AIR-PERMEABILITY OF CONCRETE

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An apparatus for defining the air permeability of concrete is described and the air permeability of concrete is defined by measuring the volume flow rate of air through the samples with the apparatus. The specific permeation coefficient D_s of concrete is calculated on the basis of the measured air volume. Eleven different types of concrete and the pressures of 1, 3 and 5 bar were examined at the tests. Other variables were temperature, the length of the sample and the age of the concrete.

Concrete has no unambiguous value of air permeability. The values of the specific permeation coefficient which appeared at measurement are set in a wide range: $10^{-16} ... 10^{-19}$ m^2.

Keywords: air-permeability; massiv structures; porosity; test method

1. INTRODUCTION

The air permeability of the porous materials depends largely on the porosity as well as on the chemical and mineralogical composition of the material. The moisture content has also strong effect upon the permeability of concrete /1-7/. On the other hand the moisture content depends on both the external conditions and the age of concrete.

In conditions where the humidity moving from environment to concrete and vice versa has been eliminated the moisture content of concrete can be maintained relatively constant if the concrete is old enough. The inner parts of massive concrete constructions can be considered to keep such relatively constant humidity although the degree of hydration is increasing in the inner parts for years. So the factors that effect strongly upon the permeability are the total porosity of concrete and the continuance of the pore network.

The total porosity of the concrete consists of gel pores, capillary pores and air-voids. The products of hydration taking place in cement are gel, which is composed of very fine colloidal and microcrystalline particles of matter. Between the gel particles there are gel pores, the size of which is estimated to be approximately 1,5...2,0 nm on an average / 8 /.

Unfilled spaces between aggregations of gel particles are capillary pores, and are formed by uncombined water in excess of that required for hydration of the cement. The size of capillary pores has been estimated to be of the order of 1,25 µm / 8 /, but they actually include a wide variety of sizes and shapes. They can be considered to vary from about 0,01 µm to 13 µm in diameter. The total volume of pores depending upon the original water-cement ratio and the degree of hydration of the cement.

In addition to the gel pores and capillaries there are air-voids in concrete. The size of the air-voids varies from about 10 µm to about 2 mm. Their volume and size depending upon including grading and maximum size of aggregate, concrete consistency, type of compaction, and so on.

According to the researches /1,3,7/ the gas permeability of concrete has been considered as a flow in capillary pores. The mean free path of most gas molecules is of the order of 50...100 nm at normal temperature and pressure, varying directly with absolute temperature and inversaly with pressure / 1 /.

A formula for the gas permeability has been derived from the research of the capillaries / 1,7 /.

(1) $$D_s = \frac{\eta \cdot l \cdot \Phi}{A \cdot \Delta p}$$

where
D_s = specific permeation coefficient, m^2
η = viscosity of the flowing gas, Ns/m^2
l = length of specimen, m
Φ = volume flow rate, m^3/s
A = area of specimen, m^2
Δp = pressure difference, N/m^2

The permeation coefficient Ds can be defined by measuring the gas volume flowing in unit time through the sample with known dimensions and knowing the pressure difference as well as the viscosity of the flowing gas.

2. MEASURING THE VOLUME FLOW RATE

For the measuring of the volume flow rate of air going through the concrete the apparatus (Fig. 1) was built up. The apparatus consists of three separate sample containers. Compressive air can be let into the other end of every container with desired pressure. The air volume passing through the sample can be measured either in the capillary tubes or in the measuring glasses turned upside down.

The sample containers of steel were built to be able to measure cylindrical specimens of 150 mm diameter and 60 to 100 mm thickness. The hollow between the specimen and steel was made airtight with bitumen. In addition two gasket rings of rubber were used (Fig. 1).

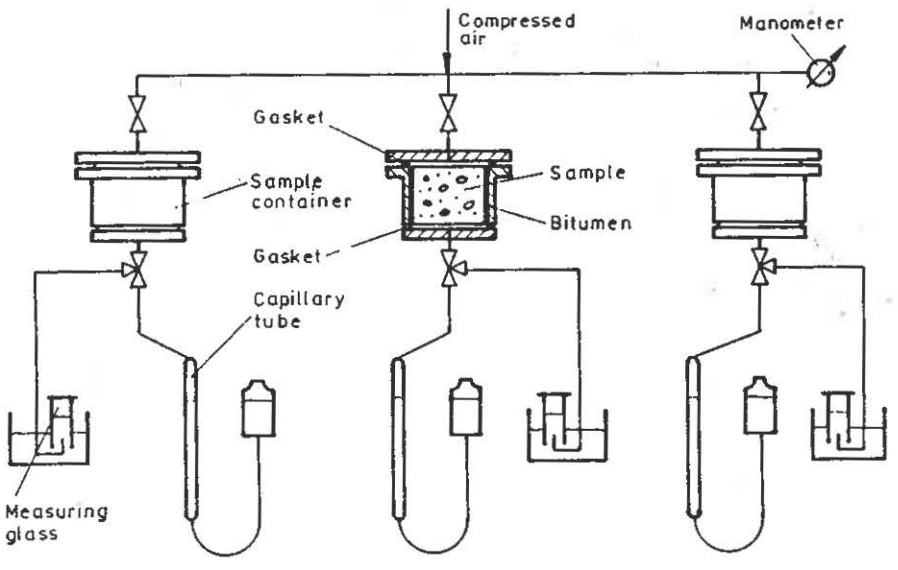

FIG. 1. Apparatus for measuring the volume flow rate.

3. EXPERIMENTAL PROCEDURE

3.1 Background of the study

All the tests performed were associated with the more extensive examination, whose purpose was to clear up whether the concrete containment without steel liner is applicable to a nuclear power station. The containment of this kind usually have relatively large dimensions. The thicknesses of the containments are mostly between 0,5...1,0 m, wherefore they can be considered massiv concrete constructions thinking of concrete technology.

In the central parts of the massive constructions the movements of huminity are relatively small when the concrete is old enough. Therefore the influence of the moisture content of concrete was not included in the study. Instead of that the curing conditions of the tested specimens were tried to make the same as they are in the centre of massiv concrete. So all the samples had plastic sheeting curing.

The tests were performed in three periods. First the permeability of concrete to air was studied with different pressures, temperatures, and with different length of test samples. The influence of the age of concrete was studied, too.

In the second period it was studied, whether the steel bars and collars going through the concrete have effect upon the air permeability of concrete and whether the air tightness of concrete can be increased by painting. In addition tests were performed with the samples including construction joints and cracks, too.

Also in the third period the paints were studied. Furthermore tests were performed with the different types of cement. In addition the air permeability of concrete was studied with the samples which were loaded by static loads of a different size.

3.2 Types of concrete

The composition of the concretes used in the test are presented in Table 1.

3.3 Test specimens

Concrete slabs of different sizes were prepared for the tests according to Table 2. The curing condition of the slabs was a plastic sheeting curing. At the earliest of the age of 28 days the test samples were drilled from the slabs. The diameter of the drilling samples was 150 mm. They had a plastic sheeting curing till the beginning of the testing time.

The samples drilled from the slabs with thicknesses of 120 or 80 mm were cut with a saw to the length of 100 or 60 mm before testing.

TABLE 1. Types of Concrete

Concrete	A	B	C	D	Ia	Ib	IIa	IIb	IIc	IId	III
Cementtype 1)	OP	OP	OP	OP	OP	OP	OP	OP	LH	LH	OP
Cement kg/m^3	330	318	332	249	263	264	253	240	253	240	265
Admixture 2)	-	P	SP	-	P	P	-	P	-	P	-
Aggregate kg/m^3	1914	1941	1924	2029	1912	1919	1967	1978	1946	1979	1961
Max.size of aggregate mm	32	32	32	32	16	16	16	16	16	16	16
Water kg/m^3	185	178	186	174	180	181	171	168	178	168	177
Water-cement ratio	0,56	0,56	0,56	0,70	0,68	0,69	0,70	0,70	0,70	0,70	0,67
Fresh concrete:											
Air content l/m^3	12	11	11	12	30	26	15	22	19	23	13
Consistency/slump mm	95	120	150	95	130	130	84	70	90	60	76
Density kg/m^3	2430	2440	2440	2450	2360	2380	2410	2400	2410	2390	2420
Compressive strength: 28 d	47,8	47,3	42,5	33,5	28,5	31,5	31,0	28,3	23,8	23,8	32,8
(MN/m^2) 91 d	56,3	56,2	50,7	-	36,0	39,5	37,0	35,3	34,8	31,8	38,0

1) OP = Ordinary Portland cement
   LH = Low heat Portland cement
2) P = Plasticiser
   SP = Super plasticiser

TABLE 2. Concrete slabs

Types of concrete	Slabs Size (mm x mm x mm)	Number of the slabs	Remarks
A, B, C	500 x 500 x 120	3	
A, B, C	500 x 500 x 80	1	
D	670 x 500 x 1002	1	1)
D	2 x (100 x 240 x 670)	1	2)
D	2 x (240 x 670 x 100)	1	3)
Ia	500 x 180 x 670	4	
Ib	500 x 180 x 670	1	
IIa, IIb, IIc, IId	500 x 100 x 670	1	
III	700 x 900 x 100	1	

1) Incl. installed steel bars (Fig. 2)
2) Incl. vertical construction joint
3) Incl. horizontal construction joint

One of the slabs made from concrete D was equiped with steel bars and collars going through the slab. The samples for the tests were drilled so that the steel bars and collars were situated in the middle of the samples (Fig. 2).

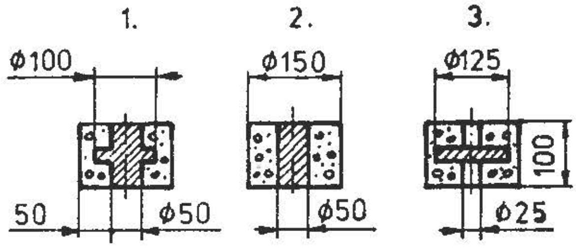

FIG. 2. Samples incl. installation of steel.

Inside the sample 1 (Fig.2) there was a steel bar of 50 mm diameter and a collar of steel was joined the middle part of the bar by welding. The diameter of the collar was 100 mm and its thickness was 5 mm. Through the sample 2 (Fig. 2) went a steel bar of 50 mm diameter. In the middle of the sample 3 (Fig. 2) there was a steel collar of 125 mm diameter and of 5 mm thickness. A hole of 25 mm diameter went through the concrete from each side of the sample to the collar.

The other two slabs of the concrete D were made in two parts in order to get both vertical and horizontal construction joints. The interval of concreting was one day. For the tests the samples were drilled so that construction joints were passing through the samples.

The slabs made of the concrete Ia were first grooved with a drill and after that the slabs were painted. Later on the samples were drilled out from the slabs along the grooves without destroying the painting.

3.4 Measuring method

All the tests, except those made with the static loaded samples, were performed with the apparatus presented in Fig. 1. The volume of air flowing through the sample in unit time was measured. For the measurings the air passing through the sample was let to the capillary tubes four times a day. The interval between the measurings was two hours. During the intervals the air was collected into the measuring glasses. The measurings were performed during two or three days.

3.5 Period I

3.5.1 Test details

Test details are presented in Table 3.

TABLE 3. Test details

Size of the samples (diam.xlength) mm	Number of the samples	Air pressure bar	Temperature °C	Age of the samples (d)	
				Concrete A	Concrete B
150 x 100	3	1	20	39	63
"	3	3	20	49	66
"	3	5	20	53	71
150 x 100	3	1	80	57	77
"	3	3	80	62	84
"	3	5	80	65	92
150 x 60	3	1	20/80	105/107	119/121
"	3	3	20/80	112/114	127/129
"	3	5	20/80	120/122	134/134
150 x 100	3	1	20	220	230
"	3	5	20	226	219

The samples of 60 mm in length were first at a temperature of 20 °C. After two days the temperature was increased to 80 °C.

3.5.3 Results

Concrete A: When using working pressure of 1 bar at the temperature of 20 °C there could be seen no measureable volume flow rate through the samples when the length of the samples was 100 mm. It was the same with one sample when the pressure was 3 bar. The ages of the samples were 39 and 49 days. When the age of the concrete was 220 days there was one impermeable sample at the 1 bar pressure. When the temperature was 80 °C two of the samples of 100 mm in length were impermeable at the pressure of both 1 and 3 bar.

The mean values of the measured volume flow rate are presented in Figs. 3...6.

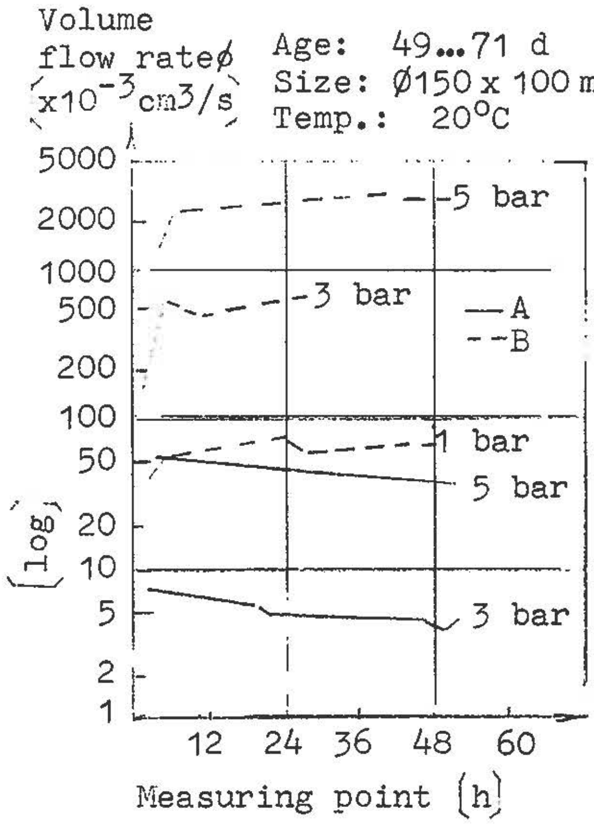

FIG. 3.

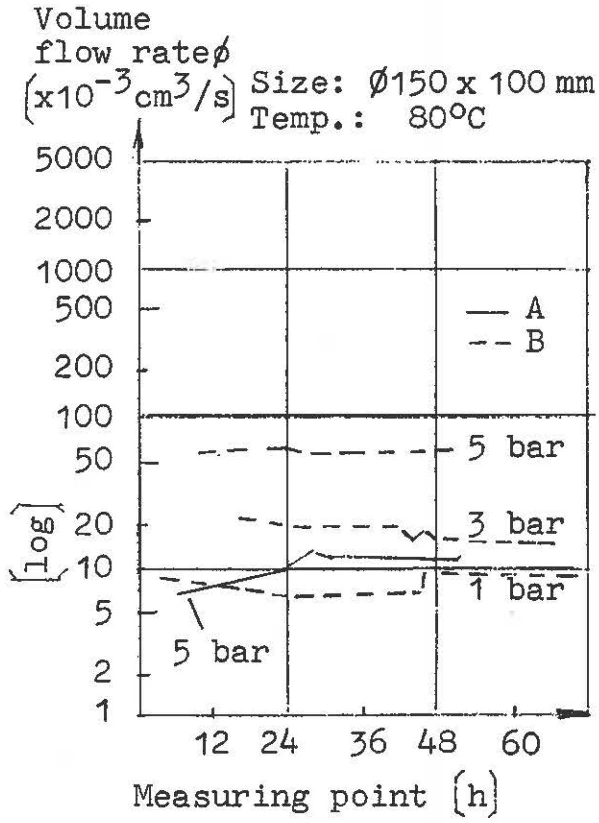

FIG. 4.

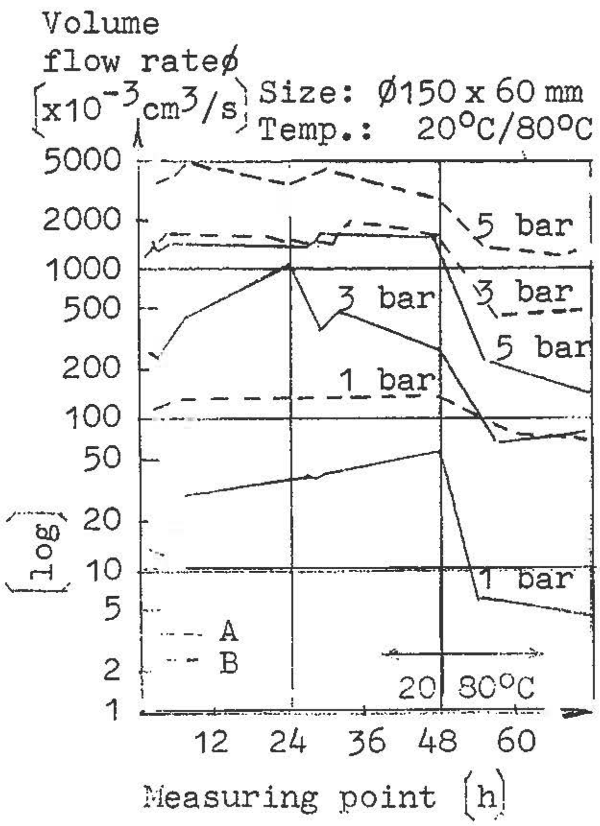

FIG. 5.

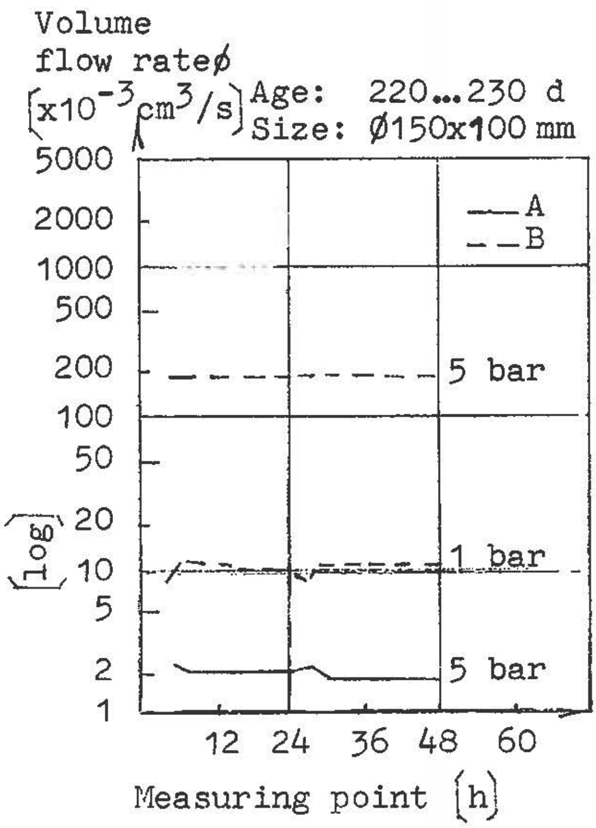

FIG. 6.

Volume flow rate at different pressures.

3.6 Period II

3.6.1 Test details

Test details are presented in Table 4.

TABLE 4. Test details

Air pressure: 5 bar
Temperature: 20 °C

Type of concrete	Size of the samples (diam.xlength) mm	Number of the samples	Age of the samples (d)	Remarks
C	150 x 100	3	255	
"	"	"	259	Paint 1
"	"	"	308	"
"	"	"	264	Paint 2
"	"	"	316	"
C	150 x 60	3	276	
"	"	"	270	Paint 1
C	150 x 100	3	290	Incl. cracks
"	"	"	291	Cracks filled by resin
"	"	"	283	Incl. cracks
"	"	"	284	Cracks filled by the paint 1
D	150 x 100	3	96	
"	"	"	54	Model 1 (Fig. 2)
"	"	"	82	Model 2 (Fig. 2)
"	"	"	89	Model 3 (Fig. 2)
D	150 x 100	3	134	Vertical constr.joint
"	"	"	146	Vertical constr.joint + Paint 2
"	"	"	149	Horiz. constr. joint
"	"	"	155	Horiz. constr. joint + Paint 2

A part of the samples drilled out of the slabs were painted with paint based on epoxi. Painting was performed by hand and only at the end which was against the air pressure. Two different paints were used. The thickness of the painting film was about 0,5 mm on an average.

Part of the samples were cracked by loading them as in the splitting test of concrete. Afterwards the cracks were filled with epoxi resin. Paint was also used to fill in the cracks of some samples, but only the cracks which were at the pressure end. The whole end was painted, too. Also the part of the samples which included construction joints were painted.

3.6.2 Results

Three of the samples painted with both paint 1 and paint 2 were impermeable. The length of the samples was 100 mm.

The samples including the cracks had no air tightness. After filling in the cracks with epoxi resin the volume flow rate was as in the other samples of concrete C. All the cracked samples which had been filled in with paint and painted were impermeable.

All the samples including steel bar without collar (Fig. 2, Model 2) had holes on the bonding surface between steel and concrete. After filling in the holes with epoxi resin the volume of the rate was, however, bigger than that of the samples of concrete D.

The measured volume flow rates are presented in Figs. 7...10.

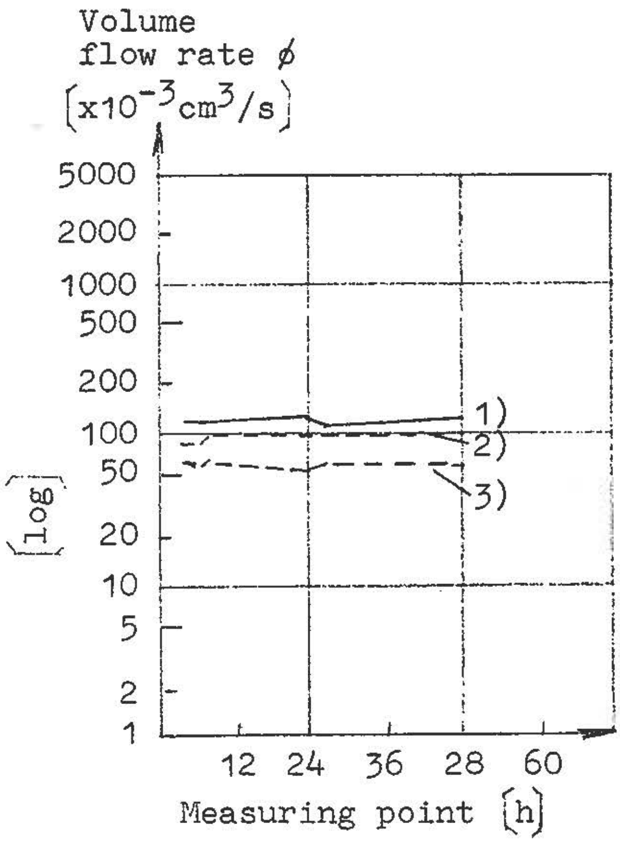

FIG. 7. Volume flow rate of the painted samples.

1) Unpainted
2) Paint 2
3) Paint 1

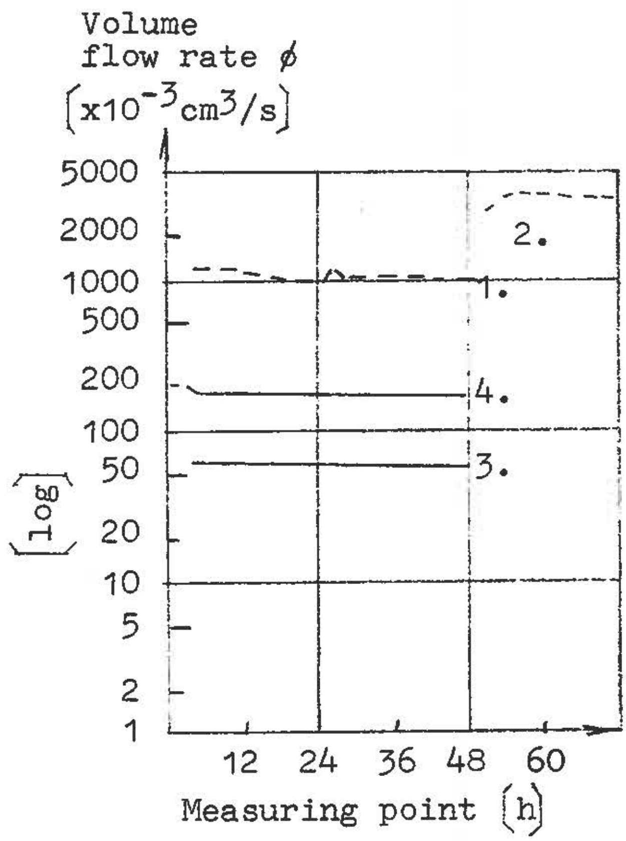

FIG. 8. Volume flow rate of the samples incl. steels (Fig. 2).

1. Model 1.
2. Model 2. (after inj.)
3. Model 3.
4. Concrete without steels.

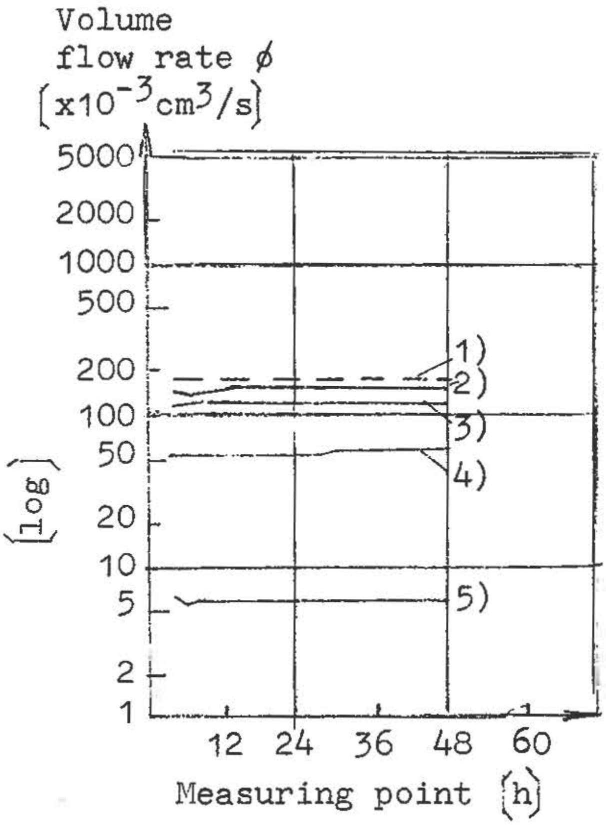

FIG. 9. Volume flow rate of the samples incl. construction joints.

1) Concrete without constr. joints
2) Vertical constr. joints
3) " " " + Paint 2
4) Horizontal constr.joints
5) " " " + Paint 2

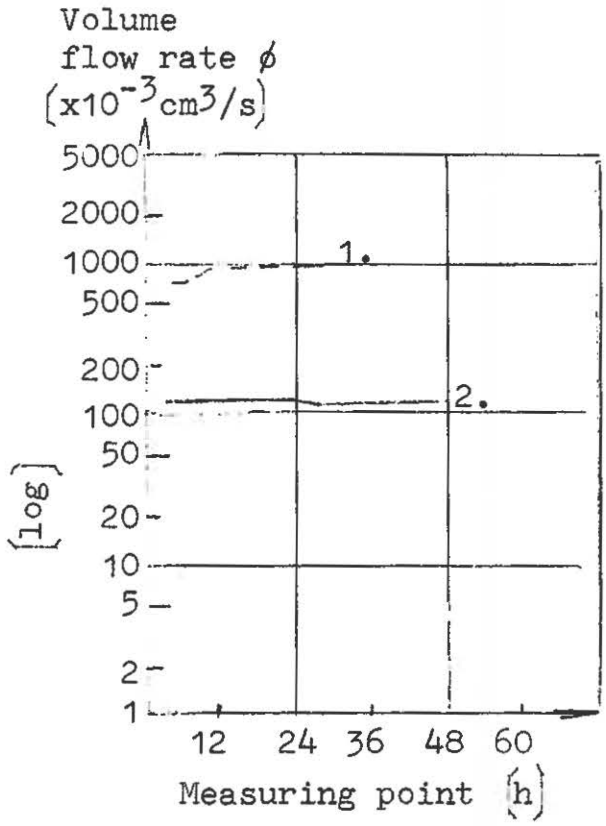

FIG. 10. Volume flow rate of concrete after injection.

1. Cracked concrete after injection
2. Uncracked concrete

3.7 Period III

3.7.1 Test details

Test details are presented in Table 5.

The paintings were made with high pressure spray gun.

The hollow cylinder samples were tested by loading them with static load. When the load had been placed on the samples a pressure of 5 bar was let into the cylinder. After that the decreasing of the pressure was measured in the cylinder (Fig. 11).

TABLE 5. Test details

Air pressure: 5 bar

Temperature: 20 °C

Size of the samples: Ø 150 x 100 mm

Type of concrete	Number of the samples	Age of the samples (d)	Remarks
Ia	3	74...148	
"	6	81...158	Paint 1 (Film thickness about 350 µm)
"	6	74...158	Paint 1 (Film thickness about 500 µm)
"	6	74...159	Paint 2 (Film thickness about 400 µm)
Ib	3	92...148	
IIa	6	106...210	Ordinary Portland cement
IIb	6	105...209	" " "
IIc	6	104...188	Low heat Portland cement
IId	6	111...188	" " " "
III	6	48...116	
"	4	65...122	Hollow samples(Ø200/100x100)

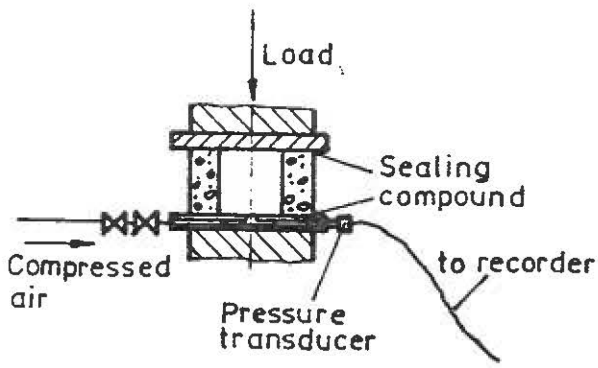

FIG. 11. Measuring method for hollow cylinders.

The loading was performed so that the first stress in the concrete was 0,3 MPa, then 3,0 MPa, then 9 MPa and the last one 15 MPa. After that the load was decreased in reverse order. Some samples were tested two times successively.

3.7.2 Results

The samples painted with the paint 2 were impermeable with one exception.

One sample with film 500 µm and two samples with film 350 µm were impermeable.

The measured volume flow rates are presented in Figs. 12 and 13.

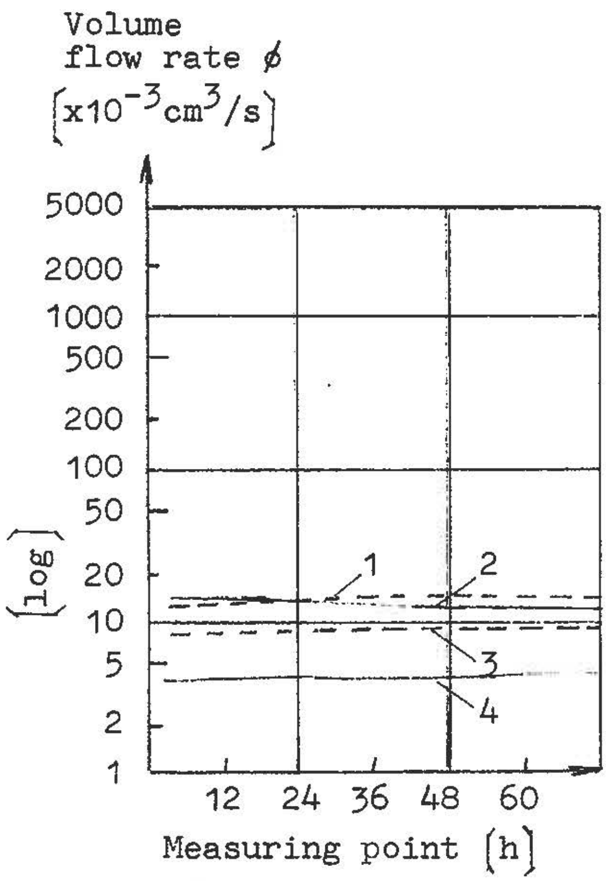

FIG. 12. Volume flow rate of the painted samples.

1. Paint 1 350 µm
2. Concrete Ia (unpainted)
3. Paint 1 500 µm
4. Concrete Ib (unpainted)

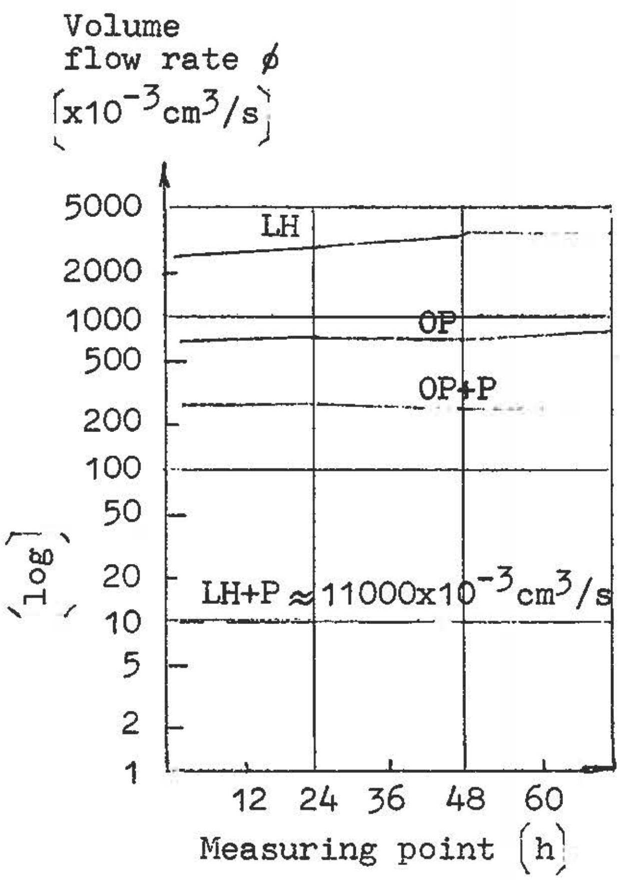

FIG. 13. Volume flow rate of different cements.

OP = Ordinary Portland cement
OP+P = -"- + Plasticiser
LH = Low heat Portland cement
LH+P = -"- + Plasticiser

4. SPECIFIC PERMEATION COEFFICIENT D_s

According to eq.(1) the calculated values of the specific permeation coefficient are set between the values 10^{-16}... 10^{-19} m^2. In the Fig. 14 there are collected the values measured with the samples of the concretes without admixtures and in the Fig. 15 there are presented those values measured from the concretes containing admixtures. The temperature has been 20 °C and the samples including painting, cracks, steel bars and collars are excluded. The cement used in the concretes has been ordinary Portland cement.

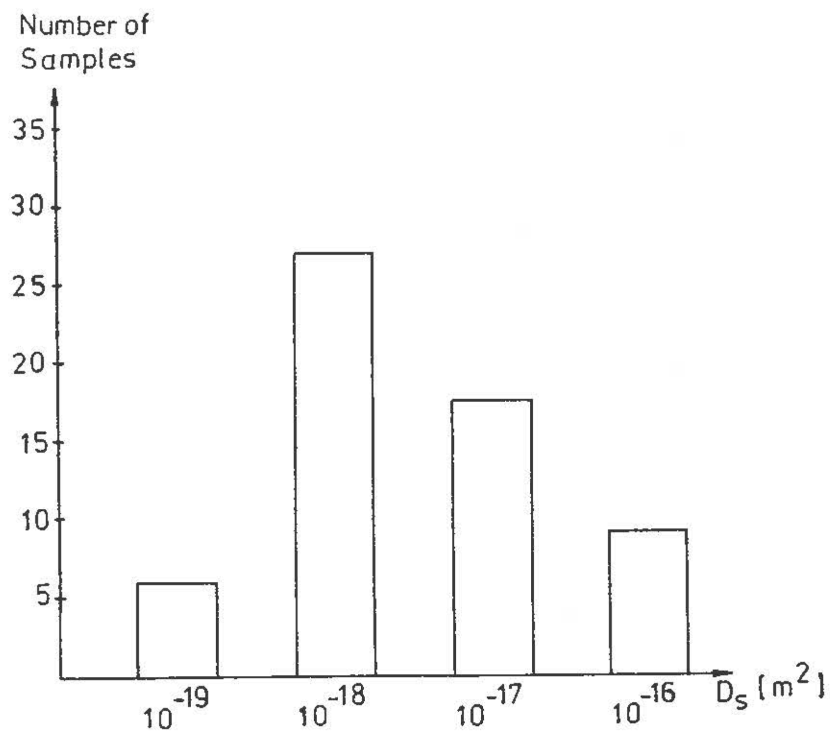

FIG. 14. Specific permeation coefficient of the concrete without admixtures.

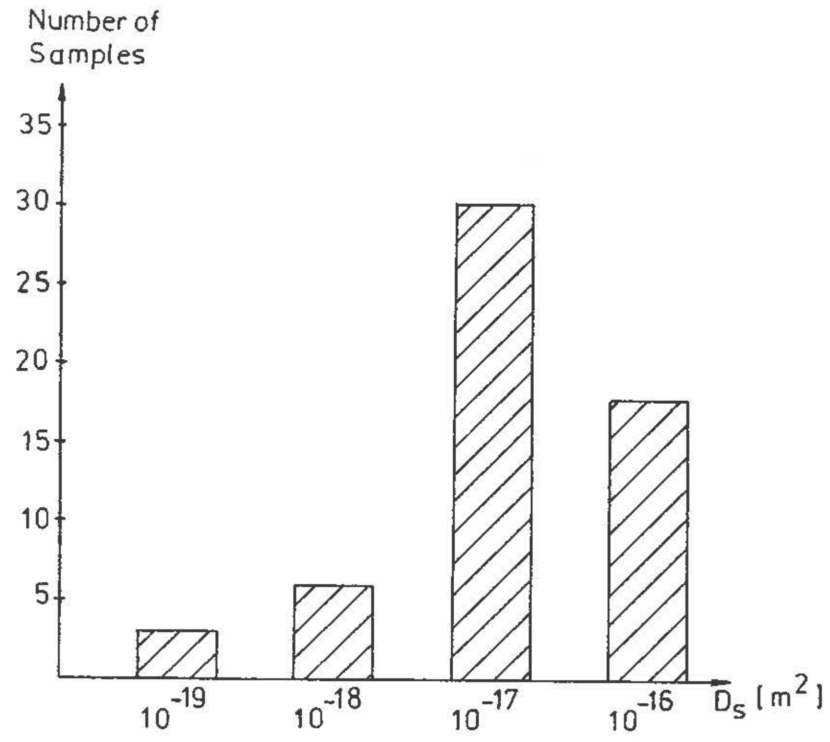

FIG. 15. Specific permeation coefficient of the concrete with admixtures.

5. DISCUSSION

D_s-values of the separate samples made from the same concrete may differ from each other even tenfold. Because of such a great deviation only those factors which make the values of D_s vary more than that can be regarded significant.

It seems that the low heat cement has a little greater perme-permeation than the ordinary portland cement. This may be caused by the different specific surface of the cements.

The influence of the composition of the tested concrete (cement: 250...330 kg/m^3, w/c ratio 0,56...0,70) upon the air permeation is not significant.

In the concretes with admixtures the air permeation has been a little greater than in the concretes without admixtures. Thus the admixtures used in test may have changed the structure of porosity in concrete into more disadvantageous.

With the increase of the age of concrete from about 60...90 d to about 200 d the air permeation has been decreased. This may be influenced most intensively by the increase of the hydration rate of the samples which have been in plastic sheeting curing.

The specific permeation coefficient according to eq.1 is as a matter of fact depending only on the porosity of material. On the basis of the results, however, both the length of the sample and the working pressure have a little influence on the value of D_s. With the larger samples and with the small working pressure the air permeation seems to be a little smaller. These factors have influence upon another factor, too, namely time-lag (that is the time needed until the air comes out from the outgoing side of the sample). The shorter samples and the greater pressure the shorter the time-lag is. With the samples of 100 mm in length the time-lag has been 1...4 hour on an average and with the samples of 60 mm in length only a few seconds.

Neither does the permeation depend on temperature, if the thermal expansion is neglected. The measurable volume flow rate decreases with increasing viscosity according to eq.1.

The steel bars without the collars going through the concrete may decrease essentially the air tightness of the structure because the bleeding causes hollows for air especially on the under sides of the steel bars. By injecting the hollows of this kind and the cracks, too, the same air tightness can be gained as in unbroken concrete.

The construction joints made with care cannot have influence on the air permeations of concrete.

The air tightness of concrete can be increased with paints. Though a great part of the painted samples were impermeable the absolute air tighness was not gained, however.

The stresses caused by different static loadings cannot have any influence on the air tighness of concrete.

6. CONCLUSIONS

The values of specific permeation coefficient of concrete vary between $10^{-16} \ldots 10^{-19}\,m^2$. The coefficient cannot be considered to have any exact numerical value or a certain range of variation which is considerably great. The deviation that mainly appears in the concrete itself has the greatest influence upon the largeness of the variation range. In addition the pressure used to measure the volume flow rate, the temperature and the length of the samples have influence on the values of D_s.

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