0.4-0.5, which is natural because of the higher w/B. The sorption isotherms for these concretes follow theory very well, with a higher sorption isotherm for a lower w/B.

### 4.2 Moisture diffusion coefficients

The average moisture diffusion coefficient  $\delta(65,100)$  measured in the interval 65-100% RH, at an age of 6.6 years, is shown in Fig. 8. The effects of w/B and silica fume replacement are clearly visible. A factor of 1/10 to 1/20 is found when going from  $w_0/B=0.5$  to 0.25. A cement replacement by 5-10% silica fume and 10-20% fly ash seems to give the lowest moisture diffusion coefficients, especially if silica fume and fly ash are combined. Silica fume has a very large effect at low w/B, 0.3 and lower, but the combination of fly ash and silica fume seems to work well also at w/B 0.40.

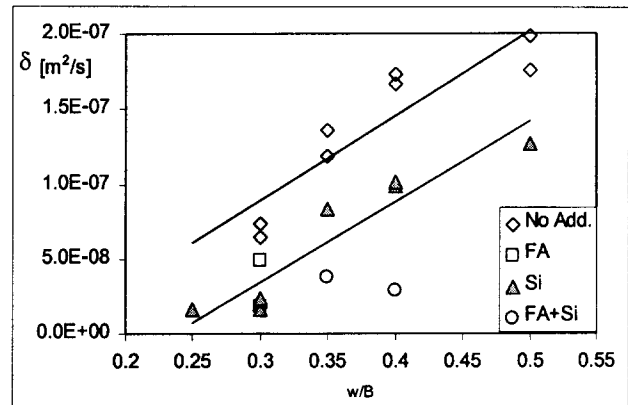


Fig. 8 - Measured moisture diffusion coefficients  $\delta(65,100)$  at an age of 6.6 years, as averages in the RH-interval 65-100%, as a function of water-binder ratio.

As can be seen in Fig. 9, the moisture diffusion coefficients  $\delta(65,100)$  is, at least to some extent, almost linearly influenced by the capillary porosity of the concrete. The capillary porosity is the porosity corresponding to the pores that are emptied when concrete is dried to 75% RH. Not surprisingly, however, the scatter is large since the pore volume says little about the connectivity between the pores.

### 4.3 Moisture dependency

In Fig. 10 a comparison is made to elucidate the moisture dependency of the moisture diffusion coefficients  $\delta(65,100)$  and  $\delta(85,100)$ . With a significant moisture dependency for  $\delta(\phi)$  for high w/C concrete as in

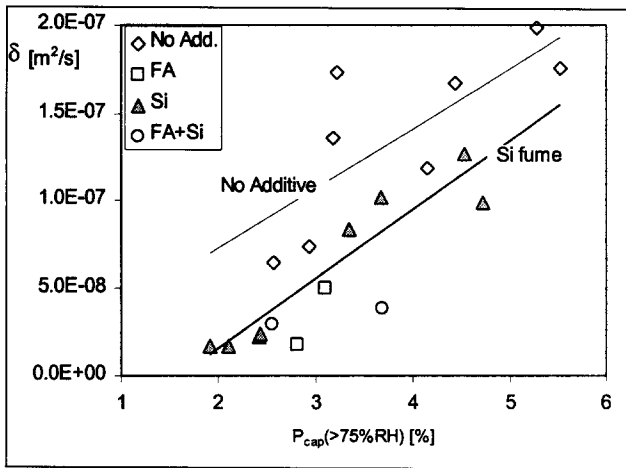


Fig. 9 - Measured moisture diffusion coefficients  $\delta(65,100)$  at an age of 6.6 years, as a function of the part of the capillary porosity that is filled above 75 % RH.

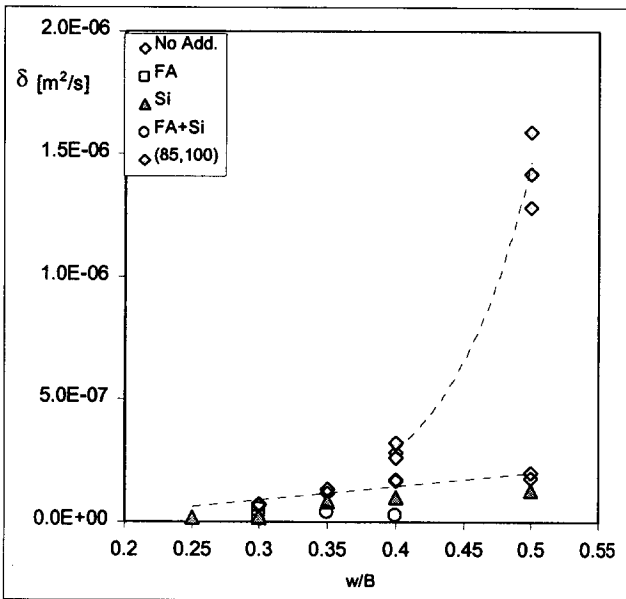


Fig. 10 - Measured moisture diffusion coefficients  $\delta(65,100)$  and  $\delta(85,100)$  as averages in the RH-intervals 65-100% and 85-100% respectively. Data for  $\delta(85,100)$  from [9].

Fig. 4, the moisture dependency of the average moisture diffusion coefficient  $\delta(\varphi_1, \varphi_2)$  will strongly depend on the RH interval limits. With the same upper limit, here  $\varphi_2=100\%$  RH, a lower low limit  $\varphi_1$  must give a smaller average moisture diffusion coefficient since the interval is larger. This is also what Fig. 10 shows, when comparing the two averages for  $\varphi_1$  equal to 65 and 85% RH respectively.

#### 4.4 Effect of age

In Fig. 11 a comparison is made of the effect of continuous aging on the moisture diffusion coefficients. The coefficient  $\delta(65,100)$  after 3.5 years is compared to the coefficient after 6.6 years. As can be seen there is a decreasing effect during this period changing the coefficient with a factor of 0.80. The exceptions are the two SRPC concretes with  $w/B$  of 0.50 where the diffusion

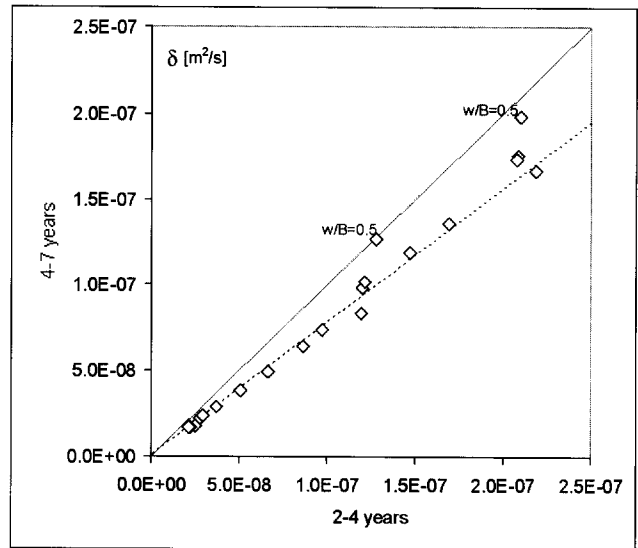


Fig. 11 - Measured moisture diffusion coefficients  $\delta(65,100)$  at ages of 3.5 and 6.6 years respectively.

coefficient seems to have reached a “final” value after 4 years. The diffusion coefficient for OPC concrete with  $w/B=0.50$  continued to decrease after 4 years.

The aging effect may very well be concentrated to the wet part of the discs where the supply of water is continuous. The dry half of the discs most probably has an RH below some 80%, which means that hydration should not progress. This means that the moisture transport properties are different in the different parts of the specimens and that the data given in the tables and figures are some type of averages for the RH intervals. There is no simple way to avoid this complication when performing long-term studies of moisture transport through concrete.

#### 4.5 Moisture profiles

A steady-state moisture distribution for a concrete structure is obviously not linear, since the moisture diffusion coefficient  $\delta(\varphi)$  is not a constant. The distribution may be predicted by integrating the last part of Equation (2) and utilizing average moisture diffusion coefficients  $(\varphi_1, \varphi_x)$  from Fig. 4 step-wise in a series of RH intervals. The depth  $x(\varphi_x)$  where RH equals  $\varphi_x$  can be calculated from [12]:

$$\frac{x}{L} = \frac{\int_{\varphi_1}^{\varphi_x} \delta(\varphi) d\varphi}{\int_{\varphi_1}^{\varphi_2} \delta(\varphi) d\varphi} = \frac{(\varphi_x - \varphi_1) \cdot \bar{\delta}(\varphi_1, \varphi_x)}{(\varphi_2 - \varphi_1) \cdot \bar{\delta}(\varphi_1, \varphi_2)} \quad (4)$$

By selecting a series of  $\text{RH}=\varphi_x$  between the two boundary conditions  $\text{RH}(x=0)=\varphi_1$  and  $\text{RH}(x=L)=\varphi_2$ , the non-linear moisture distribution  $x/L(\varphi)$  can be constructed from Equation (4).

The results of two examples from such calculations are shown in Fig. 12 for two concretes with  $w/C=0.4$

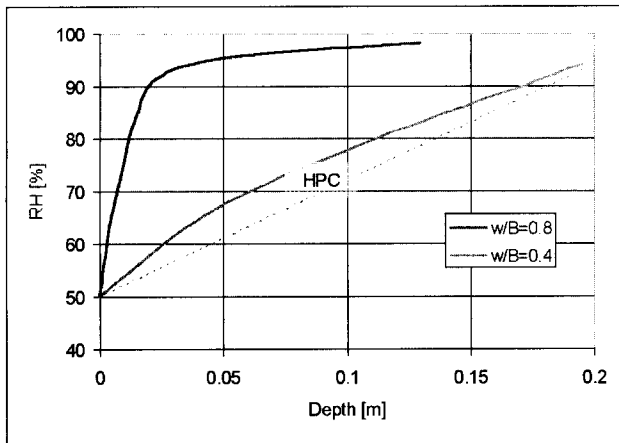


Fig. 12 - Predicted steady-state RH profiles through 0.2 m thick concrete structures with one face in contact with water and 50 % RH at the dry side.

and 0.8 respectively. Since HPC most probably has a smaller moisture dependency than OPC-concrete with a w/C of 0.4, the moisture profiles for HPC should be between the profile for w/C=0.4 and a straight line, cf. Fig. 12. The shape of the RH distribution will be closer and closer to a straight line the lower the w/B. The moisture distribution for different HPC will fall within the small area marked in Fig. 12.

The predicted steady-state moisture profile for HPC in Fig. 12 will be achieved only after a very long time. The “initial” moisture profile will follow from the self-desiccation that creates an internal RH that is almost constant at all depths. The wet side will then continue to mature and the moisture flow into the concrete will be extremely small, given by the moisture transport properties in Figs. 8-11. An example of such a case is shown in Fig. 13, from the exposure program described by [6], where submerged HPC still is far from saturated after 10 years of exposure.

A degree of capillary saturation  $S_{cap}$  of some 0.82, as in Fig. 13, is approximately what is expected from pure self-desiccation from the desorption isotherm for w/C 0.3 in Fig. 2, corresponding to an RH lower than 85-90% due to self-desiccation in Fig. 3.

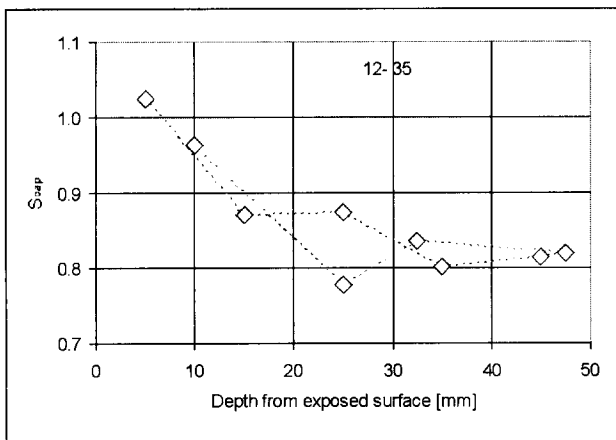


Fig. 13 - Measured degree of capillary saturation  $S_{cap}$  in a 100 mm thick slab of concrete 12-35, submerged in sea water for 10 years.

## CONCLUSIONS

From the study a number of conclusions may be drawn.

- Self desiccation is a major factor for moisture transport in HPC,
- The degree of saturation is “always” high in HPC, compared to in normal concrete,
- HPC can be made (almost) impermeable,
- The type of binder, to some extent more than w/B, is decisive for the moisture flow properties, especially cement replacement by silica fume,
- The moisture dependency of the moisture diffusion coefficient for HPC is small,
- Steady-state moisture profiles for HPC are almost linear, but will be reached only after a very long-time,
- Submerged HPC is not saturated because of the self-desiccation and the extremely slow moisture transport into concrete.

## LIST OF SYMBOLS

$\nu$	water vapour content of the air [kg/m <sup>3</sup> ]
$\nu_s$	vapour content at saturation
$RH, \varphi$	relative humidity
$w_e$	moisture content [kg/m <sup>3</sup> ] in weight of moisture per volume of concrete
$u$	moisture ratio[kg/kg] in weight of moisture per dry weight of concrete
$S_{cap}$	degree of capillary saturation” [-]
$w/C$	water-cement ratio
$w/B$	water-binder ratio; without activity factors
$J$	moisture flow [kg/m <sup>2</sup> /s]
$\delta$	moisture diffusion coefficient [m <sup>2</sup> /s]
$D_w$	moisture diffusivity [m <sup>2</sup> /s]

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