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Water permeability of fly ash concretes

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The water permeability of two series of concretes made with one type of fly ash and two types of Portland cement (OPC and SRPC) was tested by the method prescribed by DIN 1048. It is concluded that the cementing efficiency factor of the fly ash with respect to water permeability is approximately 0.3, independent of type of cement and curing time (28 days and 56 days). In practical terms this means that 1 kg of cement would have to be replaced by approximately 3 kg of fly ash in order to maintain the same watertightness of the hardened fly ash concretes. Thus, addition of fly ash is not likely to improve the watertightness of concrete.

1. INTRODUCTION

Results from earlier studies on the watertightness of fly ash concretes have been reviewed by Helmuth [1] and others. Although most researchers agree that the addition of fly ash to ordinary concrete somewhat reduces the water permeability of hardened concretes, little is known about the magnitude of this reduction.

In order to investigate this matter the present authors have carried out a systematic experimental study of the water permeability of two series of concretes made with one type of fly ash and two different types of Portland cement (OPC and SRPC). In both series the water permeability was measured according to the method prescribed by DIN 1048, after 28 days of standard curing in water at 20°C, and for one series the water permeability was also tested after 56 days of standard curing.

2. THEORY

Assuming that Darcy's law applies for stationary, laminar flow of liquid water through circular pores in hardened concrete, it can be expected that the following equation will apply for transport of water in a concrete specimen which is exposed to one-sided water pressure over a given period of time:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \Phi \frac{h}{x} \qquad (1)$$

where x = depth of water penetration from that side of the specimen which is submitted to pressure (m), t = time (s), h = external water pressure (m) and Φ = coefficient of water permeability (m s^{-1}). Integrating Equation 1 from the time 0 when water pressure is first applied, to the time t at which the depth of penetration x_t is measured, we obtain

$$x_t = (2\Phi h t)^{1/2} \qquad (2)$$

Solving for Φ we obtain

$$\Phi = \left(\frac{x_t}{(2ht)^{1/2}}\right)^2 \qquad (3)$$

on the basis of which the coefficient of water permeability of concrete can be calculated, when h is constant and x_t is measured at time t.

3. EXPERIMENTAL PROCEDURE

3.1 Experimental design

The main purpose of the current investigation has been to compare the water permeability of fly ash concretes which were produced with different fly ash/water and cement/water ratios, when such ratios were varied in a systematic manner. Two series of concretes were produced, as shown in Table 1. Series 1 was tested for compressive strength and watertightness after 28 and 56 days of standard curing in water at 20°C. Series 2 was only tested after 28 days of standard curing.

Table 1 Series of concrete tested in the current investigation

Type	Series 1	Series 2
Cement	SRPC	OPC
Fly ash	Asnæs	Asnæs

SRPC = Sulphate-resistant Portland cement; OPC = ordinary Portland cement.

3.2 Equipment

Fig. 1 illustrates the basic principle of the standard method for the testing of watertightness of hardened concrete according to German Standard DIN 1048 [2]. When testing the specimens, the following procedure is used:

(a) The tops of 12 cm × 20 cm × 20 cm hardened concrete test specimens are carefully brushed with a steel

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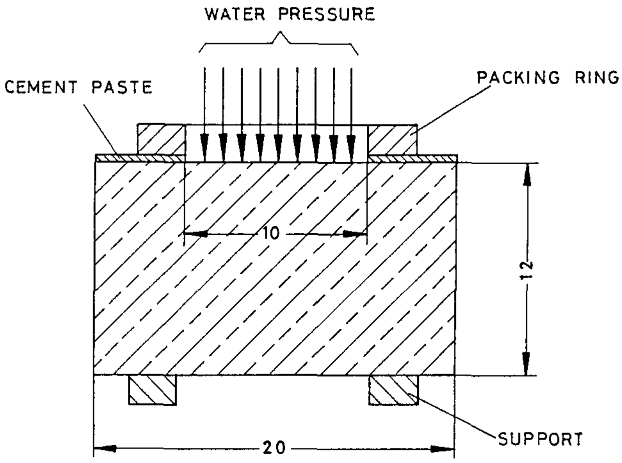

Fig. 1 Principle of watertightness test on 12 cm × 20 cm × 20 cm hardened concrete specimens according to DIN 1048.

brush to remove the surface skin and expose that area which is to be subjected to water pressure.

(b) In each test, three specimens are clamped into the equipment. Then the specimens are exposed to a regime of three subsequent water pressures in the following order: 1 kg cm^{-2} for 2 days, followed by 3 kg cm^{-2} for 1 day, followed by 7 kg cm^{-2} for 1 day. Because of practical difficulties with our equipment, concretes in the current investigation were only submitted to 6 kg cm^{-2} for 1 day at this stage.

(c) After 4 days, the three specimens are split, the water penetration profile is recorded, and the maximum penetration depth, x_{max}, is measured.

As the test is conducted at three different pressure levels h_1, h_2 and h_3 for different periods of time t_1, t_2 and t_3, the coefficient of water permeability can be calculated by stepwise application of Equation 3:

$$\Phi = \left(\frac{x_{max}}{2^{1/2}(h_1t_1 + h_2t_2 + h_3t_3)^{1/2}}\right)^2 \qquad (4)$$

Introducing in Equation 4 the true values of pressure and time which are used in our experiment, we obtain the following equation for calculating the coefficients of water permeability of our concretes:

$$\Phi \approx \left(\frac{x_{max}}{4360}\right)^2 \text{ m s}^{-1} \qquad (5)$$

It must be kept in mind that application of this particular test method has definite limitations concerning the numerical range of water permeability coefficients that can be measured. The lowest penetration depth that can be determined with reasonable accuracy is 1 mm, which corresponds to a minimum coefficient of permeability of 0.05×10^{-12} m s^{-1}. The highest coefficient of permeability that can be determined is 758×10^{-12} m s^{-1}, which corresponds to the height of the test specimens.

According to Walz [3], more than 50 years' experience with the DIN equipment in Germany indicates that for all practical purposes a concrete will be 'watertight' when the penetration depth is less than 0.05 m. By the term 'watertight' is meant that properly constructed concrete walls of 0.12 m thickness, or larger, will not under normal circumstances allow any liquid water to percolate through a wall when the concrete is used for construction of water tanks, sewage facilities, basement walls subject to ground water pressure, or similar structures. According to Equation 4, 0.05 m penetration depth corresponds to a water permeability coefficient of approximately $\Phi \approx 1.2 \times 10^{-10}$ m s^{-1}.

3.3 Materials

Two different Portland cements were used in this investigation. SRPC, which was used in series 1, is a low-alkali sulphate-resistant Portland cement from Aalborg in Denmark. It is somewhat similar in properties to an ASTM Type IV–V cement. OPC, which was used in series 2, is an ordinary Portland cement from the Slite cement works in Sweden. It is somewhat similar in properties to an ASTM type I–II cement. Chemical compositions of the two cements are shown in Table 2.

One particular fly ash from the Asnæs power station in Denmark was used in both series of tests. It was derived from the burning of Polish coals. The chemical composition of the fly ash is shown in Table 3. It has a density of 2200 kg m^{-3}.

Pure quartz sand from Voervadsbro was used as fine aggregate and crushed granite from Rønne was used as coarse aggregate for production of all concretes. Both geographical locations are in Denmark.

3.4 Mix proportions

The mix proportions of all concretes are shown in Table 4.

Table 2 Chemical composition of cements

	SRCP (%)	OPC (%)
SiO_2	24.43	19.84
Al_2O_3	2.33	2.08
Fe_2O_3	2.88	2.08
CaO	66.0	63.47
MgO	0.63	3.0
SO_3	2.08	2.88
Loss on ignition	0.8	2.42
Total	99.15	97.74
Total alkalis		
K_2O	0.18	1.25
Na_2O	0.16	0.21
$Na_2O_{eqv.}$	0.28	1.03

Table 3 Chemical composition of fly ash

	Content (wt %)
SiO_2	54.92
Al_2O_3	30.26
Fe_2O_3	5.55
CaO	3.24
MgO	1.17
SO_3	0.22
Loss on ignition	2.23
Total	97.18
Total alkalis	
K_2O	1.45
Na_2O	0.37
$Na_2O_{eqv.}$	1.32

4. RESULTS

4.1 Compressive strengths of hardened concretes

Mean compressive strength test results after 28 and 56 days of curing are shown in Table 4. Six 60 mm × 120 mm cylinders were tested for each concrete and at each age of curing.

4.2 Water penetration depths and coefficients of water permeability

Mean water penetration depths and corresponding standard deviations were determined after 28 and 56 days of curing for both series of specimens, and only after 28 days of standard curing for one series. Three 120 cm × 200 cm × 200 cm specimens of each concrete were tested at each age of curing. The results are shown in Tables 5 and 6. Corresponding permeability coefficients are also shown in Tables 5 and 6 as calculated from Equation 5.

5. DISCUSSION

5.1 Concrete mix proportions and properties

Essentially the same materials and mix proportions were used to produce the concretes in this investigation as in two other investigations earlier reported by the authors [4,5] in this journal. Statistical analysis revealed that there is no significant difference in properties of fresh or of hardened concretes produced in the three investigations. Thus, the results obtained for those series of concretes which are common in the three studies can be directly compared.

5.2 Comments on DIN 1048

Application of DIN 1048 to the testing of watertightness of concrete is time-consuming. The fact that only one piece of equipment was available in our laboratory, and that only three specimens could be tested at any one time in the equipment, made it necessary to limit the number of series of concrete and the curing ages at which the concretes could be tested, compared to what was done in earlier work [4,5].

DIN 1048 requires that the surface skin is removed and that the aggregate is exposed at those concrete surfaces which are to be exposed to water pressure. The results of a pilot test clearly showed that this requirement is justified. When the skin was not removed from concrete and the aggregate was not exposed before testing, the standard deviation of test results became so large that the results were impossible to interpret. Thus, it may be concluded that the quality of the concrete surface skin is one of the major factors affecting the overall water permeability of concrete structures. The surface skin was removed from all specimens in the main investigation.

5.3 Effect of type of cement on water permeability of concrete

Statistical analysis showed that, with the two cements and the one fly ash used in this investigation, there was no significant effect on water permeability of concretes produced with cements of types SRPC and OPC. The water permeability of all concretes turned out to be statistically identical when concretes were produced with the same c/w and the same f/w ratios, regardless of the type of cement used.

5.4 Effect of curing time on water permeability of concrete

Statistical analysis showed that there was no significant difference in water permeability of concretes tested after 28 or 56 days of standard curing in water at 20°C, regardless of whether concretes were produced with or without fly ash. This is interesting, considering the appreciable increase in compressive strength which was measured for all concretes between 28 and 56 days (see Table 4). It appears that any change in pore structure of the gel which gives rise to strength development at later ages has no effect on water permeability.

Møller [6] earlier found a considerable reduction in the permeability of fly ash concretes tested after periods between 2 and 28 days of standard curing in water at 20°C. This reduction was over and above the decrease in permeability of comparable ordinary concretes which were produced without fly ash. It would appear from our results that whatever positive influence fly ash may have on the water permeability of concrete, it is only effective at early ages.

5.5 Mathematical models for water permeability of ordinary concretes and fly ash concretes

By means of the SAS procedures REG, RSQUARE, STEPWISE etc., as described by Sall [7], we attempted to develop a simple correlation between measured coefficients of permeability and concrete mix composition. The results were disappointing. We were not able

Table 4 Mix proportions for 1 m^3 concrete with aggregates in SSD condition

Obs. No.	c/w	f/w	Cement ($kg\ m^{-3}$)	Ash ($kg\ m^{-3}$)	Sand ($kg\ m^{-3}$)	Stone ($kg\ m^{-3}$)	Super plasticizer (%)[a]	Compressive strength (MPa)	
								28 days	56 days
Series 1									
1	0.2	1.6	36	280	621	1153	0.0	6.7	8.1
2	0.6	0.8	108	144	712	1162	0.0	6.0	8.6
3	0.6	1.2	108	216	648	1152	1.2	5.2	7.5
4	0.6	2.0	100	360	543	1083	3.9	6.7	8.1
5	1.0	0.0	200	–	863	1054	0.0	n.a.	15.3
6	1.0	0.4	100	72	741	1159	0.0	14.5	20.7
7	1.0	0.0	100	144	657	1169	0.0	16.0	23.4
8	1.0	1.2	175	210	537	1234	0.0	18.3	25.4
9	1.0	1.6	180	280	557	1082	2.8	20.2	25.0
10	1.0	2.0	180	360	517	1049	0.0	17.1	25.2
11	1.4	0.0	273	–	766	1103	0.0	22.2	26.1
12	1.4	0.4	252	72	685	1167	0.0	29.8	37.2
13	1.4	0.0	252	144	613	1139	0.0	31.7	42.4
14	1.4	1.2	252	216	566	1099	3.2	31.1	39.4
15	1.4	1.6	252	280	525	1066	7.5	31.0	41.6
16	1.4	2.0	252	360	477	1014	10.3	29.2	37.5
17	1.8	0.0	324	–	685	1171	0.0	36.8	46.2
18	1.8	0.4	324	72	645	1147	0.0	43.6	56.6
19	1.8	0.8	324	144	500	1125	2.9	45.0	n.a.
20	1.8	1.2	324	216	534	1064	6.1	45.0	55.4
21	1.8	1.6	333	296	491	996	10.0	38.5	45.1
22	2.2	0.0	429	–	625	1112	0.0	52.0	60.5
23	2.2	0.4	396	72	601	1117	3.0	44.1	57.0
24	2.2	0.8	396	144	526	1093	5.6	53.7	60.1
25	2.6	0.0	507	–	590	1095	3.0	53.2	n.a.
Series 2									
26	0.2	2.0	36	360	630	1169	3.4	1.8	n.a.
27	0.6	0.8	105	141	696	1180	0.0	8.1	n.a.
28	0.6	1.2	105	211	619	1164	2.8	9.1	n.a.
29	0.6	1.6	105	281	569	1139	1.3	7.2	n.a.
30	0.6	2.0	105	352	522	1093	8.7	12.8	n.a.
31	1.0	0.0	200	–	842	1055	0.0	13.8	n.a.
32	1.0	0.4	180	72	721	1166	0.0	16.3	n.a.
33	1.0	0.8	176	141	640	1168	0.0	18.8	n.a.
34	1.0	1.2	186	223	576	1138	0.0	21.1	n.a.
35	1.0	1.6	180	288	501	1097	4.3	22.6	n.a.
36	1.0	2.0	176	352	498	1067	8.7	26.6	n.a.
37	1.4	0.0	273	–	735	1121	0.0	18.6	n.a.
38	1.4	0.4	246	70	660	1174	0.0	26.3	n.a.
39	1.4	0.8	246	141	600	1159	0.0	28.0	n.a.
40	1.4	1.2	252	216	544	1110	3.6	34.8	n.a.
41	1.4	1.6	246	282	506	1076	6.0	38.1	n.a.
42	1.4	2.0	252	360	465	1017	12.0	39.0	n.a.
43	1.8	0.0	351	–	661	1130	0.0	39.1	n.a.
44	1.8	0.4	317	70	617	1167	0.0	38.5	n.a.
45	1.8	0.8	324	144	558	1122	4.4	39.9	n.a.
46	1.8	1.2	317	211	514	1093	10.1	44.6	n.a.
47	1.8	1.6	317	282	482	1043	12.3	46.2	n.a.
48	2.2	0.0	422	–	607	1123	0.0	51.0	n.a.
49	2.2	0.4	396	72	572	1135	4.3	41.9	n.a.
50	2.2	0.8	387	141	531	1182	7.3	51.0	n.a.
51	2.6	0.0	587	–	565	1096	0.7	61.6	n.a.

[a] By weight of cement + fly ash.

Table 5 Water penetration depths (x_{max}) and coefficient of water permeability (Φ) of concretes in series 1 (made with SRPC and Asnæs fly ash)

f/w	Curing (days)	c/w 0.2			0.6			1.0			1.4			1.8			2.2			2.6		
		x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})
2.0	28				>12.0	0.00	>757.5	2.0	0.07	22.1	1.7	0.15	14.7									
	56				>12.0	0.00	>757.5	1.6	0.07	14.3	1.6	0.28	13.5									
1.6	28	>12.0	0.00	>757.5				2.2	0.21	26.6	2.3	0.14	27.8	1.1	0.06	6.0						
	56	>12.0	0.00	>757.5				3.0	0.07	48.9	2.0	1.13	21.0	0.6	0.25	2.1						
1.2	28				>12.0	0.00	>757.5	3.4	0.85	60.8	2.4	0.78	29.1	0.2	0.00	0.2						
	56				>12.0	0.00	>757.5	5.0	1.06	128.9	1.5	0.00	11.8	0.8	0.07	3.0						
0.8	28				>12.0	0.00	>757.5	5.2	0.64	139.5	1.7	0.35	16.1	1.6	1.04	13.5	1.7	1.56	15.2			
	56				>12.0	0.00	>757.5	2.9	0.28	44.2	1.1	0.42	6.4	1.3	0.10	8.2	0.8	0.14	3.4			
0.4	28							6.4	0.85	215.5	2.4	0.64	29.1	1.8	0.00	17.0	0.7	0.15	2.8			
	56							3.9	1.98	80.0	1.7	0.42	15.2	1.9	0.71	19.0	1.6	1.25	13.0			
0.0	28							6.3	0.35	212.1	3.2	0.58	53.9	1.9	0.53	18.6	2.9	1.27	44.2	0.1	0.00	0.1
	56							6.6	0.85	229.1	2.0	0.00	21.0	1.3	0.00	8.2	1.6	0.78	12.6	0.1	0.00	0.1

Table 6 Water penetration depths (x_{max}) and coefficient of water permeability (Φ) of concretes in series 2 (made with OPC and Asnæs fly ash)

f/w	Curing (days)	c/w 0.2			0.6			1.0			1.4			1.8			2.2			2.6		
		x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})	x_{max} (cm)	Std. dev. (cm)	Φ (10^{-12} m s^{-1})
2.0	28	>12.0	0.00	>757.5	3.5	0.17	64.4	1.4	0.29	9.9	0.2	0.00	0.2									
1.6	28				8.4	0.66	371.2	1.3	0.06	9.3	0.3	0.00	0.5	0.7	0.06	2.4						
1.2	28				7.6	0.78	301.5	3.3	0.26	57.3	1.2	0.12	7.2	0.3	0.00	0.5						
0.8	28				10.6	0.96	591.1	4.8	1.04	122.7	2.1	0.32	23.9	1.6	0.36	13.5	0.9	0.10	4.3			
0.4	28							6.4	0.40	215.5	3.3	0.38	58.3	1.7	0.49	15.7	1.1	0.06	6.0			
0.0	28							8.8	0.10	407.4	4.3	0.81	98.6	1.8	0.15	17.6	1.3	0.15	9.3	0.2	0.00	0.2

to establish any one model which was capable of predicting coefficients of water permeability for both ordinary concretes and fly ash concretes. Perhaps this is not surprising. Considering that our experiments cover a wide range of w/c ratios from 0.38 to 5.0, and considering the limitations of the testing method described earlier, it was hardly to be expected that any one single equation would describe the water permeability of the entire spectrum of mixes. The best mathematical model for calculating coefficients of water permeability of ordinary concrete without fly ash was found to be

$$\Phi = 2.8 \times 10^{-10} \left(\frac{w}{c}\right)^5 \tag{6}$$

where w = free water content of concrete (kg m^{-3}) and c = cement content of concrete (kg m^{-3}).

The fact that the statistical coefficient of correlation between the predictions of Equation 6 and experimental results was as low as $R^2 = 0.85$ is an indication that the model does not take all significant parameters into account and that the testing method has severe limitations concerning the numerical values of diffusion coefficients which can be measured. Nevertheless, Equation 6 does show that the watertightness of concrete increases with the water/cement ratio raised to the power of minus five, while the compressive strength of concrete is known to increase with the water/cement ratio raised to the power of approximately minus one. In practical terms this means that any reduction in the water/cement ratio of a concrete will have a much more beneficial effect on watertightness of the concrete than it will have on compressive strength. It illustrates the well-known fact that the water/cement ratio is an important parameter for watertightness of concrete.

By similar statistical analysis, the best mathematical model for calculating the coefficients of water permeability of both fly ash concrete and ordinary concrete without fly ash was found to be

$$\Phi = \exp\left[-4.3\left(\frac{c + 0.31f}{w} + 4.0\right)\right] \tag{7}$$

where the same notation is used as in Equation 6, except that f = fly ash content of concrete (kg m^{-3}).

The fact that the coefficient of correlation between experimentally determined values and those calculated from Equation 7 is as low as $R^2 = 0.73$ shows that our mathematical model fails to take one or more important physical or chemical parameters into account, and it reflects the fact that the testing method has severe limitations. However, Equation 7 does indicate that the water permeability of fly ash concrete is apparently a function of an equivalent water/cement ratio, where the cementing efficiency index of fly ash, k_v, is approximately 0.3. In practical terms this means that 1 kg of cement would have to be replaced by approximately 3 kg of the particular fly ash used in this investigation in order to maintain the same watertightness of hardened fly ash concrete. Neither differences in type of cement nor differences in curing time (28 and 56 days) changed this conclusion. Thus, addition of fly ash is not likely to improve the watertightness of concrete.

6. CONCLUSIONS

1. It is concluded that the cementing efficiency factor of the fly ash tested with respect to watertightness is approximately 0.3, independent of type of cement and curing time (28 and 56 days). In practical terms this means that 1 kg of cement would have to be replaced by approximately 3 kg of fly ash in order to maintain the same watertightness of the hardened fly ash concrete. Thus, addition of fly ash is not likely to improve the watertightness of concrete.

2. The best-fitting mathematical model for calculating coefficients of water permeability of ordinary concrete without fly ash as a function of mix composition was found to be the equation

$$\Phi = 2.8 \times 10^{-10} \left(\frac{w}{c}\right)^5$$

3. The best-fitting mathematical model for calculating coefficients of both fly ash concretes and ordinary concretes without fly ash as a function of mix composition was found to be

$$\Phi = \exp\left[-4.3\left(\frac{c + 0.31f}{w} + 4.0\right)\right]$$

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RESUME

Perméabilité à l'eau des bétons aux cendres volantes

On a essayé par la méthode DIN 1048 la perméabilité à l'eau de deux séries de bétons fabriqués avec un type de cendres volantes et deux types de ciment Portland (OPC et SRPC). On en a conclu que le coefficient d'activité des cendres volantes en rapport avec la perméabilité à l'eau est environ de 0,3, quels que soient le type de ciment et le temps de conservation (28 et 56 jours). Ceci signifie qu'il conviendrait de remplacer 1 kg de ciment par environ 3 kg de cendres volantes afin de maintenir une étanchéité constante des bétons aux cendres volantes durcis. L'addition de cendres volantes n'améliore donc pas sensiblement l'étanchéité à l'eau du béton.