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Moisture conditioning and transport properties of concrete test specimens

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An experimental investigation is reported of drying and conditioning concrete at 50°C to obtain a uniform moisture distribution, prior to testing for air permeability and water absorption rate. The use of 100 mm cubes of concrete with a cast-in cylindrical cavity facilitated assessment of moisture distribution and measurement of air permeation through the surface layers of concrete: the moisture distribution was assessed by comparing the relative humidities measured within the cavity and at the surface of the test specimen. Partial drying followed by sealed storage at 50°C for a few days provided a rapid and convenient method of obtaining a uniform moisture distribution. The test results for a range of concretes indicated that air permeability and water absorption rate were very sensitive to the moisture content of the concrete, particularly at relative humidities above 60% and which were common for field exposure. The transport properties of the empty capillary pore system could be assessed using test specimens preconditioned at 60% relative humidity, but preconditioning at 85% relative humidity might be more appropriate for assessing field performance if there is a risk of carbonation induced corrosion.

1. INTRODUCTION

The amount of pore water in concrete and its spatial distribution can greatly affect field performance and the properties of laboratory test specimens [1–4]. Gas permeation and the rate of water absorption are particularly sensitive to the moisture state at the time of testing [5–8]. Several months of drying at 55–60% relative humidity and 20°C are required to achieve approximate moisture equilibrium in specimens only a few centimetres thick [9, 10], and several years may be required when the drying thickness of the specimen is increased to 20 centimetres [2]. There is current interest in European Codes and Standards committees in using transport properties such as permeability and absorption for indicating the potential durability of concrete [6] but a long period of moisture conditioning prior to testing would be a major disadvantage. Oven drying reduces the required preconditioning time, but there is evidence to suggest that sustained elevated temperatures that lead to severe drying of the cement gel will alter the microstructure of the cementitious binder and increase permeability [6, 11–14]. Limiting the oven temperature to 50°C minimizes the extent of microstructural alteration [11, 13, 15] but will eventually produce unrealistically dry test specimens.

This investigation examines a method of drying and conditioning at 50°C where the equilibrium relative humidity achieved in the concrete is within the range normally encountered in structural concrete, i.e., 40–100% [2]. In relation to the use of permeability for the control of damage arising from carbonation induced corrosion, the range 70–90% relative humidity is of particular significance: at lower humidities reinforcement corrosion will be minimal [16–18] whereas at higher humidities carbonation will be minimal [4, 19].

2. EXPERIMENTAL

2.1 Materials

The characteristics of the cements used in this investigation are shown in Table 1. Cement A is a rapid hardening Portland cement and cements B and C are Portland–limestone cements each containing 25% by mass of limestone. The compositions of the concretes used in this investigation are shown in Table 2 together with the results of crushing tests on 100 mm cubes. Dry river

Table 1 Cement characteristics

	Cement A	B	C
pr ENV 197 type	CEI	CEII/B-L	CEII/B-L
Density (kg m^{-3})	3095	3040	3005
% mass of			
SiO_2	19.7	16.3	26.2
Al_2O_3	5.2	4.1	3.1
Fe_2O_3	2.1	2.3	3.2
CaO	65.4	60.2	58.9
MgO	1.0	1.8	0.6
SO_3	3.3	2.4	2.6
K_2O	0.55	0.63	–
Na_2O	0.22	0.09	–
Ignition loss	1.3	11.2	5.0

Table 2 Concretes

Concrete	Cement	Free water/cement ratio	Cement content (kg m^{-3})	Cube strength (MPa)	
				3 days	28 days
1	B	0.59	300	16.9	33.5
2	B	0.59	300	16.9	33.5
3	A	0.59	300	27.6	42.2
4	A	0.46	315	41.5	55.4
5	C	0.59	300	10.5	26.9
6	C	0.72	290	5.2	16.1
7	C	0.72	290	5.9	15.3
8	A	0.47	315	41.3	52.4

Table 3 Scope of experiments

Concrete code[a]	Initial 20°C cure (days)	Days at 50°C			Days at 20°C Sealed
		Total	Drying	Sealed	
1-59B3	3	8	1, 2, 3, 4, 8	7, 6, 5, 4, 0	17
2-59B3	3	11	1, 4, 5, 6, 7, 8	10, 7, 6, 5, 4, 3	14
3-59A3	3	7	1, 4, 7	6, 3, 0	18
4-46A3	3	7	1, 4, 7	6, 3, 0	18
5-59C3	3	7	1, 4, 7	6, 3, 0	18
6-72C3	3	7	1, 4, 7	6, 3, 0	18
7-72C1	3	7	1, 4, 7	6, 3, 0	18
8-46A28	28	7	1, 4, 7	6, 3, 0	18

[a] Code gives concrete – water/cement × 100 + cement + cure.

gravel, with a maximum aggregate size of 12.5 mm, was presoaked for 1 h with sufficient water to saturate the aggregate and provide the required free water/cement ratio. Cement was then added and the concrete was mixed for 4 min in a horizontal pan mixer. Fifteen minutes after the start of mixing the concrete was remixed for one minute.

The concrete was cast into 100 mm cube moulds and compacted on a vibrating table. Six cube moulds were fitted with 20 mm diameter ×35 mm steel cylinders to form a central cavity in a vertical face of the concrete cubes: these cubes were used for air permeability and relative humidity measurements [10]. Eight plain cubes were cast for compressive strength and outdoor carbonation measurements. The cubes were stored for 24 h in a moist curing chamber at 100% relative humidity and 20°C. Plastic sheeting was placed over the concrete to minimize any gain or loss of moisture. Pairs of cubes were stored in water and crushed at ages of 3 days and 28 days and four cubes were exposed outdoors for carbonation tests: the carbonation results will be the subject of a future report.

2.2 Measurements

The concrete cubes for permeability and relative humidity measurements were cured without gain or loss of water for the periods indicated in Table 3. Each cube was then placed in an oven with forced air circulation and heated at 5°C per hour up to 50°C. After the appropriate period of drying each cube was sealed in a lidded plastic container and maintained at 50°C for the periods indicated in Table 3. The period of sealed storage at 50°C was intended to speed up redistribution of the residual moisture and the attainment of a uniform moisture content. After the appropriate period in the oven the cubes were cooled at 5°C per hour and thereafter they were maintained at 20 ± 1°C. Weight changes of the cubes were monitored from an age of 1 day and these indicated that there were no significant weight losses after the plastic containers were fitted with their lids.

The lids were fitted with a rubber grommet and a rubber bung as indicated in Fig. 1, so that the relative

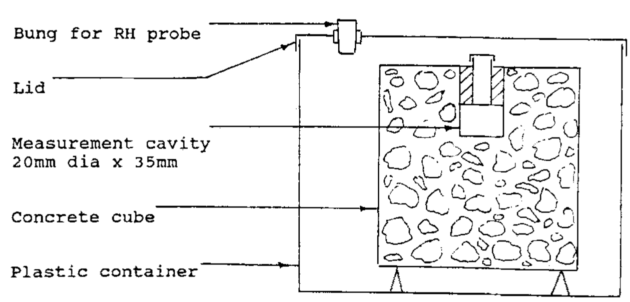

Fig. 1 Sealed storage of 100 mm concrete cube.

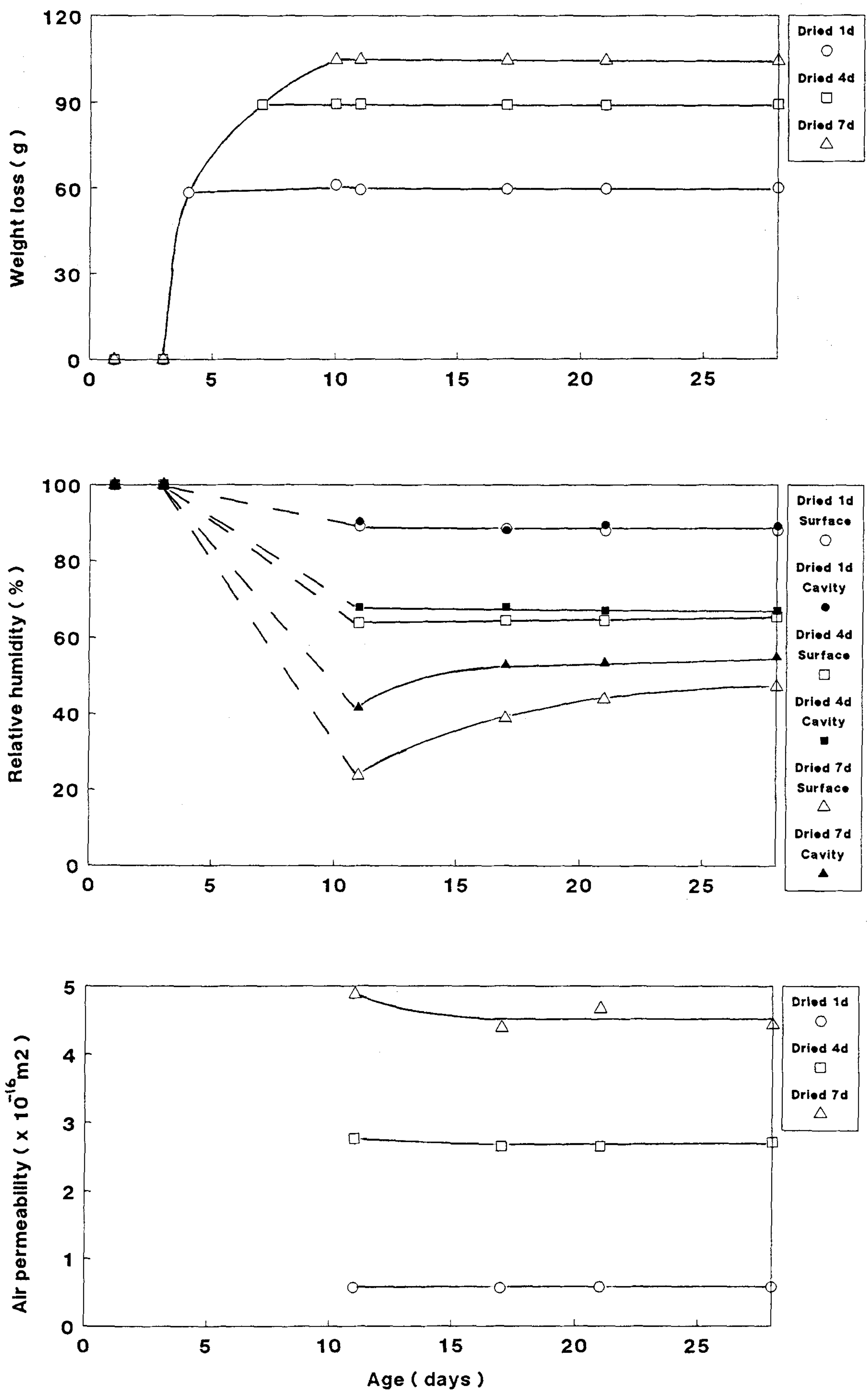

Fig. 2 Weight loss, relative humidity and air permeability results for concrete 3-59A3.

humidity at the concrete surface could be monitored [2, 10]. Relative humidities within the concrete were also monitored; this involved removing the cube from the container for a few minutes but, by covering the exposed surface of the cube to avoid moisture exchange with the laboratory atmosphere, it was found that specimen weight changes were negligible up to the end of the sealed storage at 20°C. Air permeability was also monitored after each relative humidity measurement [7, 10]. Twenty-five days after the start of drying the rate of water absorption was measured up to 6 h [8]; the value corresponding to 4 h was determined by direct measurement and confirmed by interpolation. The final stage of the experiment involved oven drying at 105°C to constant weight and measuring the air permeability.

3. RESULTS AND DISCUSSION

Fig. 2 shows a typical set of results for weight changes, relative humidities and air permeabilities. Drying for 1 day followed by 6 days of sealed storage at 50°C caused a substantial weight loss. The relative humidities at the external surface of the concrete cube and within the cavity were in the range 88–90% and the air permeability remained virtually constant throughout the subsequent 18 day period of sealed storage at 20°C. Drying for 4 days followed by 3 days of sealed storage at 50°C caused a small relative humidity gradient in the concrete cube that gradually diminished with age: the corresponding changes of air permeability were insignificant. Drying for 7 days at 50°C without any subsequent moisture equilibration at 50°C caused a significant relative humidity gradient in the concrete that did not disappear fully during the 18 day period of sealed storage at 20°C. However, there were only limited changes of air permeability during this period.

The average relative humidities (ARH) and the differences between the interior and the surface of the cubes (RHD) are shown for each concrete in Table 4. Positive values of RHD signify that the interior relative humidity is higher than that at the surface of the cube. The larger relative humidity gradients diminished significantly between 12 days and 25 days after the start of drying. Small positive values of RHD were usually observed 25 days after the start of drying but values of around 8% were obtained with concretes 3, 4 and 8 when drying for 7 days was not followed by a period of sealed storage at 50°C. The results in Table 4 suggest that the

Table 4 Relative humidities 12 and 25 days after start of drying

Concrete code	Days at 50°C Total	Days at 50°C Dried	After 12 days ARH (%)	After 12 days RHD (%)	After 25 days ARH (%)	After 25 days RHD (%)
1-59B3	8	1	91.8	−1.1	94.5	1.0
	8	4	73.7	6.6	76.4	1.1
	8	8	42.8	20.8	56.9	4.7
2-59B3	11	1	94.4	−3.8	89.8	2.6
	11	4	75.7	3.4	75.9	1.5
	11	7	56.0	0.0	58.7	4.0
3-59A3	7	1	88.3	−0.5	88.7	1.1
	7	4	66.2	3.5	66.3	1.6
	7	7	45.9	14.0	51.1	7.8
4-46A3	7	1	85.8	−1.1	80.2	−0.4
	7	4	65.7	3.6	66.5	2.2
	7	7	45.5	15.1	53.6	8.0
5-59C3	7	1	88.0	2.8	88.1	2.5
	7	4	62.3	2.3	63.0	2.1
	7	7	33.1	11.7	40.1	3.4
6-72C3	7	1	89.1	2.3	89.6	3.8
	7	4	57.7	−0.6	56.5	0.4
	7	7	24.5	1.8	29.2	2.0
7-72C1	7	1	87.8	4.0	86.9	1.6
	7	4	39.8	0.2	39.5	0.6
	7	7	11.4	3.5	12.8	1.5
8-46A28	7	1	80.7	−0.1	79.3	0.6
	7	4	66.2	1.7	65.8	1.7
	7	7	51.4	11.9	53.0	8.3

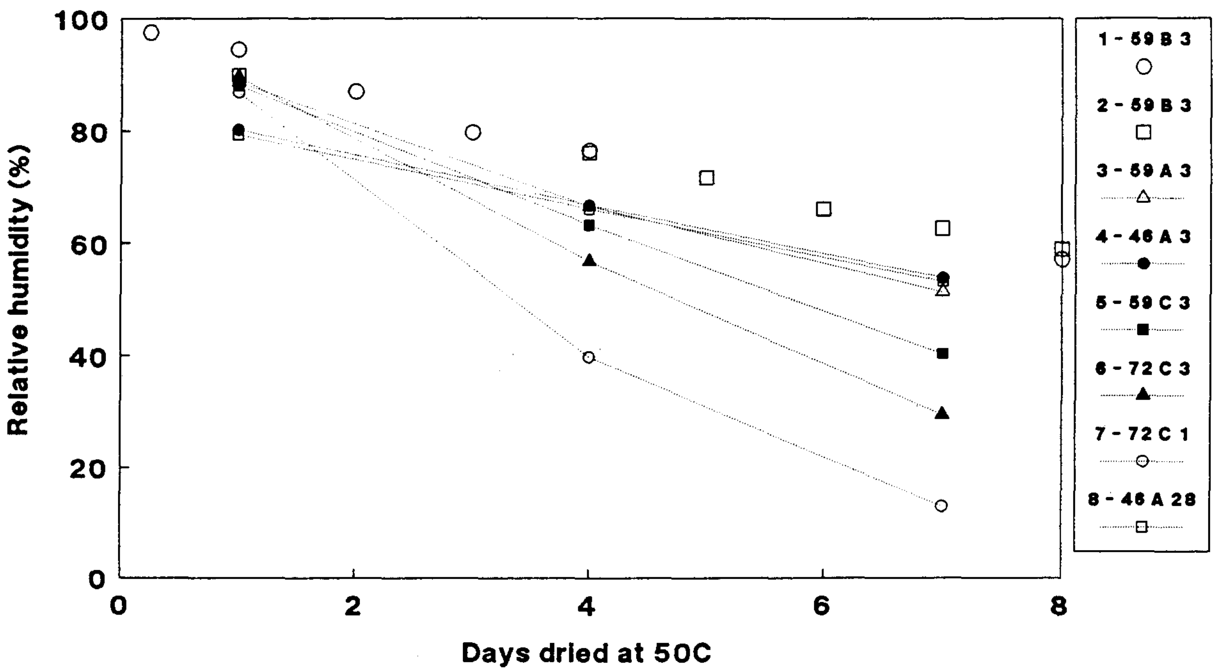

Fig. 3 Average relative humidities achieved in different concretes 25 days after the start of drying.

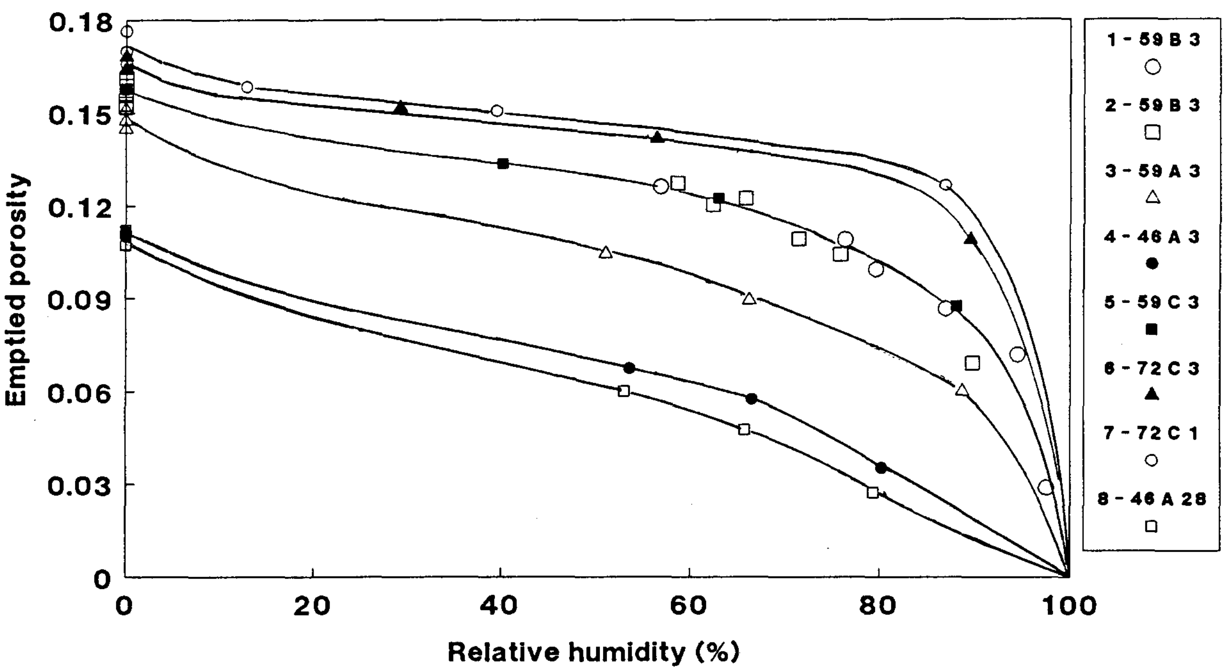

Fig. 4 Emptied porosity versus relative humidity for different concretes.

period of sealed storage at 50°C should be comparable with or greater than the period of drying in order to achieve small gradients of relative humidity through the concrete.

Fig. 3 indicates that drying periods at 50°C of 2.5–7 days and 1.3–3 days are required to obtain average relative humidities of 60% and 80%, respectively. Prolonged drying at 50°C would be required for all but the most porous concretes to obtain relative humidities of 50% or below.

The weight losses per unit volume of concrete (i.e., the emptied porosities) 25 days after the start of drying are plotted in Fig. 4 against the corresponding average relative humidities. The porosity emptied at relative humidities above 60% arises from spaces between the original cement grains that have not become filled with cement hydrates and may be regarded as capillary porosity [20]. As would be expected, the results in Fig. 4 indicate that high water/cement ratios are associated with high total and high capillary porosities. It is also evident from the results for concretes 1, 2, 3 and 5 that a smaller capillary porosity is obtained with Portland cement A than with Portland–limestone cements B and

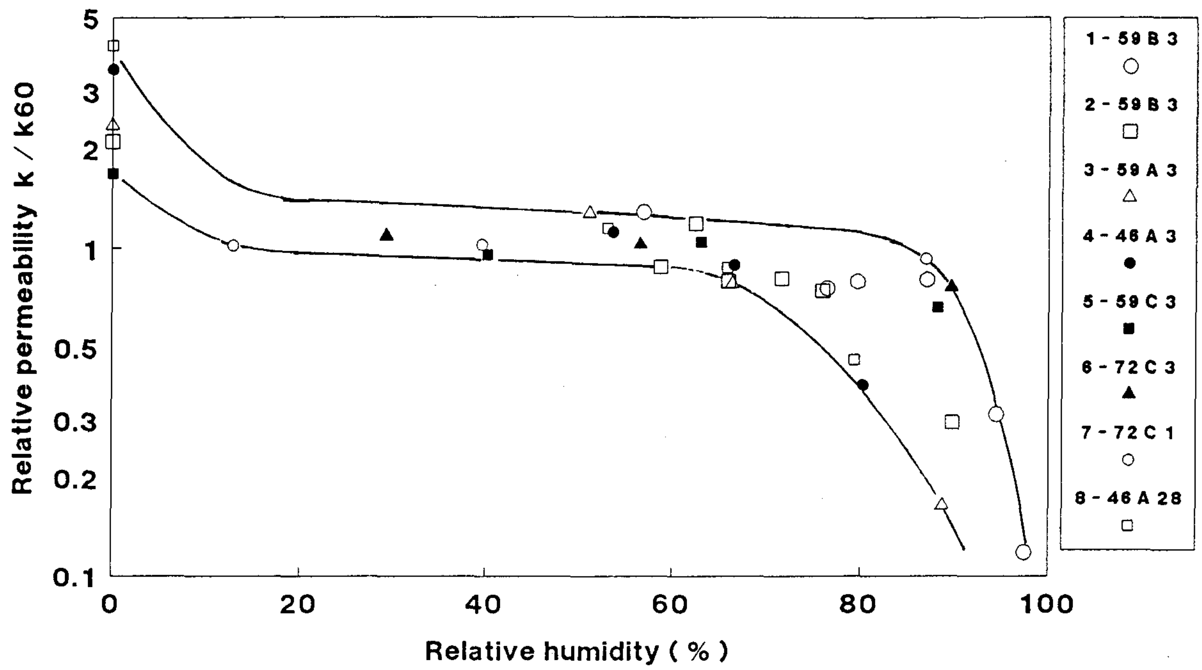

Fig. 5 Air permeability, relative to that at 60% RH, versus relative humidity.

C: this can be accounted for simply by the greater proportion of reactive cement clinker in cement A. Comparisons of the results for concretes 6 and 7 and for concretes 4 and 8 indicate that shorter curing periods lead to a greater capillary porosity. The results in Fig. 4 are consistent with a simple model of cement paste pore structure in which microporous cement hydrates grow into spaces originally occupied by the mix water [20].

It can be observed from Fig. 2 that there were only small changes of air permeability of concrete 3 with time after removal from the 50°C oven. Similar results were obtained with the other concretes: the average decrease for all concretes from 12 days to 25 days after the start of drying was only 2.7%. This means that permeability measurements could be completed without serious compromise at an age equal to the curing period plus 12 days.

Fig. 5 indicates that the effect of the relative humidity achieved after drying upon air permeability is small within the range 20–60%. At higher relative humidities the lower porosity concretes exhibit a gradual reduction in permeability while the higher porosity concretes exhibit a sharp reduction at about 90% relative humidity. In many northern and central European climates relative humidities in the range 80–90% are common and Fig. 5 suggests that in such conditions air permeation is restricted to a greater extent in the lower porosity concretes by capillary condensation and pore blocking than it is in the higher-porosity concretes. The results in Fig. 5 are consistent with a review of published permeability data [6] and with results showing that carbonation of high porosity cement pastes reached a maximum at higher relative humidities than did carbonation of low porosity cement pastes [4]. The results of Fig. 5 indicate that in order to assess the permeability of the capillary pore system of concrete it is desirable to dry at a relative humidity of about 60% or less. However, the permeability results would not then necessarily give a reliable indication of the relative *field* performance of different concretes exposed to wetter conditions, particularly if they differed significantly in pore structure.

An alternative view of the results is shown in Fig. 6 where air permeability is plotted against emptied porosity. It can be seen that although permeability increased with emptied capillary porosity for each concrete there is not a unique relationship for the combined results. This may be due to the additional effect of connectivity in the emptied pores: at a given emptied porosity the channels in the higher porosity concretes seem to be more interconnected than those in the lower porosity concretes. Published values for the air permeability of concretes dried for two months at 60% relative humidity and 20°C [10] were, for a given emptied porosity, comparable to those shown in Fig. 6. This suggests that heating at 50°C did not greatly affect the pores that control gas transport, but further investigation of this point seems desirable.

The water absorption results exhibited patterns that were strikingly similar to those for permeability in Figs 5 and 6. Thus, when the 4 h water absorption was plotted against air permeability there was a fairly close relationship, as shown in Fig. 7. The time function for water absorption can be described by a power law [8] and Fig. 8 shows that the power exponent increases with increasing emptied porosity over a wide range of relative humidities and capillary porosities.

There is much interest in concrete performance tests that can be completed at an early age and are indicative of long term durability [6]. The present results show that the relative performance of concretes can depend upon

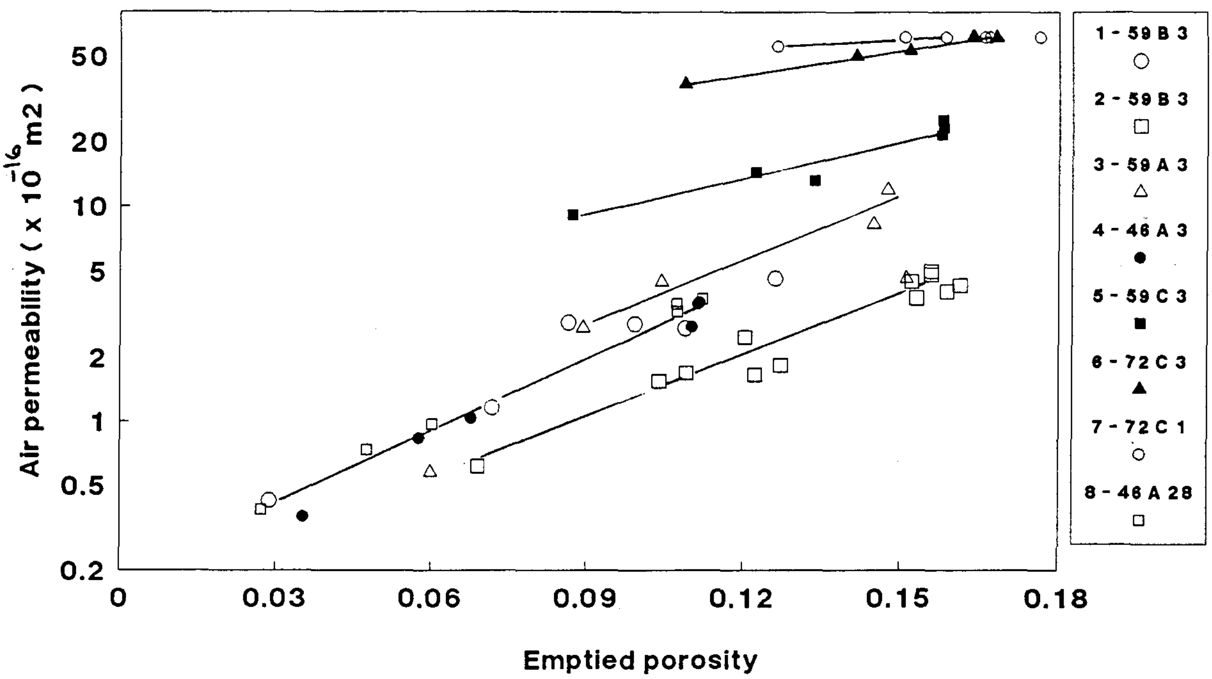

Fig. 6 Air permeability versus emptied porosity in different concretes.

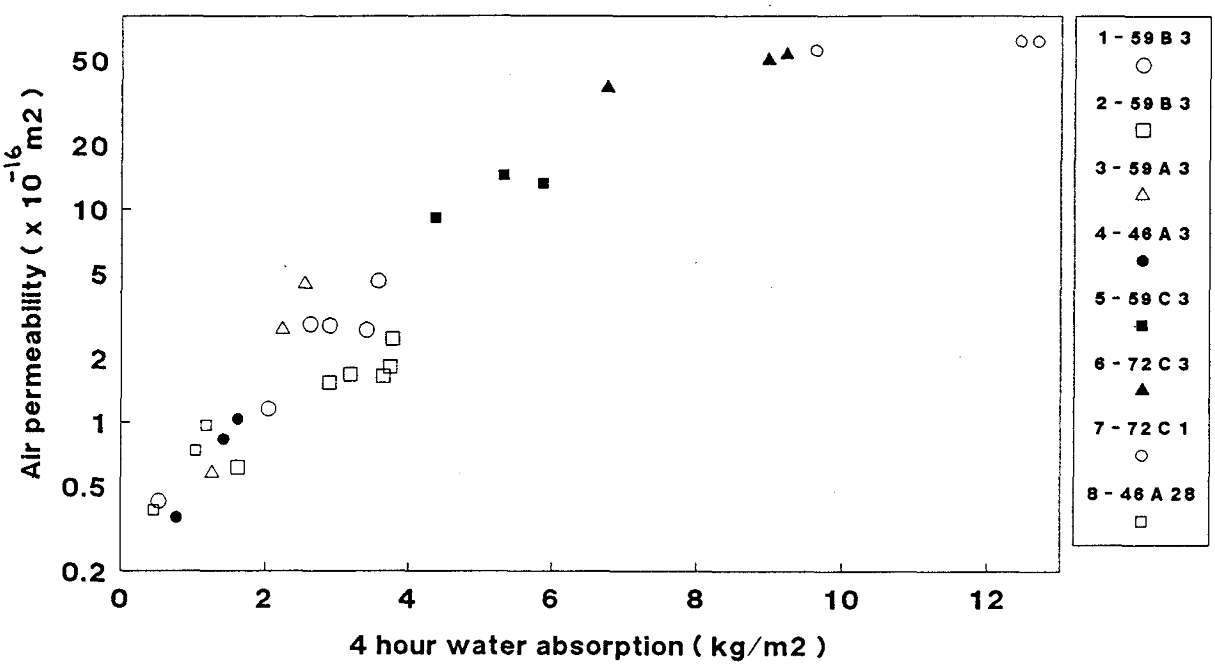

Fig. 7 Air permeability versus 4 h water absorption in different concretes.

the type of test and the extent of drying prior to testing. Table 5 compares a high porosity concrete, 5-59C3, with a low porosity concrete, 8-46A28, and it can be observed that for 85% relative humidity the performance differences between low and high porosity concretes are much more pronounced than they are under drier conditions. Furthermore, air permeability is a more sensitive indicator of concrete performance than are 4 h water absorption and emptied porosity. Additional investigation is desirable to determine the applicability of the method of drying to larger or to sawn 100 mm cube specimens that contain aggregate particles bigger than 12.5 mm.

4. CONCLUSIONS

The use of a concrete cube with a cast-in cavity facilitates the assessment of moisture distribution after partial drying: the cavity can be used also for measurement of air permeability in the surface layers of the concrete. Partial oven drying at 50°C followed by sealed storage for a few days at 50°C provides a rapid and convenient

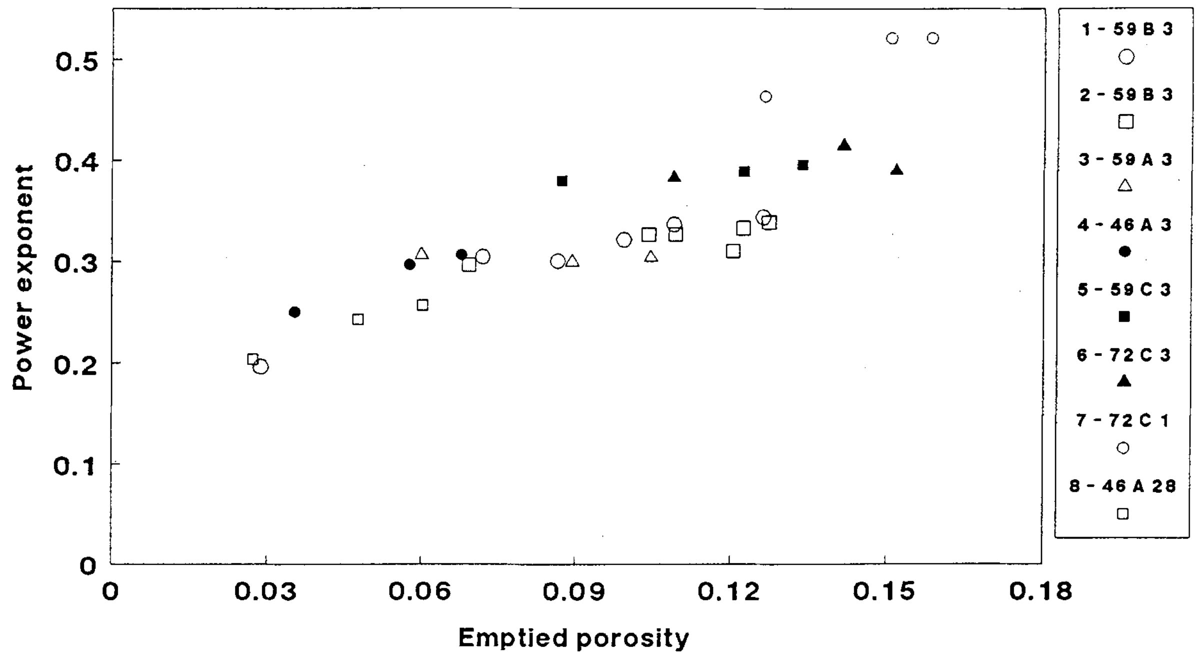

Fig. 8 Power exponent of water absorption time function versus emptied porosity for different concretes.

Table 5 Influence of drying method upon relative performance of concretes 5 and 8

	Degree of drying		
	85% RH	60% RH	105°C
	Air permeability ($\times 10^{-16}$ m^2)		
Concrete 5	9.80	13.8	23.2
Concrete 8	0.260	0.845	3.49
5/8	38	16	6.7
	4 h Water absorption (kg m^{-2})		
Concrete 5	4.50	5.55	–
Concrete 8	0.19	1.12	–
5/8	24	5	–
	Emptied porosity		
Concrete 5	0.093	0.126	0.158
Concrete 8	0.021	0.055	0.109
5/8	4.4	2.3	1.5

method of obtaining a uniform moisture distribution in a 100 mm cube test specimen. The relative humidity achieved in the concrete depends upon the duration of drying and the pore structure of the concrete. The test results for a range of concretes indicate that the air permeability and water absorption rate are very sensitive to the moisture content of the concrete under test, particularly at relative humidities above 60% and which are common for field exposure. The moisture condition of test specimens should be appropriate to the purpose of the test for reliable comparisons of performance. Thus comparisons for assessing field performance where there is a risk of carbonation induced corrosion might be based upon specimens predried to 85% relative humidity whereas comparisons for assessing the transport properties of the empty capillary pore system might be based upon specimens preconditioned at a relative humidity of 60% or less. If two concretes differ in their pore structure then an assessment of their relative performance under damp field conditions, based upon test specimens dried at 60% relative humdity, may not be reliable.

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RESUME

Conservation de l'humidité et propriétés de transfert d'éprouvettes en béton

On décrit une étude expérimentale de séchage et de conservation du béton à 50°C pour obtenir une distribution uniforme de l'humidité avant l'essai du taux de perméabilité à l'air et de la vitesse d'absorption de l'eau. L'utilisation de cubes de 100 mm de côté comportant une cavité cylindrique a facilité l'évaluation de la répartition de l'humidité et la mesure de la perméabilité à l'air au travers des couches superficielles du béton: la répartition de l'humidité a été évaluée en comparant les humidités relatives mesurées à l'intérieur de la cavité et à la surface de l'éprouvette. Un séchage partiel suivi d'un stockage étanche à 50°C pendant quelques jours apparaît comme une méthode rapide et commode pour l'obtention d'une répartition uniforme de l'humidité. Les résultats d'essais sur un éventail de bétons ont montré que la perméabilité à l'air et la vitesse d'absorption de l'eau étaient très liées à la teneur en humidité du béton, en particulier pour des humidités relatives dépassant 60%, qui sont courantes pour l'exposition in situ. On a pu évaluer les propriétés de transfert du système de capillarité des pores vides à l'aide d'éprouvettes préconservées à 60% d'humidité relative; cependant, la préconservation à 85% d'humidité relative pourrait convenir mieux à l'évaluation de la performance in situ s'il existe un risque de corrosion due à la carbonatation.