Determination of water vapour permeability in concrete (contribution to CIB W40 meeting in Lund, Sept 1991)

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DETERMINATION OF WATER VAPOUR PERMEABILITY IN CONCRETE

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1 INTRODUCTION

With a method relying on measurements of the rate of the water vapour flow from a specimen and on measurements of the distribution of the relative humidity in the specimen at steady state conditions, it is possible to calculate the moisture permeability and to determine its dependence on the relative humidity (RH).

2 EXPERIMENTS

2.1 Experimental arrangement

The experimental arrangement in principle is shown in FIG 2.1. The flow of water vapour is unidimensional and goes from the bottom to the top of the specimen. FIG 2.2 shows a photo of one specimen and FIG 2.3 shows a photo of the climate room where the specimens are. There were totally about 150 specimens.

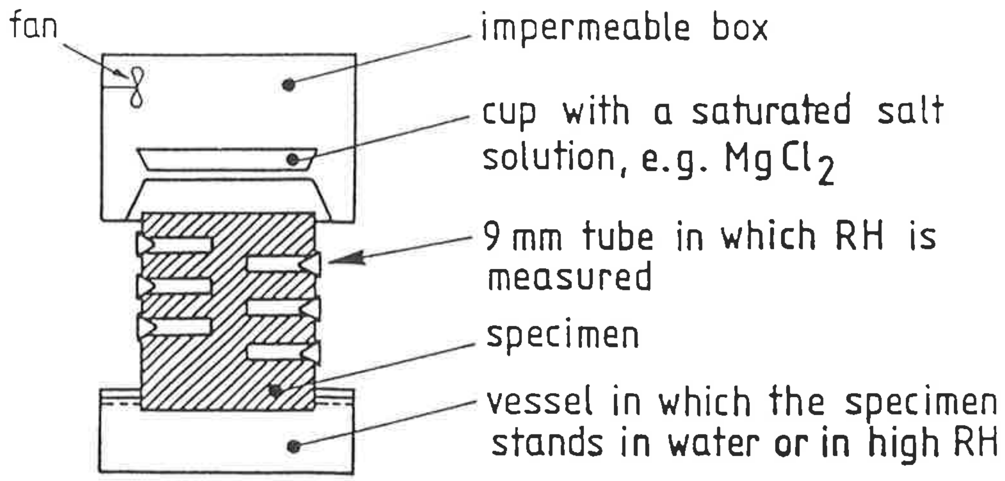

FIG 2.1 The experimental arrangement in principle.

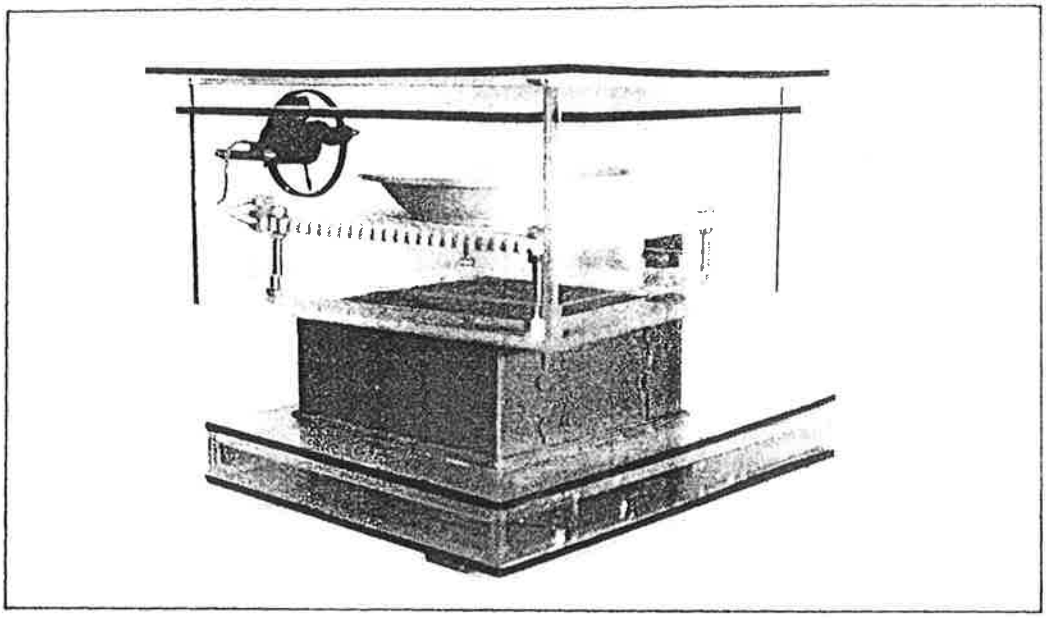

FIG 2.2 Photo of a specimen.

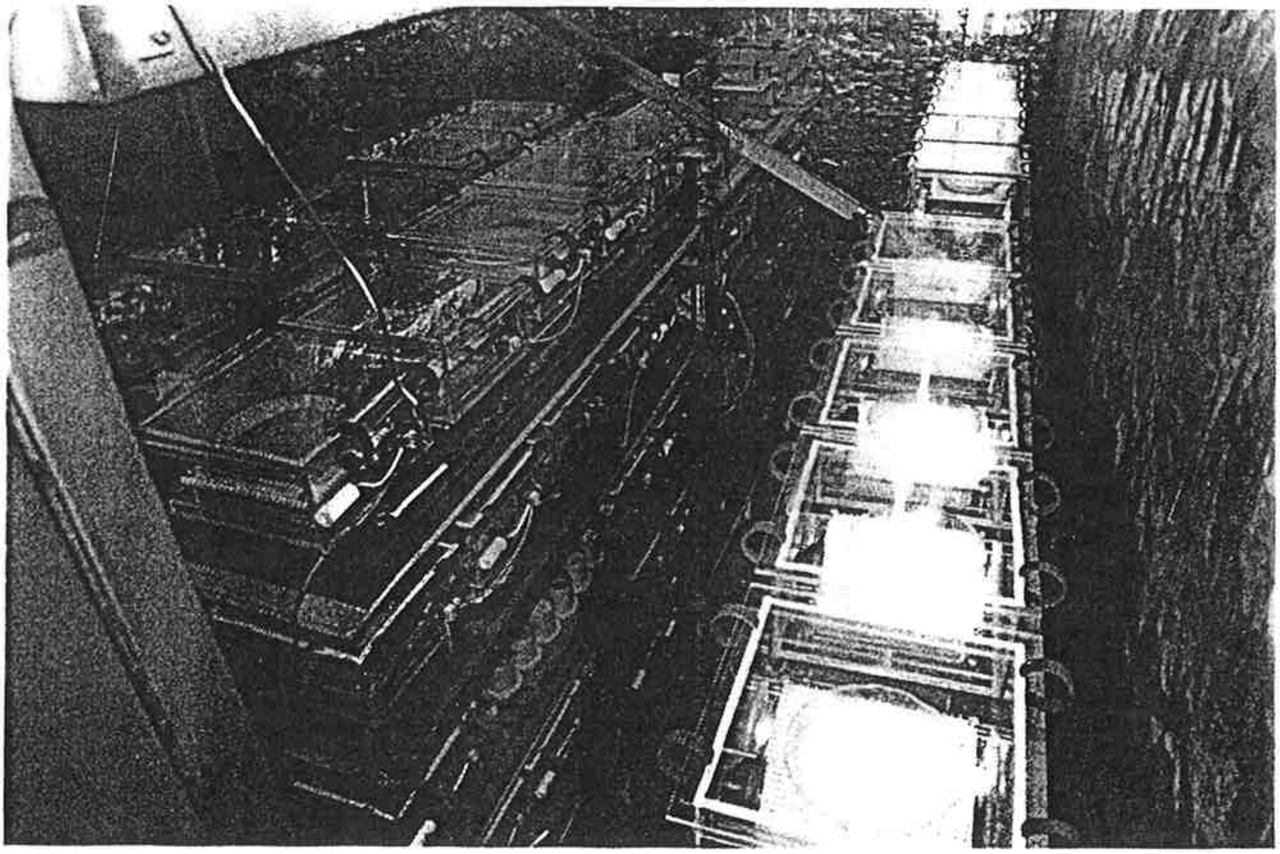

FIG 2.3 Photo of the climate room where the specimens were stored.

The upper part of the experimental arrangement consits of a nearly impermeable box in which RH is held constant by means of a "saturated" salt solution in a cup. In our case, magnesium chloride for which RH is about 33 %. The cup is weighed regularly, every week, to obtain the flow from the specimen. When the magnesium chloride in the cup has increased in weight about 0.01 kg it is replaced by "new" salt. The wet salt is regenerated in an oven at 40 °C and used again. The top surface of the specimen is exposed to the air inside the box. A small fan circulates the air inside the box.

The surfaces of the specimen exposed to the surrounding air in the room are sealed with 2 mm nearly impermeable epoxy resin. The bottom surface of the specimen stands in water or in air with high RH, which is brought about by a water surface some centimetres below the specimen.

Tubes, with about 14 mm external and about 9 mm internal diameter, are embedded in the sides of the specimen. The length of the tubes is about 80 mm. The external surface of the tubes is grooved to get good adherence to the cement paste in the specimen. The internal end surface of the tubes is open towards the specimen and RH in the tubes is in equilibrium with RH in the specimen. Starting with the uppermost tube, with the lowest RH, the relative humidity is measured gradually downwards with the help of a small capacitive RH-sensor.

The RH-sensors are made by Vaisala in Finland but rebuilt by our technicans, so the external diameter of a RH-sensor is about 8.5 mm. There is a packing ring, about 10 mm from the end of the RH-sensor, which makes a water vapour tight sealing to the tube in the specimen. A RH-sensor is shown in FIG 2.4.

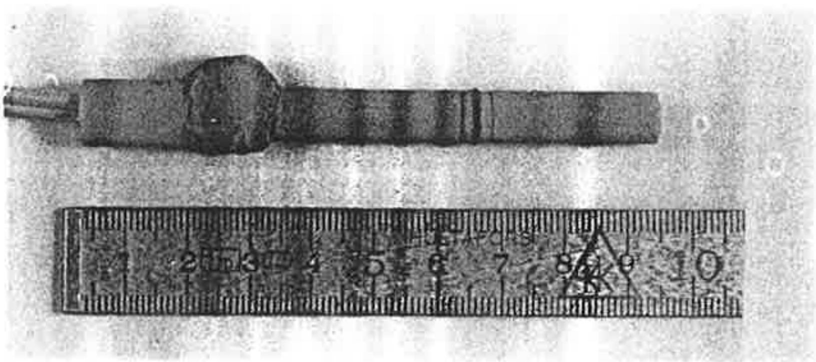

FIG 2.4 Photo of a RH-sensor.

The bottom surface of the specimen is 0.2*0.2 m. The heights of the specimens are 0.063, 0.100 and 0.150 m.

Before the tests are started the specimens were seal cured for at least one month and then the specimens were allowed to suck water for some weeks, so that they really should be on their desorption isotherm during the tests.

2.2 Tested materials

The tested materials comprise concrete, cementmortar and cement paste, but in this paper only concrete is reported. From each tested quality there are normally 6 specimens.

2.2.1 Concrete

The following test program concerning different compositions of concrete is carried out.

Concrete with W_o/C 0.4, 0.5, 0.6, 0.7 and 0.8, all with the same amount of aggregate, see TABLE 2.1.

Concrete with W_o/C 0.7 with different amounts of aggregate, see TABLE 2.2.

Concrete with W_o/C 0.7 with different amounts of air, see TABLE 2.3.

TABLE 2.1 Composition of concrete with different W_o/C.

W_o/C	Cement, C kg/m^3	Water, W_o kg/m^3	Sand/Gravel kg/m^3	Crushed stone 8-18 mm kg/m^3
0.4	418	167.2	990	810
0.5	368	184.0	990	810
0.6	328	196.8	990	810
0.7	296	207.2	990	810
0.8	270	216.0	990	810

TABLE 2.2 Composition of concrete with W_o/C 0.7 with different amounts of aggregate.

Tot amount aggregate kg/m^3	Cement C kg/m^3	Water W_o kg/m^3	Sand/Gravel kg/m^3	Crushed stone 8-18 mm kg/m^3
1692	334	233.8	931	761
1730	320	224.1	952	778
1765	307	215.1	971	794
1800	296	207.2	990	810
1827	285	199.2	1005	822
1854	274	192.1	1020	834

TABLE 2.3 Composition of concrete with W_o/C 0.7 with different amounts of air.

Nominal air content %	Measured air content %	Cement C kg/m^3 Nominally	Water W_o kg/m^3 Nominally	Total amount of aggregate kg/m^3 Nominally
4	4.4	275	192.2	1800
6	6.1	255	178.5	1800
8	8.0	235	164.8	1800
10	9.2	216	151.1	1800

The gradation curve for sand/gravel is shown in FIG 2.5.

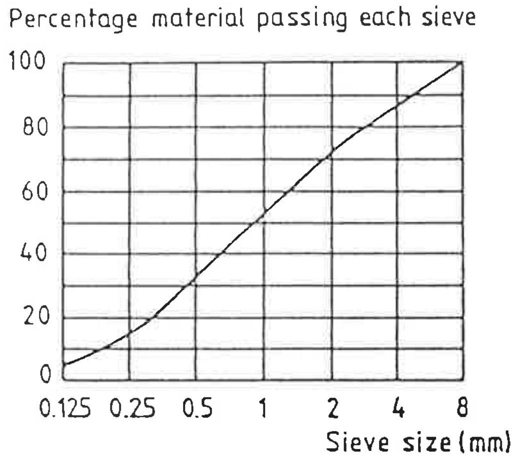

FIG 2.5 Gradation curve for sand/gravel to the concrete.

The crushed stone, 8-18 mm, consists of quartzite.

The slump for the concretes were measured, although not at the same time as the specimens were cast. The results are shown in TABLE 2.4.

TABLE 2.4 Measured slump.

Different W_o/C		W_o/C 0.7 with different amounts of aggregate.	
W_o/C	Slump mm	Aggregate kg/m^3	Slump mm
0.4	5	1692	230
0.5	23	1730	200
0.6	70	1765	155
0.7	135	1800	135
0.8	210	1827	105
		1854	75

3 EVALUATION OF THE MOISTURE PERMEABILITY

According to Fick's first law we can write

$$g = -\delta_v * \text{grad } v \qquad (3.1)$$

g is the density of moisture flow rate $(kg\ m^{-2}\ s^{-1})$.
v is the humidity by volume in the pores of the specimen $(kg\ m^{-3})$.
Under isothermal conditions, (3.1) can be written

$$\delta_v = -g/(v_s * \text{grad } \varphi) \qquad (3.2)$$

v_s is v at saturation
φ is the relative humidity in the pores of the specimen (-).

Under stationary conditions g and grad φ can be measured and δ_v can be calculated as a function of φ.

The moisture flow rate from the top surface of a specimen advances according to FIG 3.1. The moisture flow rate in FIG 3.1. is not corrected for the influence of the tubes in the specimen, the tightening between the specimen and the upper box, and the flow through the epoxy resin.

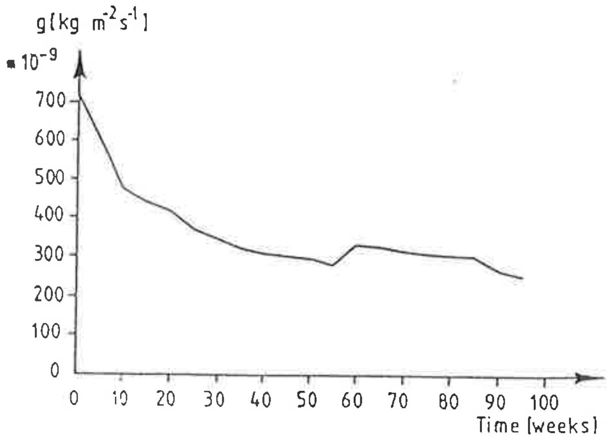

FIG 3.1 Moisture flow rate from a specimen.

The principal φ-distribution in a specimen is shown in FIG 3.2. Grad φ is graphically derived from the slope of the φ-distribution curve.

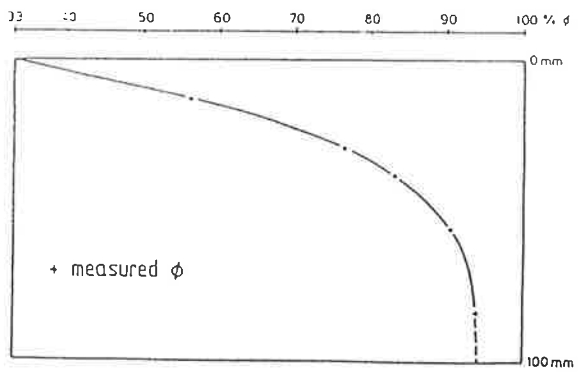

FIG 3.2 Principle φ-distribution in a specimen with a height of 0.100 m.

4 RESULTS

The results which are presented in this chapter show the moisture permeability with regard to humidity by volume in the pores of the specimens (δ_v) as function of RH or as the mean moisture permeability for specimens with definied moisture conditions at the boundaries.

4.1 Different water cement ratios

The concrete qualities that are shown in FIG 4.1 to FIG 4.4 have water cement ratio 0.5, 0.6, 0.7 and 0.8. The amount of aggregate is the same in the diffrent concrete qualities. The mean measured δ_v for up to 6 specimens of each concrete quality are shown in FIG 4.1 to FIG 4.4. The measured maximum and minimum δ_v are also shown in the same figures. The maximum and minimum δ_v -curves are from the specimens, with the same W_o/C, with the highest and lowest fundamental potential, when account have been taken to the total uncertainty in the RH - measurement. For the definition of the fundamental potential, see Arfvidsson et al (1989).

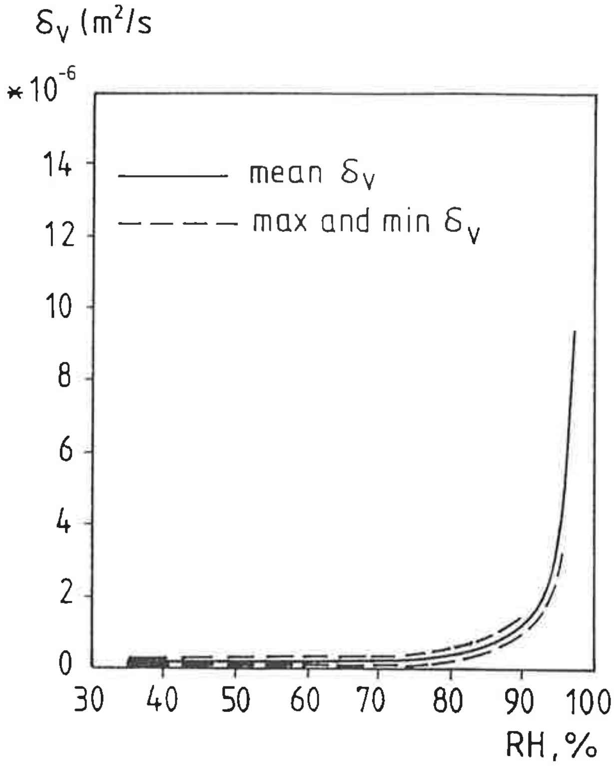

FIG 4.1 Measured moisture permeability for concrete with W_o/C 0.5.

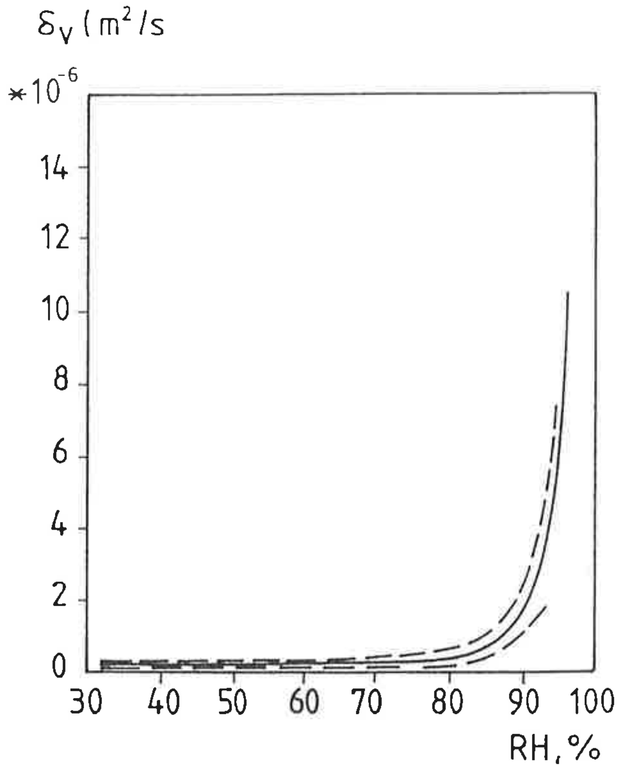

FIG 4.2 Measured moisture permeability for concrete with W_o/C 0.6.

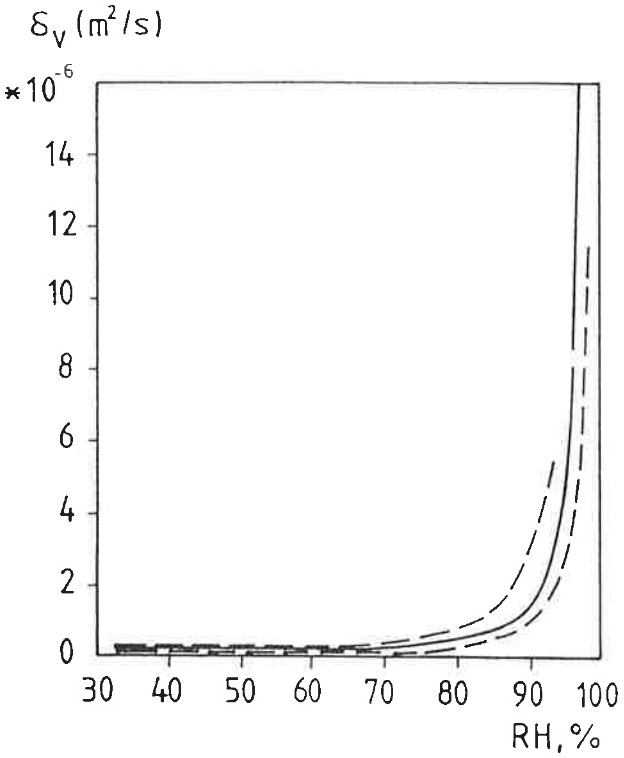

FIG 4.3 Measured moisture permeability for concrete with W_o/C 0.7.

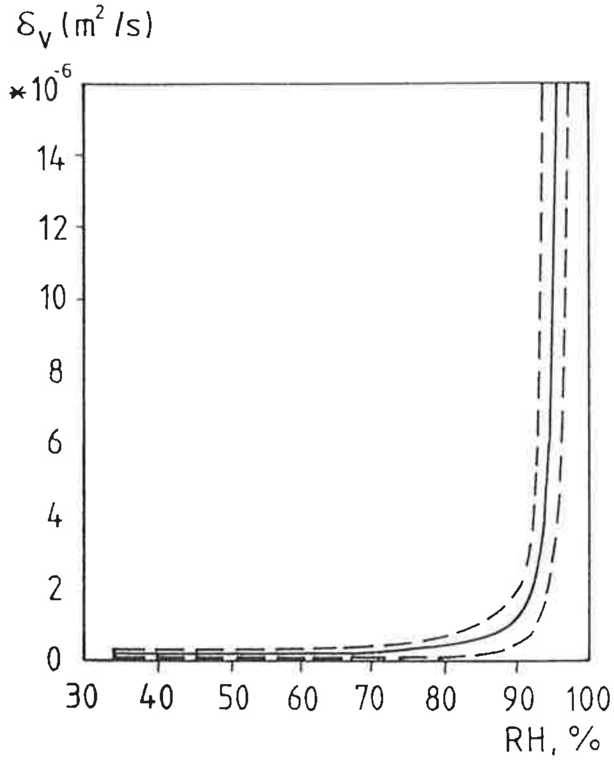

FIG 4.4 Measured moisture permeability for concrete with W_o/C 0.8.

In FIG 4.1 to FIG 4.4 it is shown that the moisture permeability depends on RH. For lower RH, up to about 70 %, δ_v is nearly constant. Between about 70 % and 90 % RH there is an increase in δ_v with RH. Above about 90 % RH δ_v increase strongly with increasing RH. δ_v is not determind the whole way up to the moisture saturation point. The saturation point lies probably somewhat lower than 100 % RH, as the cement contains alkali wich lowers the maximum RH.

The measured maximum and mimimum δ_v - curves have the same shape as the mean δ_v - cuves.

When the mean δ_v - curves for the different water cement ratios are compared with each other there are no or very small influence with W_o/C. The results for different W_o/C and RH are shown in TABLE 4.1. The mean moisture permeability for all the W_o/C at the different RH - levels are shown in the fifth column. In the sixth column are the coefficients of variation shown.

TABLE 4.1 Moisture permeability for concrete with different W_o/C.

RH	$\delta_v * 10^6$ (m^2/s)					Coef.of
%	W_o/C 0.5	W_o/C 0.6	W_o/C 0.7	W_o/C 0.8	Mean val.	var.
33 - 65	0.174	0.148	0.174	0.181	0.169	0.086
70	0.174	0.213	0.230	0.228	0.211	0.026
75	0.251	0.290	0.321	0.295	0.289	0.100
80	0.380	0.421	0.431	0.436	0.417	0.061
84	0.495	0.611	0.594	0.570	0.568	0.090
86	0.639	0.812	0.756	0.686	0.723	0.105
88	0.837	1.200	1.019	0.887	0.986	0.165
90	1.132	1.741	1.270	1.176	1.330	0.211
91	1.421	2.121	1.759	1.449	1.688	0.194
92	1.639	2.794	2.039	1.920	2.098	0.235
93	1.99	3.72	2.70	2.88	2.82	0.25
94	2.66	4.82	3.76	4.62	3.97	0.25
95	3.43	6.65	4.86	10.13	6.27	0.46
96	5.61	10.52	7.02	18.86	10.50	0.56
97	≈9.4		16.51	27.52	17.81	
98				39.97		
	5	5	5	6	Number of specimens	

The moisture permeability is not evaluated for higher RH than 96 to 98 %, because it is very difficult to evaluate the steep slops of the RH - curves. The results in TABLE 4.1 clearly show that W_o/C have no or very small influence on δ_v up to about 95 % RH. This is a surprisingly result.

4.1.1 Influence of Wo/C on the mean moisture permeability between water and 33 % RH

The mean moisture permeability ($\delta^{mean,1}$) has been calculated for the specimens that stand in water.

$$\delta^{mean,1} = g * h / (v_s * (1 - 0.33)) \qquad (4.1)$$

h is the height of the specimen (m)
0.33 is RH at the top of the specimen (-)

It is questionable whether $\delta^{mean,1}$ is a correct measure as most of the differences in the moisture flow are depending on what occurs above 95 % RH. But it is used since it is comparable with the results obtained by Nilsson (1980) and since there are some results for concrete with W_o/C 0.4. For different W_o/C $\delta^{mean,1}$ is shown in FIG 4.5

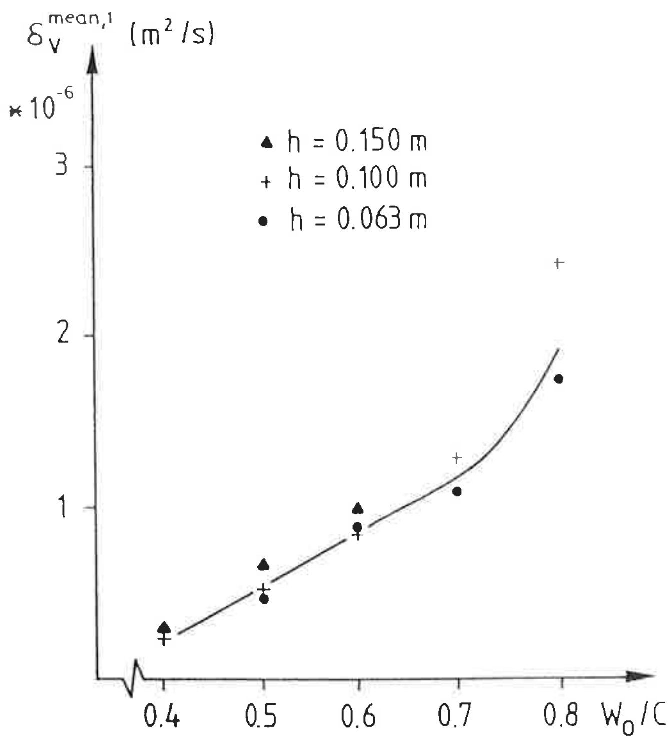

FIG 4.5 Effect of water-cement ratio on the mean moisture permeability, $\delta^{mean,I}$ between water and 33 % RH.

FIG 4.5 shows that the ratio between W_o/C 0.8 and 0.5 is about 4. Nilsson (1980) has found about the same ratio for the diffusivity for cement mortars with W_o/C 0.5 and 0.8. The results in FIG 4.5 and the results obtaind by Nilsson are not directly comparable as the results from Nilsson has the moisture content mass by volume as potential and they are for cement mortar and the results in FIG 4.5 have the humidity by volume in the pores of the specimen as potential and are for concrete. But in the both cases the curve shapes are nearly the same and the ratios for $\delta^{mean,I}$ and for the diffusivity between W_o/C 0.5 and 0.8 have the same magnitude.

In FIG 4.5 it is shown that for nearly all W_o/C that the higher the specimen the higher is $\delta^{mean,I}$. One explanation can be that carbonation has occurred at the top surface of the specimen, giving lower δ_v at the surface. If the carbonation depth for specimens with the same Wo/C is the same the carbonation depth should have greater influence for lower specimens. One another explanation can be that the moisture flow has not reached equilibrium for the highest specimens. For this explanation speaks that for W_o/C 0.7 and 0.8 have the specimens with a height of 0.150 m not reached equilibrium of the moisture flow (after 120 weeks) and $\delta^{mean,I}$ for the two heighs 0.063 and 0.100 m are nearly the same at Wo/C 0.4, 0.5 and 0.6.

4.1.2 Influence of W_o/C on the mean moisture permeability between about 95 % and 33 % RH

The mean moisture permeability ($\delta^{mean,2}$) has been calculated for the specimens that stand in moist air which is brought about with a water surface some centimetres below the specimen. It is assumed that the RH at the bottom of the specimen is 95 %.

$$\delta^{mean,2} = g * h / (v_s *(0.95 - 0.33)) \qquad (4.2)$$

The effect of the water-cement ratio on $\delta^{mean,2}$ is shown in FIG 4.6.

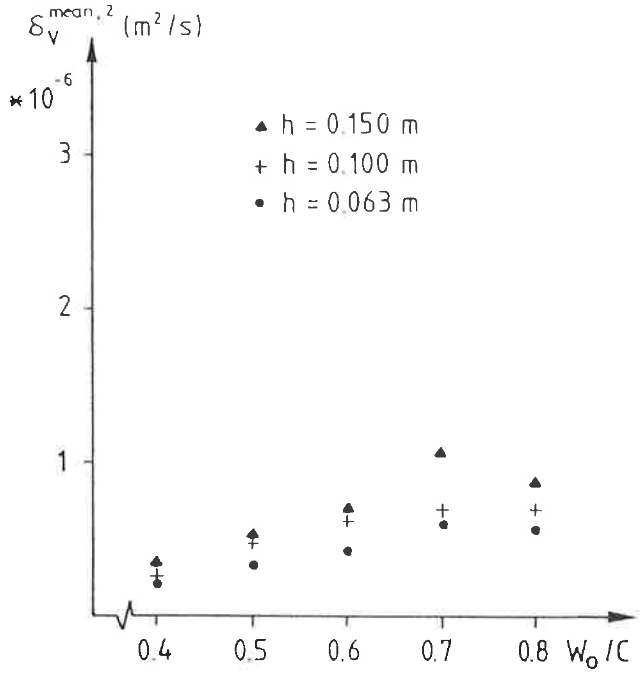

FIG 4.6 Effect of water cement ratio on the mean moisture permeability ($\delta^{mean,2}$) between about 95 % and 33 % RH.

In FIG 4.6 it is shown that $\delta^{mean,2}$ is in the same magnitude for W_o/C 0.6, 0.7 and 0.8. There is no or very small influence of W_o/C on $\delta^{mean,2}$ and on the moisture flow if the specimens stand in moist air.

For W_o/C 0.4 and 0.5 $\delta^{mean,2}$ is nearly the same as $\delta^{mean,1}$ in FIG 4.5. For these W_o/C there is only a small difference in the moisture flow if the specimens stand in water or in high RH.

The influence of the height of the specimen are the same in FIG 4.6 as in FIG 4.5. For explanations see 4.1.1.

4.2 Different amounts of air in the concrete

In FIG 4.7 $\delta^{mean,1}$ according to eq. (4.1) is shown as a function of the air content of the concrete. The concretes have W_o/C 0.7.

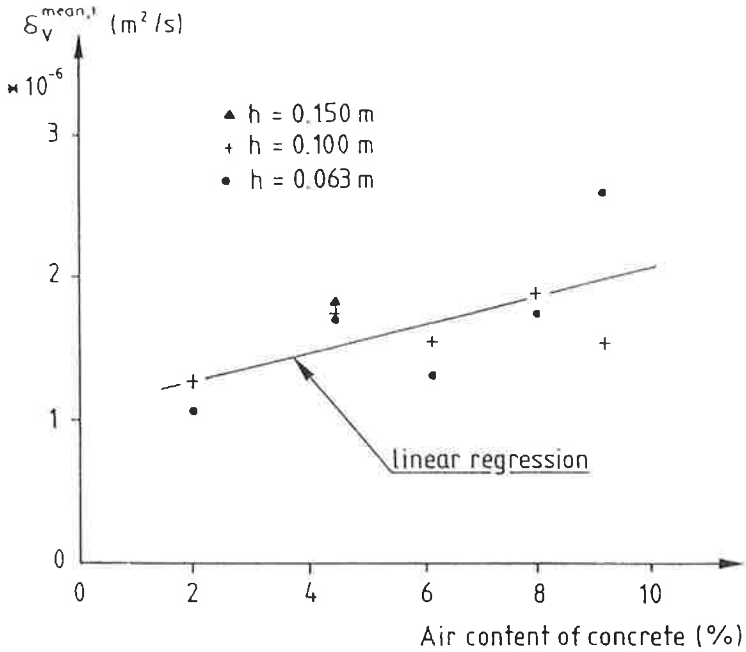

FIG 4.7 Effect of the air content of concrete on mean moisture permeability, $\delta^{mean,1}$, for concrete with W_o/C 0.7.

The concrete without additional air is supposed to have an air content of 2 %. The scatter is great in FIG 4.7, but it seems like higher air content gives higher $\delta^{mean,1}$. Linear regression for the measured results gives that $\delta^{mean,1}$ has increased about 60 % when the air content is increased from 2 % to 10 %.

For 4 specimens, with different amounts of air and with a height of 0.100 m, δ_v has been calculated between 33 % and about 75 % RH. In this region δ_v is nearly constant for a specimen. In FIG 4.8 δ_v, between 33 % and about 75 % RH, is shown as a function of the air content of the concrete and the air content of the "paste" (cement paste and air).

Hillerborg (1979) has proposed a simple composite model, that can be expressed in terms of moisture permeability for the "paste".

$$\delta_{vp} = (1-V) * \delta_1 + V * D \qquad (4.3)$$

δ_{vp} = moisture permeability for the "paste" including air (m^2/s)
δ_1= moisture permeability for the "paste" exluding air (m^2/s)
D = water vapour diffusion coefficient in the air (m^2/s)
V = air content of "paste". $0 < V < 1$ (-)
n = a constant that depends on the ratio D/δ_1. $-0.5 < n < 0.5$. When $D/\delta_1 = 25/0.12 \approx 200$ Hillerborg proposes that $n = -0.35$.

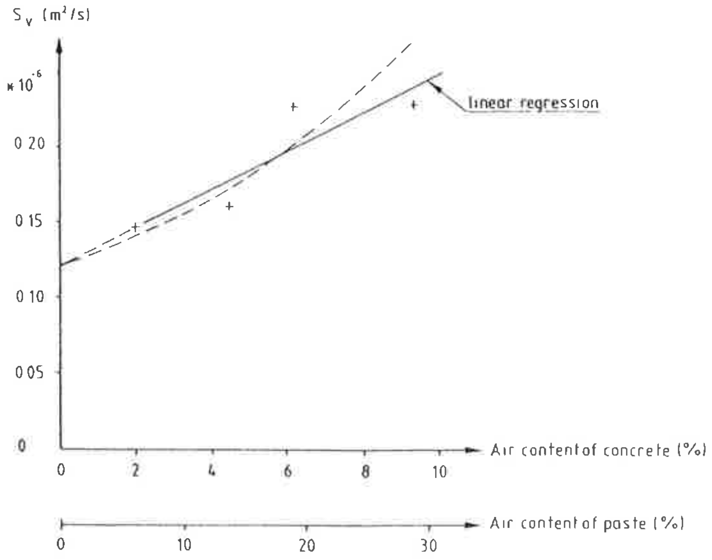

FIG 4.8 Effect of air content of concrete on the moisture permeability between 33 % and about 75 % RH. Concrete with W_o/C 0.7.

Linear regression for the measured results in FIG 4.8 gives that δ_v has increased about 65 % when the air content of the concrete is increased from 2 % to 10 % . The 4 specimens that are used in FIG 4.8 are different from the specimens that are used in FIG 4.7, but the gradient of the linear regression lines are nearly the same.

In eq. (4.3) it is assumed that all moisture transport occurs in the cement paste. The composite model fits the linear regression curve very well.

Nilsson (1980) has measured the effect of air content of the "paste" for cement mortars , see FIG 4.9. Nilsson measured the diffusivity from the time which is needed to evaporate 25 % of the exess water in the specimens. The results are presented as the quotient between the diffusivity and the diffusivity at the natural air content.

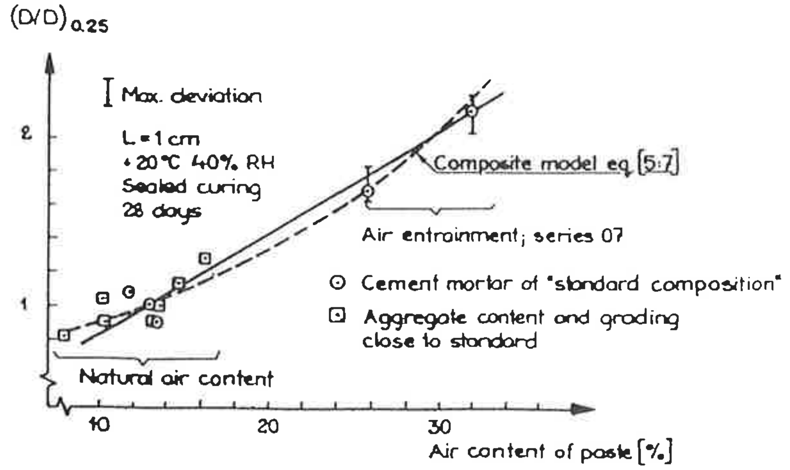

FIG 4.9 Effect of air content of the "paste" for cement mortars. Results from diffusivity measurements. Nilsson (1980).

FIG 4.9 shows that the diffusivity (D_w) has increased about 100 % when the air content of the "paste" is increased from about 13 % to 30 %. Even Nilsson had used the composite model of Hillerborg. The model is used so that it coincidence with the linear regression curve at $(D/D_o)_{0.25} = 1$.

It is possible to relate D_w with δ_v. If the quotient between the diffusivity and the diffusivity when the "paste" has no air is established, we got

$$D_w/D_{w1} = \delta_{w1}/\delta_w * \delta_{vp}/\delta_1 \qquad (4.4)$$

D_w = moisture diffusivity for the "paste" including air (m^2/s)
D_{w1} = moisture diffusivity for the "paste" excluding air (m^2/s)
δ_{w1}/δ_w = difference in moisture capacity with and without air (-)

If W_o/C is the same for the "paste" and the water content in the air in the paste is neglected, there is only a volume effect from the air on δ_{w1}/δ_w.

$$\delta_w = (1-V) * \delta_{w1} \qquad (4.5)$$

Eq. (4.4) and (4.5) gives

$$D_w/D_{w1} = 1/(1-V) * \delta_{vp}/\delta_1 \qquad (4.6)$$

With eq. (4.6) it is possible to calculate the results in FIG 4.8 to diffusivities. When the air content of the "paste" in FIG 4.8 is increased from 13 % to 30 % δ_v has increased 60 % according to the composite model. Eq.(4.6) gives that the diffusivity has increased 100 %. The results in FIG 4.8 are comparable with the results in FIG 4.9, where the increase is about 100 %. Also Nilsson (1980) has used eq.(4.6) in his thesis.

4.2.1 Calculated moisture permeabilities for concrete with different amounts of air

In FIG 4.7, 4.8 and 4.9 it is shown that the simple composite model (eq.(4.3)) probably could describe the influence of different amounts of air in the concrete. In FIG 4.7 it is shown that $\delta^{mean,1}$ between 33 % RH and water probably obey the composite model and FIG 6.8 shows that δ_v between 33 % and about 75 % RH probably obeys the same model.

The mean moisture permeabilities for W_o/C 0.5 to 0.8 at different RH-levels in TABLE 4.1 (the fifth column) are used as input data to calculate, with eq.(4.2), the influence of different amounts of air on δ_v. In TABLE 4.2 the colums 2, 3 and 4 show the calculated δ_v:s as function of RH. The columns 5, 6 and 7 show the increase in δ_v from the input values.

TABLE 4.2 Calculated moisture permeability for concrete with different amounts of air.

RH	$\delta_v * 10^6$ (m^2/s)			Increase in δ_v (%)			n
%	air 6 %	air 8 %	air 10 %	air 6%	air 8%	air 10%	(-)
33 - 65	0.235	0.281	0.341	39	66	102	-0.360
70	0.311	0.371	0.449	39	66	100	-0.350
75	0.399	0.474	0.572	38	64	98	-0.345
80	0.571	0.676	0.810	37	62	94	-0.335
84	0.772	0.908	1.083	36	60	91	-0.325
86	0.975	1.144	1.356	35	58	88	-0.315
88	1.312	1.526	1.792	33	55	82	-0.310
90	1.751	2.023	2.359	32	52	77	-0.290
91	2.195	2.518	2.912	30	49	73	-0.280
92	2.701	3.080	3.536	29	47	69	-0.260
93	3.565	4.022	4.563	26	43	62	-0.240
94	4.888	5.438	6.076	23	37	53	-0.210
95	7.406	8.058	8.790	18	29	40	-0.175
96	11.733	12.401	13.123	12	18	25	-0.125
97	18.63	19.05	19.49	5	7	9	-0.060

The results in TABLE 4.2 are of course only theoretical but they could be used for a qualitative analysis. For all three air contents it is seen that the effect of the air is decresed (in percent) for increasing RH. This is quite natural as the quotient D/δ_v become smaller when RH increase. When $D/\delta_v=1$ there should be no increase in δ_v with increasing air content, as the "transport velocity" in the air and in the "paste" without air are the same. The value of n is choosen according to Hillerborg (1986), where n is in principle given as function of D/δ_v.

4.3 Different aggegate contents in the concrete

The effect of the aggregate content on $\delta^{mean,1}$ and $\delta^{mean,2}$ are shown in FIG 4.10. The concrete has W_o/C 0.7. $\delta^{mean,1}$ is defined in 4.1.1 and $\delta^{mean,2}$ is defined in 4.1.2.

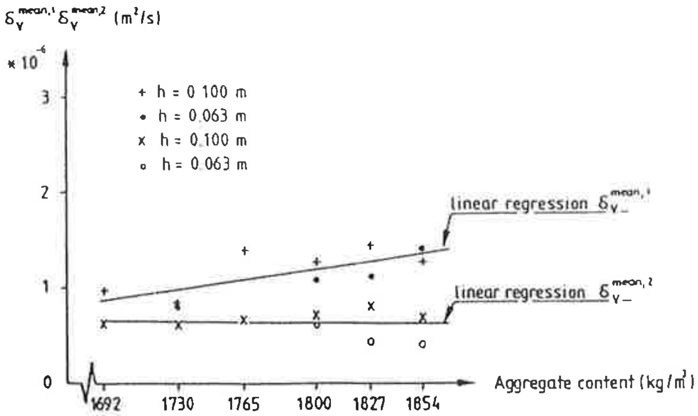

FIG 4.10 Effect of the aggregate content on the mean moisture permeability, $\delta^{mean,1}$ and $\delta^{mean,2}$. Concrete with W_o/C 0.7.

If it is assumed that the permeability of the aggregate is zero, then according to the composite model $\delta^{mean,1}$ and $\delta^{mean,2}$ should decrease when the aggregate content increases.

The linear regression curve for $\delta^{mean,2}$ in FIG 4.10 shows that $\delta^{mean,2}$ is the same or may decrease somewhat when the aggregate content is increased. There are no results of $\delta^{mean,2}$ from specimens with a height of 0.063 m. at the lower aggregate content 1692, 1730 and 1765 kg/m^3. As $\delta^{mean,2}$ seem to have a lower value for the height 0.063 m. than for the height 0.100 m. it is probable that $\delta^{mean,2}$ are the same for all the aggregate contents.

The linear regression curve for $\delta^{mean,1}$ in FIG 4.10 shows that $\delta^{mean,1}$ increases or is the same when the aggregate content is increased.

An explanation to the result for $\delta^{mean,2}$ and $\delta^{mean,1}$ is that the boundary zone between "paste" and aggregate increase when the aggregate content increase. In this boundary zone the resistance to water flow is low. In the measure $\delta^{mean,1}$ there is more water flow, in the specimen,than in $\delta^{mean,2}$. Consequently should $\delta^{mean,1}$ increase more with the aggregate content than $\delta^{mean,2}$.

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