DETERMINATION OF MOISTURE PERMEABILITY IN CONCRETE UNDER HIGH MOISTURE CONDITIONS

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ABSTRACT

With a method relying on measurements of the flow of water vapour from a specimen and measurements of the distribution of the relative humidity in the specimen at steady state conditions, the moisture permeability can be calculated and its dependence on the relative humidity can be determined.

The specimens are of dimensions that are used in ordinary buildings.

Key-words: Moisture transport, moisture permeability, concrete, relative humidity.

1. INTRODUCTION

Many attemps have been made to determine the moisture transport coefficients for cement paste, cement mortar and concrete, as a function of the relative humidity (ϕ) or the moisture content (w).

Some of these results are shown in FIG. 1 which is taken from /1/. The driving force in FIG. 1 is the moisture content mass by volume (kg/m^3).

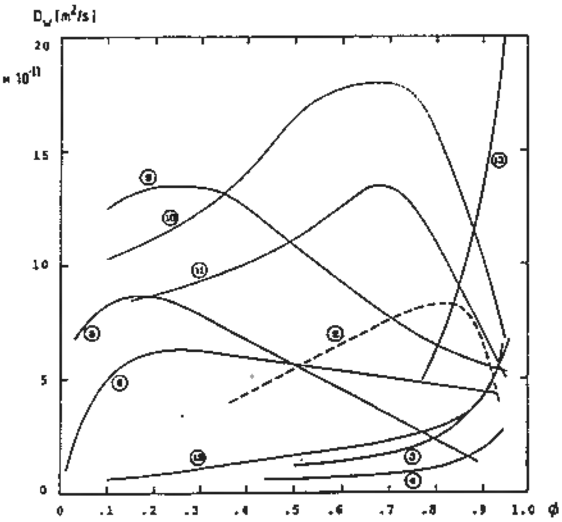

FIG. 1. Moisture diffusivity versus relative humidity.

(2), (3) and (4) are cement mortars and (5), (6), (9), (10), (11) are cement pastes and (13) is concrete. We see that concrete seems to behave in a different manner than cement mortar and cement paste.

Nilsson /2/ has determined the moisture permeability as a function of the relative humidity and the water-cement ratio (W_o/C), see FIG. 2. For W_o/C 0.6 and 0.8 the moisture permeability is not determined up to the saturation point.

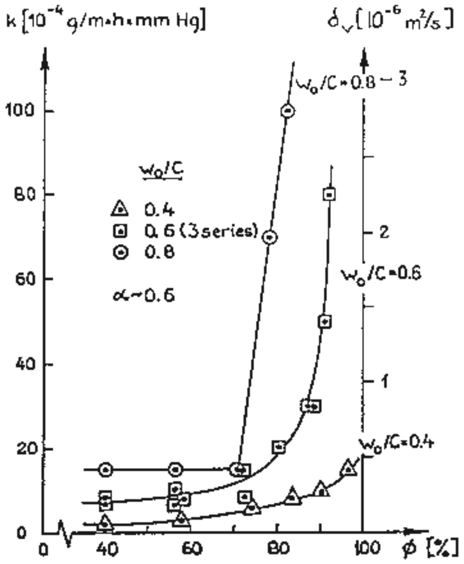

FIG. 2. Moisture permeability as a function of pore humidity for cement mortars of different water-cement ratios.

Among the above related moisture transport coefficients not many are from concrete qualities or dimensions of structures that are used in practice.

Some of the ideas behind our attempt to determine the moisture transport coefficients are listed below.

- Dimensions of the specimens should be in the same range as those used in ordinary buildings.
- Compositions of the concrete qualities to be used in this investigation should closely correspond to compositions of the most commonly used concrete qualities in Sweden.
- To see if there is a great increase in flow from the specimens in direct contact with water (capillary suction) as compared to specimens in contact with moist air.
- To simulate the customary conditions, e.g. slab on the ground, seal curing and drying from one side with normal relative humidity on that side.

2. EXPERIMENTAL ARRANGEMENT

By using a method which relies on measuring the water vapour flow from a specimen and the distribution of the relative humidity (ϕ) in the specimen, under stationary conditions, the moisture permeability with regard to humidity by volume in the pores of the specimen (δ_v, kg/m^3) can be calculated. δ_v:s dependence on ϕ can be determined. The flow of water vapour is unidimensional and goes from the bottom to the top of the specimen. The experimental arrangement in principle is shown in FIG. 3 and FIG. 4.

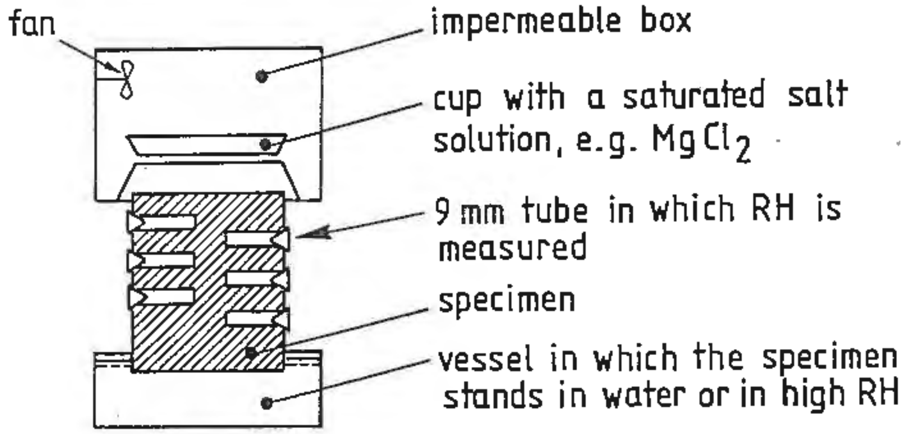

FIG. 3. Principle of the experiment.

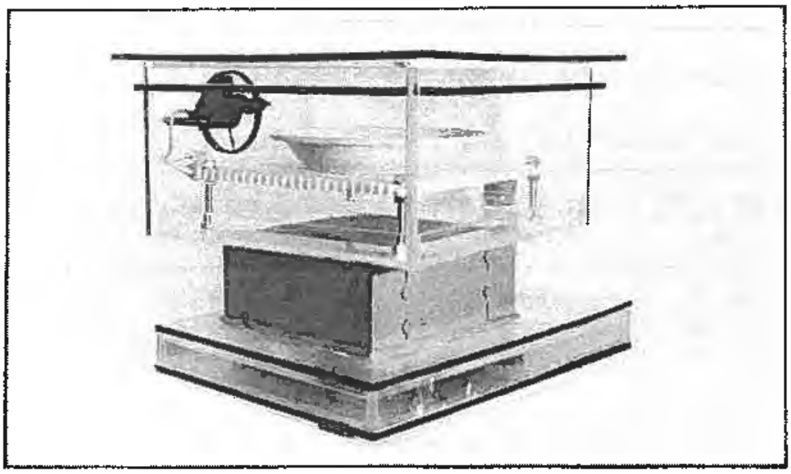

FIG. 4. Photo of the experimental arrangement.

The upper part consists of a nearly impermeable box in which ϕ is held constant by means of a saturated salt solution in a cup. In our case magnesium chloride for which ϕ is 33 %. The cup is weighed regularly, every week, in order to obtain the flow from the specimen. A small fan circulates the air inside the box. The top surface of the specimen is exposed to 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 stands in water or in air with high relative humidity, which is brought about by a water surface some centimetres below the specimen.

Tubes, about 9 mm diameter are embedded in the sides of the specimen. The internal end surfaces of the tubes are open towards the concrete and ϕ in the tubes is in equilibrium with ϕ in the concrete. Starting with the uppermost tube, with the lowest ϕ, the relative humidity is measured gradually downwards with help of a small, capacitive ϕ-sensor. The ϕ-sensor is calibrated with saturated salt solutions before and after measurements of relative humidity in the specimen.

The bottom surface of the specimen is 0.2 x 0.2 m. The heights of the specimen are 0.063 m, 0.100 m and 0.150 m. The results which are presented in this paper are mainly from specimens with a height of 0.100 m.

Before the tests are started the specimens are seal cured for at least one month, so δ_v are determined for concrete which has not dried to a large extent before the test, to simulate slab on the ground conditions.

3. TESTED MATERIALS

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

Concrete with W_o/C 0.5, 0.6, 0.7 and 0.8. Concrete with W_o/C 0.7 with different amounts of aggregate. Concrete with W_o/C 0.7 with different amounts of air.

Compositions of the concrete are shown in TABLE 1, 2 and 3.

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

Total amount of aggregate kg/m^3	Cement C kg/m^3	Water W_o kg/m^3	Sand/Gravel kg/m^3	Crushed stone 8-18 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 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. 5.

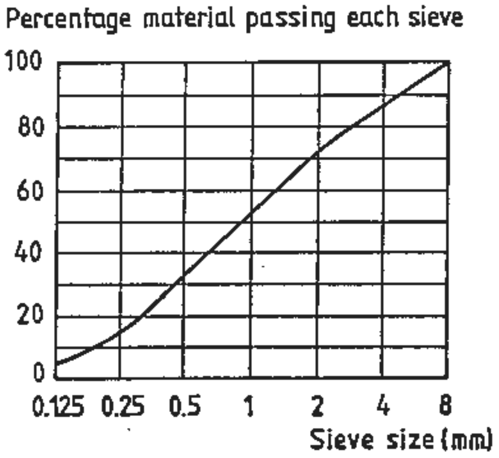

FIG. 5. Gradation curve for sand/gravel.

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 4.

TABLE 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
		1692	230
0.5	23	1730	200
0.6	70	1765	155
0.7	135	1800	135
0.8	210	1827	105
		1854	75

4. EVALUATION OF THE MOISTURE PERMEABILITY

According to Fick's first law we can write

$$g = - \delta_v \cdot \text{grad } v \qquad (1)$$

where
g is the density of moisture flow rate (kg m^{-2} s^{-1})
δ_v is the moisture permeability with regard to humidity by volume (m^2 s^{-1})
v is the humidity by volume in the pores of the specimen (kg m^{-3})

(1) can be written

$$\delta_v = - g/\text{grad } v \qquad (2)$$

(2) can be written under isothermal conditions

$$\delta_v = - g \,/\, v_s \,/\, \text{grad } \phi \qquad (3)$$

where
v_s is v at saturation
ϕ is the relative humidity

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

The moisture flow rate from the top surface of the specimen advances according to FIG. 6. The moisture flow rate in FIG. 6 is not corrected for influence of the tubes in the specimen and the tightening between the specimen and the upper box.

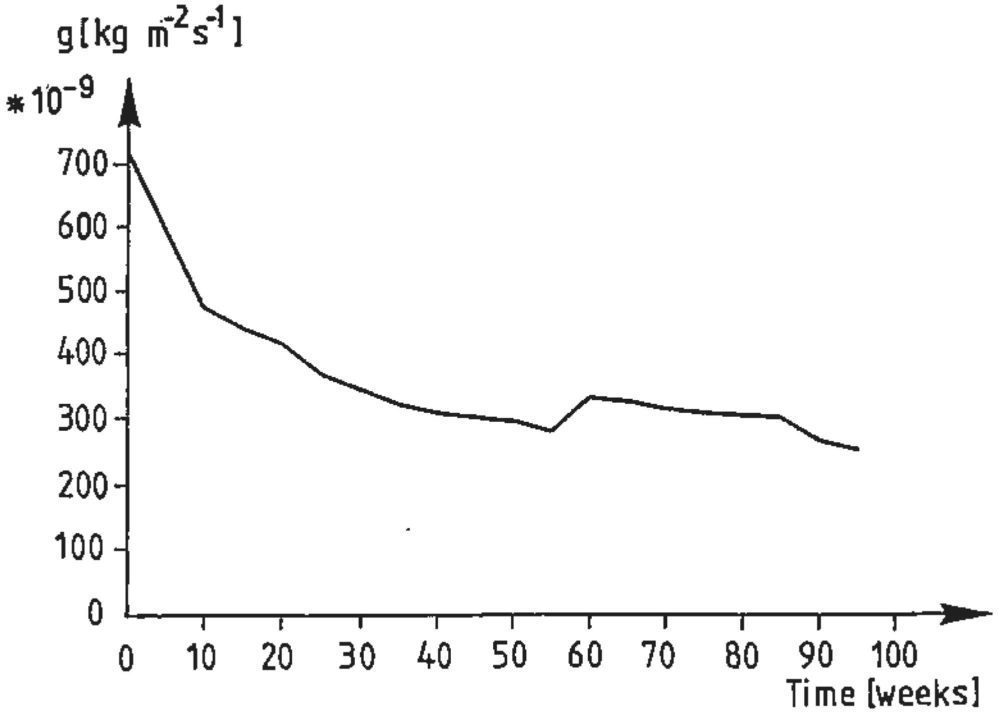

FIG. 6. Moisture flow rate from a specimen with a height of 0.10 m.

The principal ϕ-distribution in a specimen is shown in FIG. 7.

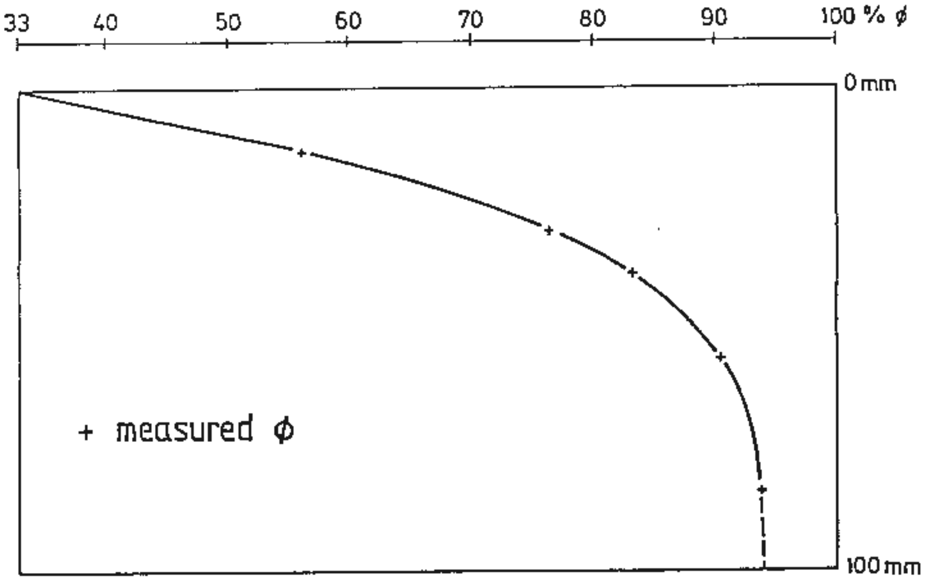

FIG. 7. Principal ϕ-distribution in a specimen with a height of 0.10 m.

Grad ϕ is graphically derived from the slope of the ϕ-distribution curve.

5. RESULTS

5.1 Flows and ϕ-distributions

ϕ-distributions from the specimen with different W_o/C are shown in FIG. 8. In the box on the upper side of the specimen a fan circulates the air above the specimen with a velocity of about 0.5 m/s. According to Nevander and Elmarsson /3/ the flow from the specimen can be written

$$g = \beta \cdot (\phi_{surface} - \phi_{air}) \cdot v_s \qquad (4)$$

which gives

$$\phi_{surface} = g/\beta/v_s + \phi_{air} \qquad (5)$$

Maximum g is about $300 \cdot 10^{-9}$ kg m^{-2} s^{-1}.
β is about $5 \cdot 10^{-3}$ m s^{-1} when the air velocity is 0.5 m s^{-1}
$v_s = 17.28 \cdot 10^{-3}$ kg m^{-3} at 20°C
ϕ_{air} is 0.33
$\phi_{surface} = 0.333 = 33.3$ %

The top surface has about the same ϕ as the air.

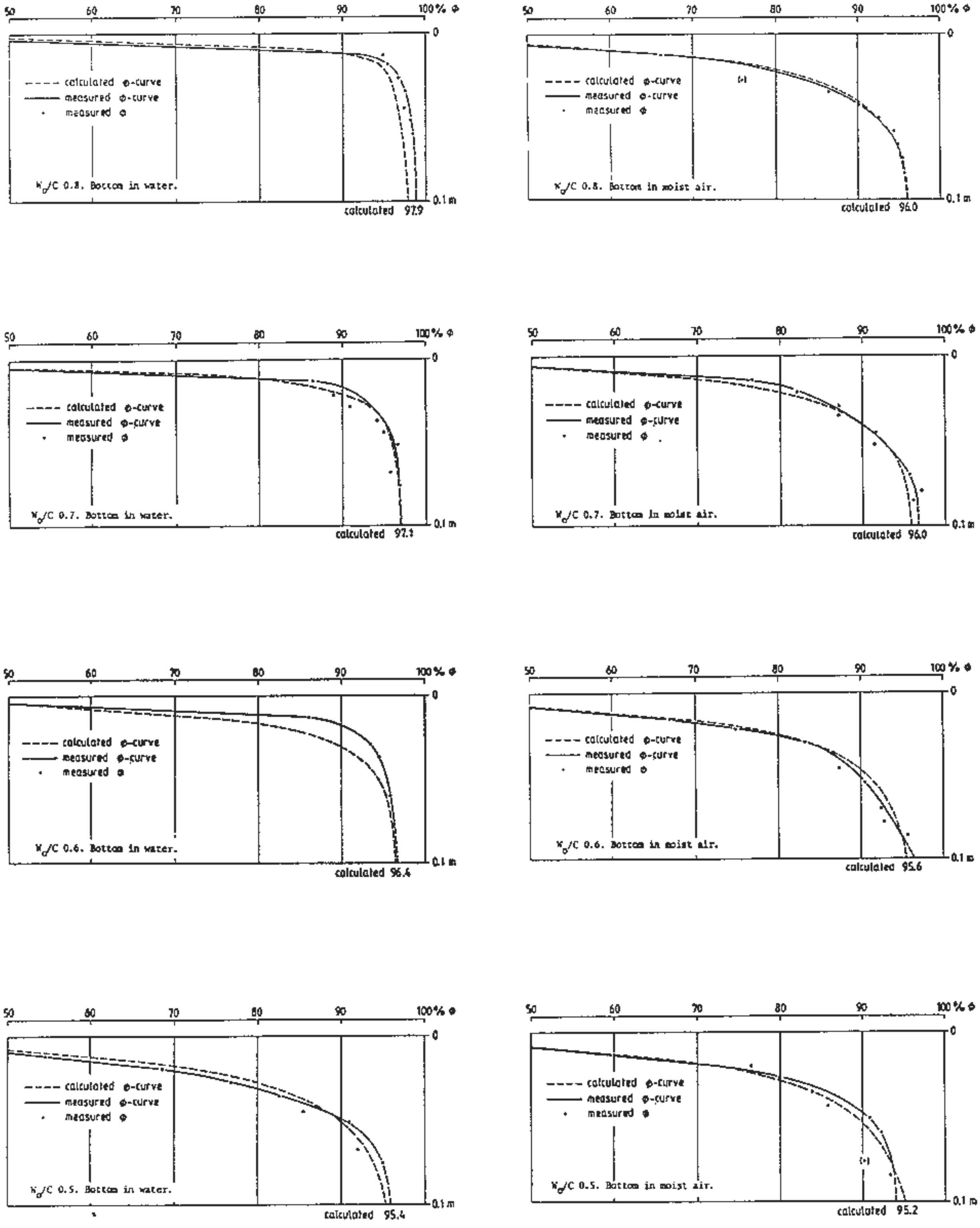

FIG. 8. Distributions of the relative humidity in specimens with a height of 0.10 m.

For most of the specimens we can see that the measured and the calculated ϕ-distributions are nearly the same. In the calculated ϕ-distributions the flows are assumed to be correctly measured and the calculated flows are the same as the measured flows. For the calculated ϕ-distributions see mean value TABLE 7.

As can be see in FIG. 8 the relative humidities in the bottom side of the specimens that stand in water are probably lower than 100 %. This can be explained by the fact that cement containing alkali metal compounds has a lower maximum ϕ than 100 %. TABLE 5 is taken from Hedenblad /4/.

TABLE 5. The relation between W_o/C and maximum ϕ in cement products at total hydration and membrane hardening.

W_o/C	Estimated max ϕ
0.8	98.4
0.7	98.0
0.6	97.6
0.5	97.0

In TABLE 6 the measured flows are shown as a function of W_o/C and of the circumstances at the bottom of the specimens.

TABLE 6. Flows from 0.1 m high specimens.

W_o/C	g from specimen where the bottom is in water kg m^{-2} s^{-1}	g from specimen where the bottom is in moist air kg m^{-2} s^{-1}	$g_{water}/g_{most\ air}$
0.5	$65 \cdot 10^{-9}$	$62 \cdot 10^{-9}$	1.05
0.6	$105 \cdot 10^{-9}$	$71 \cdot 10^{-9}$	1.48
0.7	$165 \cdot 10^{-9}$	$84 \cdot 10^{-9}$	1.96
0.8	$297 \cdot 10^{-9}$	$82 \cdot 10^{-9}$	3.62

As can be seen, the difference between the flows for W_o/C 0.5 is very small when the specimen stands in water or in moist air. And for W_o/C 0.8, the difference is only a factor of about 4. The flows for the specimens that stand in moist air is nearly the same for different W_o/C. This means that W_o/C have very little influence on the moisture flow if ϕ on the most moisty side is below about 95 %.

5.2. Evaluated moisture permeability.

Moisture permeability (δ_v) is evaluated according to chap. 4 and is shown in TABLE 7.

ϕ %	$\delta_v \cdot 10^6 (m^2/s)$									Coefficient of variation
	W_o/C 0.5		W_o/C 0.6		W_o/C 0.7		W_o/C 0.8		mean val.	
	bott. in water	bott. in moist air	bott. in water	bott. in moist air	bott. in water	bott. in moist air	bott. in water	bott. in moist air		
33-70	0.19	0.18		0.19				0.16	0.18	0.08
70	0.19	0.18		0.27				0.26	0.22	0.21
75	0.38	0.18		0.31				0.39	0.32	0.31
80	0.49	0.42		0.45		0.69		0.60	0.53	0.21
84	0.62	0.61		0.73		1.04		0.80	0.76	0.23
86	0.71	0.80		1.19		1.13		0.93	0.95	0.22
88	0.77	1.05	0.70	1.62	0.91	1.40		1.12	1.08	0.31
90	0.93	1.45	1.15	2.12	1.69	1.71		1.49	1.51	0.26
91	1.10		1.60	2.41	2.43	1.93		1.76	1.87	0.27
92	1.40		2.15	2.79	3.29	2.13		2.02	2.30	0.29
93	1.82		3.02	3.07	4.12	2.52	1.96	2.47	2.71	0.29
94	2.86		4.99	3.27	5.49	3.01	3.12	3.06	3.69	0.29
95	5.37		9.48		7.06		5.20		6.78	0.29
									estimated mean values	
96			23		14		9		23	
97							17		60	
98									130	
98.8									250	

The results in TABLE 7 clearly show that W_o/C have no infuence on δ_v up to about 95 % relative humidity. We still lack an explanation to such surprising results. The moisture permeability is not evaluated for higher ϕ than 95 %, because it is very difficult to evaluate the steep slopes of the ϕ-distribution curve. In the calculated ϕ-distribution curve δ_v are estimated above ϕ=95 %. The idea behind the estimated values above ϕ=95 % is that the largest pores in the cement paste, about 200-500 nm, are not filled with water until ϕ is near its maximum value. As long as the greatest pores are not filled with liquid water they slow down the water transport and when filled the water transport increases considerably. For concrete with high W_o/C is the volume largest pores higher than in concrete with low W_o/C, and consequently have higher δ_v when the pores are filled.

As in practice it is very difficult to measure small differences in ϕ so δ_v is assumed to be the same for different W_o/C when ϕ is equal. It is probably possible to measure maximum δ_v for different W_o/C with the help of specimens that allow water to be sucked capillaryly and measure the increase in weight.

δ_v and ϕ is adjusted until the calculated ϕ-distribution curve nearly fits the measured ϕ-distribution curve. The maximum ϕ at the bottom of the specimen is adjusted until the calculated flow is the same as the measured flow.
This gives maximum ϕ in the specimens according to TABLE 8.

TABLE 8. Maximum calculated ϕ in the specimens.

W_o/C	Bottom surface in		Maximum ϕ calculated	Maximum ϕ according to TABLE 5
	water	moist air		
0.5	x		95.4	97.0
		x	95.2	
0.6	x		96.4	97.6
		x	95.6	
0.7	x		97.1	98.0
		x	96.0	
0.8	x		97.9	98.4
		x	96.0	

5.2 Influence of W_o/C on the mean moisture permeability

The mean moisture permeability (δ_v^{mean}) has been calulated for the specimens that stand in water.

$$\delta_v^{mean} = g \cdot \frac{h}{v_s(1-0.33)} \qquad (6)$$

where h is the height of the specimen. 0.33 is ϕ at the top of the specimen. It is questionable whether δ_v^{mean} is the correct measure as most of the differences in the moisture flow are depending on what occurs above ϕ=95 %. But it is used since it is comparable with the results obtained by Nilsson /2/.

δ_v^{mean} are shown in FIG. 9 as a function of W_o/C.

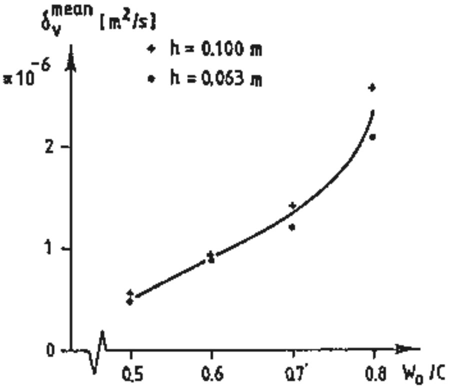

FIG. 9. Effect of water-cement ratio on mean moisture permeability.

FIG. 9 shows that the ratio between W_o/C 0.8 and W_o/C 0.5 is about 5. Nilsson /2/ has found about the same ratio for cement mortars with W_o/C 0.5 to 0.8. As seen in FIG. 9 specimens with h=0.063 m have a higher δ_v^{mean} than the specimens with h=0.100 m. One explanation can be that carbonation has occurred at the top surface of the specimens, giving lower δ_v at the surface. The carbonation depth for specimens with the same W_o/C is the same for the two heights and has a greater influence on specimens with h=0.063 m.

5.3 Influence of the air content on mean moisture permeability

In FIG. 10 δ_v^{mean} is shown as a function of the air content of the concrete.

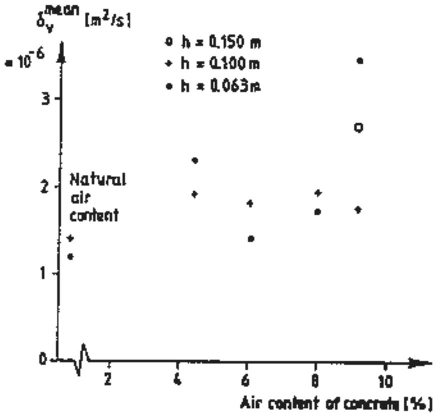

FIG. 10. Effect of air content of concrete on mean moisture permeability for concrete with W_o/C 0.7.

The scatter is great in FIG. 10, but it seems like higher air content gives higher δ_v^{mean}.

If δ_v^{mean} is drawn as a function of the air content of solely the cement paste FIG. 11 is obtained.

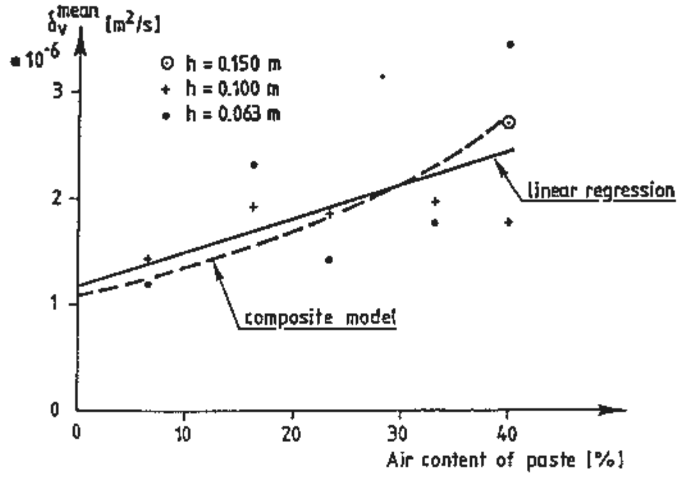

FIG. 11. Effect of air content of the "paste" on mean moisture permeability for concrete with W_o/C 0.7.

Even in FIG. 11 the scatter is great.

Hillerborg /5/ has proposed a simple composite model, that can be expressed in terms of moisture permeability for cement "paste", i.e. cement + water + air (δ_{vp})

$$\delta^n_{V,P} = (1-V) \cdot \delta^n_1 + V \cdot D^n \qquad (7)$$

δ_1 = moisture permeability for the "paste" excluding air

D = water vapour permeability of air

V = air content of "paste". $0 \leq V \leq 1$

n = a constant that depends on the ratio D/δ_1 $-0.5 \leq n \leq 0.5$

When $D/\delta_1 = 25 \cdot 10^{-6}/1.1 \cdot 10^{-6} = 25$ Hillerborg proposes that $n = -0.3$.

The composite model curve fits the linear regression curve very well.

Nilsson /2/ has found the same influence of the air content on moisture permeability of cement mortars. From the composite model, the conclusion can be drawn that the moisture flow finds its way through the air voids where the resistance for moisture flow is much less than in the "paste" excluding air.

5.4 Influence of the aggregate content on the mean moisture permeability

The effect of the aggregate content on δ_v^{mean} is shown in FIG. 12.

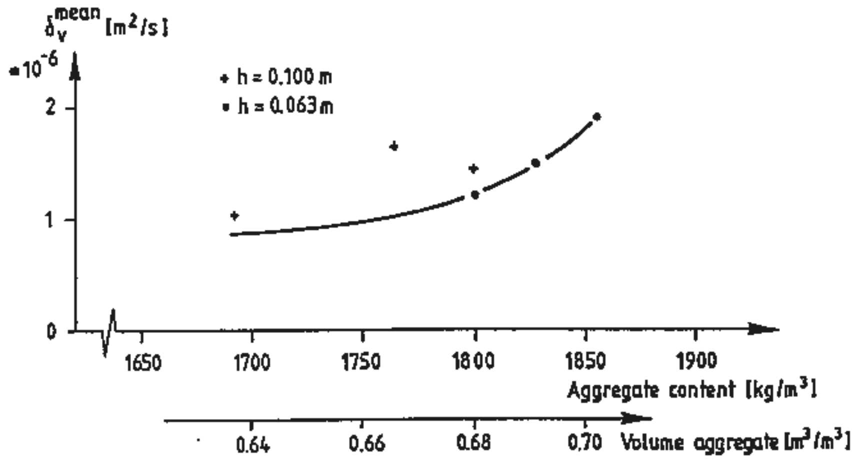

FIG. 12. Effect of the aggregate content on the mean moisture permeability for concrete with W_o/C 0.7.

If it is assumed that the permeability for the aggregate is zero, then according to the composite model δ_v^{mean} should decrease when the aggregate content increases. FIG. 12 shows that δ_v^{mean} is the same or increases when the aggregate content is increased. An explanation is that the boundary zone between "paste" and aggregate increase and the resistance to water flow in the boundary zone is low.

6. SOME PRACTICAL APPLICATIONS

If we restrict ourselves to

- the stationary case
- isothermal conditions
- no hysteresis

with "no hysteresis" is meant that the possible differences in δ_v, which depends on whether the material is under absorption or desorption, are neglected.

Eq. (2) can then be written

$$g \cdot h = v_s \int_{\phi_{ref}}^{\phi_1} \delta_v \cdot \partial\phi \qquad (8)$$

Between two ϕ-borders is $v_s \int \delta_v \cdot \partial\phi$ constant and equal to $g \cdot h$, see FIG. 13. A doubling of the thickness gives half the flow.

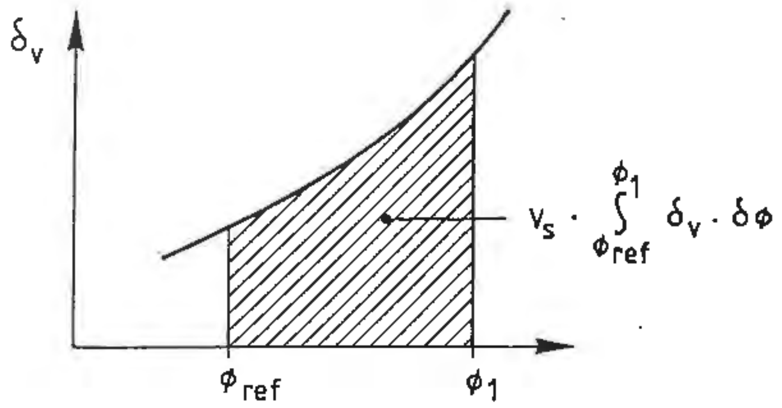

FIG. 13 . The area under δ_v-curve is constant between two ϕ-borders.

Example 1:
How large is the moisture flow through a concrete slab with $W_o/C=0.5$, if the slab is 200mm and its upper side is in 50 % relative humidity (ϕ) and ϕ=85 % at its bottom side?

The material data is given for a 100 mm thick slab where ϕ at its upper side is 33 % and the bottom side is in water.

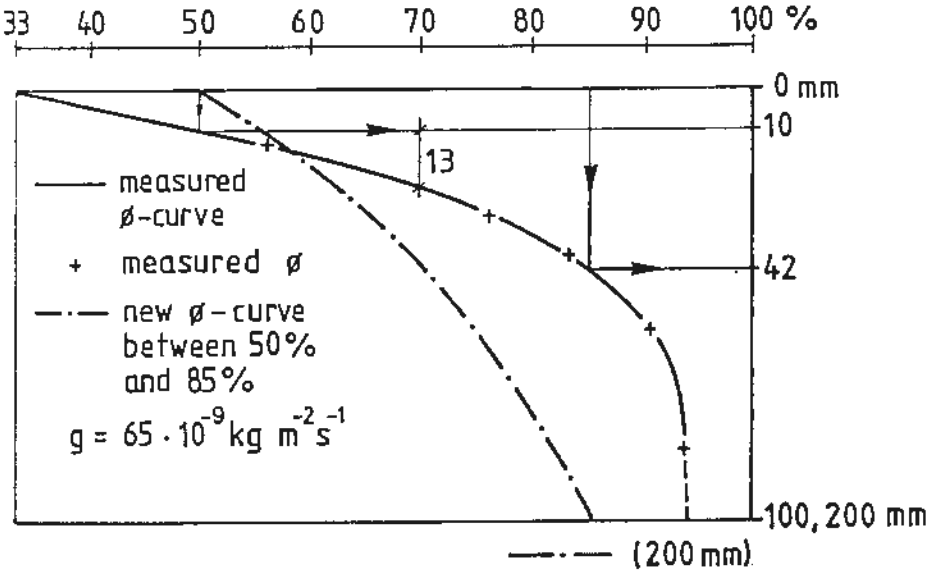

FIG. 14. Distribution of ϕ in example 1.

Measured moisture flow for the 100 mm thick slab is $65 \cdot 10^{-9}$ kg $m^{-2}s^{-1}$.

In FIG. 14 it is read that ϕ=50 % is at 10 mm depth and ϕ= 85 % is at 42 mm depth in the measured curve.

Eq. (8) gives $g_1 \cdot L_1 = g_2 \cdot L_2$ when the ϕ-boarders are equal.
L_1=42-10=32 mm

$65 \cdot 10^{-9} \cdot 32 = g_2 \cdot 200 \Rightarrow g_2 = 10.4 \cdot 10^{-9}$ kg $m^{-2}s^{-1}$

The ϕ-curve between 50 and 85 % is scaled with the factor 200/32=6.25

As an example, in the distribution curve one gets that the distance between 50 % and 70 % is 13 mm. New distances between 50 and 70 % in the 200 mm thick slab is 13·6.25=81 mm.

Example 2:
Another practical application is to estimate the influence on ϕ in a house if there is no water barrier between the slab and the ground or the slab stands in water. A house with an area of 100 m^2 and a volume (V) of 250 m^3 and the bottom of the 100 mm slab is in water. How much does ϕ increase? The air change rate of the building (n) is 0.5(AC/h). W_o/C=0.8.

If we assume that ϕ on top of the slab is about 33 %, TABLE 6 gives the flow of about 300 x 10^{-9} kg $m^{-2}s^{-1}$.

From /3/ the increase in v (Δv) is written

$$\Delta v = G \cdot n^{-1} V^{-1} \qquad (9)$$

G is the moisture production (kg s^{-1})

$G = 300 \cdot 10^{-9} \cdot 100 = 30 \cdot 10^{-6}$ (kg s^{-1})

$\Delta v = 30 \cdot 10^{-6}/0.5 \cdot 3600/250 = 0.86 \cdot 10^{-3}\ kg/m^3$

$\Delta\phi \approx 0.86 \cdot 10^{-3}/17.3 \cdot 10^{-3} = 0.05 = 5\ \%$

Of course the slab on the ground should be dry but when there is mould growth high up on the walls and on the ceiling then the wet slab on the ground is probably not the main reason for the mould growth.

7. CONCLUSIONS

The reported moisture permeability shows that it is dependent on the relative humidity. For relative humidity up to about 95 % the results clearly show that W_o/C have no influence on δ_v. We still lack an explanation to such surprising results. The maximum δ_v and the maximum ϕ depends on W_o/C.

The flows that are reported from the specimens that stand with their bottom in water and the top surface in 33 % relative humidity are much lower than earlier calculated. One practical result is that it is easy to calculate the influence on the relative humidity in a house if the slab on ground has no water barrier between the slab and the ground or the slab stands in water.

8. ACKNOWLEDGEMENTS

Financial support for this project was provided by the Swedish Council for Building Research to the Moisture Research Group at Lund Institute of Technology.

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