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Water absorption in cover concrete

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Measurements of initial water absorption are reported for concretes exposed indoors or outside for 1.5 years. Water absorption after a given wetting time was increased with an increase of water/cement ratio, a reduction of moist curing and partial replacement of the Portland clinker component of the cement. Absorption after outdoor exposure was less than that after laboratory exposure, especially if rain could fall on the concrete surface. Absorption results correlated approximately with weight losses during initial exposure and with compressive strengths at the start of exposure. There was a near-linear relationship between carbonation depths and absorption measured in cover concrete after 1.5 years of exposure

1. INTRODUCTION

The rate at which water is absorbed into concrete by capillary suction can provide useful information relating to the pore structure, permeation characteristics and durability of the concrete surface zone that is penetrated [1–18]. Water absorption tests on concrete can be conducted in the laboratory, normally using specimens dried in a standard way, or in the field.

In the laboratory the penetration depth after various periods of wetting can be determined by direct observation on split specimens [14], nuclear magnetic resonance imaging [19] or by deduction based upon measured specimen weight gains and a measured value of porosity (e.g. [16]). The depth of water penetration usually increases linearly with the square root of wetting time in many porous materials, provided that porosity and initial moisture content are uniform throughout the test specimen [20]. The slope of this linear plot is termed sorptivity [12,14,16] and its units are $m\ s^{-1/2}$. The term sorptivity has also been used to describe the slope for plots of volume (or weight) of water imbibed per unit area of wetted surface versus square root of wetting time, but the term 'absorption rate' is preferred in these cases. It is worth noting that calculations of the depth of water penetration from the weight or volume of water imbibed involve the assumptions that porosity does not vary with depth and that water penetrates as a sharp liquid front. These assumptions are only approximations of reality in a material like concrete [1,2,8,10,19–21]. A further problem associated with laboratory testing is that the method of drying can significantly affect the relative values of absorption rate that are obtained. For example drying to constant weight at either 105 or 50°C gave relative values for various concretes that were quite different to the relative values obtained by drying at 20°C [22,23]. Also differences of absorption rate between concretes were less marked when drying to constant weight at elevated temperature was used.

Under practical exposure conditions the moisture conditions and pore structure in concrete will vary with age and with depth from an exposed surface (e.g. [1,21,24,25]): hydration of cement can be restricted in cover concrete and the average capillary porosity can be higher than that of the interior concrete. Carbonation will normally cause a counterbalancing reduction of capillary porosity in the outer layers of cover concrete (e.g. [21,26]). Thus it is evident that a linear relationship between absorption depth and the square root of wetting time may not be obtained under field conditions. The problem is compounded when the amount of water required to saturate the test volume is indeterminate and when the geometry of the wetted volume is not well defined, e.g. when a selected region of a concrete surface is wetted [9,27]. It is then more appropriate to report test results in terms of the water absorbed per unit area wetted for given wetting times. It could be argued that such results are equally or more relevant than sorptivity to comparisons of field performance for concretes subjected to periodic wetting by rain or immersion. RILEM Recommendation 11.2 suggests that both the weight of absorbed water and the depth of penetration should be reported [28]. It should be noted that samples of equal sorptivity will have different absorption rates if they differ in porosity.

Most publications dealing with water absorption in concrete are concerned with samples that have been oven-dried to constant weight. In contrast, this report investigates water absorption in concretes that have been dried under more realistic conditions. The test specimens were uniaxially dried at normal temperatures and natural carbonation was permitted. All specimens were exposed for 1.5 years, either indoors or outside, prior to uniaxial water absorption measurements. The main experimental variables were exposure conditions, water/cement ratio, initial curing and replacement of Portland cement with pulverized fuel ash, ground granulated blast-furnace slag or limestone filler.

Water absorption is particularly relevant to concrete durability: freeze–thaw damage, sulphate attack, disruptive alkali–aggregate expansion, chloride ingress and reinforcement corrosion can be stimulated by water absorption, while carbonation will be inhibited. In relation to the control of concrete durability, correlations between water absorption after prolonged exposure and results from tests that can be conducted at an early age are of interest. Thus the test programme included measurements of initial weight loss during exposure and of compressive strength. The initial weight loss was a measure of the emptied porosity in cover concrete that reflects the combined effects of capillary porosity and the severity of environmental drying. Compressive strength at the start of exposure was an indirect indication of the initial porosity of the cement paste matrix in cover concrete. Compressive strength at the start of exposure is not regarded as being fundamentally related to water absorption and it clearly cannot reflect any change of moisture conditions or pore structure during exposure.

Correlations between carbonation depth and water absorption are also reported because *in situ* absorption results may be used to assess the condition and future performance of existing structures (e.g. [4,5,9]).

2. EXPERIMENTAL PROCEDURE

The reported work examines the effects of five exposure conditions, five water/cement ratios, three periods of moist curing and four cements upon water absorption: the 30 combinations of these variables that were used in the experimental programme are summarized in Table 1. Workability of the concrete was measured 10 min after the start of mixing; slump values were normally in the range 10 to 30 mm. Weight changes of the test specimens were monitored during the 1.5 year exposure period, and carbonation depths were determined on the test specimens immediately after completion of the absorption tests. Carbonation depths were also measured on similar companion specimens after a six-month exposure period. Compressive strengths were measured on saturated, 100 mm cubes at ages of 1 day, 3 days, 28 days and 1.5 years. The cements used were blended from the materials detailed in Table 2. Table 3 indicates the blend proportions and the cement types according to draft ENV 197 [29].

The test specimens for the absorption and carbonation tests were 100 mm cubes sealed against moisture exchange on five faces. Sealing was accomplished firstly by applying a bituminous waterproofing coat to the concrete; this acted as an adhesive for the aluminium foil water-vapour barrier. The final stage of sealing involved wrapping with self-adhesive, weatherproof plastic tape to give mechanical protection to the foil vapour barrier. The test specimens were cured at 100% relative humidity and 20°C in their moulds up to an age of 24 h. Subsequent moist curing involved storage in sealed conditions at 20°C (without loss or gain of moisture). The laboratory conditions during exposure were 58 ± 3% relative humidity and 20 ± 1°C. Specimens exposed outside were stored on an exposure site in South East England. Meteorological data for the area indicated that relative humidities, temperatures and rain fall were typically in the ranges 58 to 90%, 6 to 21°C and 40–70 mm per month, respectively.

Table 1 Data for each test series[a]

Series	Water/ cement ratio[b]	Cement	Length of cure (days)	Exposure[c]	Cube strength (N mm^{-2})	
					End of cure	28 days
A & L	0.59	opc	3	Lab	22.6	42.1
C	0.59	pfa	3	Lab	13.3	29.5
E	0.59	ggbfs	3	Lab	10.0	33.9
B	0.59	opc	3	OS	22.3	42.8
D	0.59	pfa	3	OS	13.3	30.0
F	0.59	ggbfs	3	OS	9.8	33.1
G	0.59	opc	3	OV	20.4	40.5
H	0.59	opc	3	OH	21.0	39.7
I	0.59	opc	3	Office	21.0	41.6
M	0.59	opc	1	Lab	11.0	41.7
N	0.59	pfa	1	Lab	5.8	29.5
O	0.59	ggbfs	1	Lab	3.0	30.9
P	0.59	opc	28	Lab	44.0	44.0
Q	0.59	pfa	28	Lab	28.2	28.2
R	0.59	ggbfs	28	Lab	30.7	30.7
S	0.71	opc	3	Lab	13.6	28.5
T	0.71	pfa	3	Lab	7.0	18.8
U	0.71	ggbfs	3	Lab	6.6	21.1
V	0.47	opc	3	Lab	29.7	55.0
W	0.47	pfa	3	Lab	20.8	40.5
X	0.47	ggbfs	3	Lab	17.2	46.6
Y	0.83	opc	3	Lab	10.9	19.6
Z	0.83	pfa	3	Lab	5.4	12.3
1	0.83	ggbfs	3	Lab	4.9	16.0
2	0.35	opc	3	Lab	53.8	70.8
3	0.35	pfa	3	Lab	34.0	56.9
4	0.35	ggbfs	3	Lab	31.2	60.5
5	0.59	Filler	3	Lab	21.0	40.7
6	0.59	Filler	3	OS	20.6	39.9

[a] Fine aggregate: Thames Valley sand, 0–5 mm; coarse aggregate: Chertsey irregular gravel, 5–10 mm; fine:coarse aggregate ratio = 1:1.5 by weight.

[b] Free water content of concretes = 188 kg m^{-3}.

[c] Lab = 60% relative humidity, 20°C; OS = outside, concrete exposed face sheltered; OV = outside, concrete exposed face vertical; OH = outside, concrete exposed face horizontal.

An indoor office exposure was also used where relative humidity was not controlled and the temperature was normally between 15 and 25°C. The long-term trends of relative humidity within a 15 mm surface layer of concrete were as follows [30]:

Laboratory	Steady drop to 58%
Office	Steady drop to 45%
Outside sheltered from rain	Fluctuated between 70 and 85%
Outside vertical exposed surface	Fluctuated between 80 and 95%
Outside horizontal exposed surface	Fluctuated between 85 and 100%

Table 2 Analyses of materials used in cements

	F (limestone filler)	P (Portland cement)	A (pulverized fly ash)	S (ground granulated blast-furnace slag)
Composition (wt%):				
SiO_2	2.5	20.3	47.7	34.5
Al_2O_3	0.3	5.02	26.6	12.6
Fe_2O_3	0.1	3.23	9.1	0.6
CaO	54.1	64.8	1.7	41.6
MgO	–	1.30	1.3	6.9
SO_3	0.04	2.96	0.8	0.81 sulphide
K_2O (total)	0.05	0.86	3.4	0.68
Insoluble residue	–	1.19	–	0.43
LOI	42.5	1.59	5.8	0.55
Free lime	–	2.06	–	–
Apparent particle density ($kg\ m^{-3}$)	2700	3110	2400	2920
SSA ($m^2\ kg^{-1}$)	1180	395	375	455
Residue (%):				
45 µm	8.3	–	7.0	11.6
150 µm	–	0.14		
90 µm	–	–	–	1.9

Table 3 Cement types

Cement name	Components by weight (%)	ENV 197 cement	
		Type	Class
opc	100% P	CEI	42.5R
pfa	70% P + 30% A	CEIV[a]	32.5R
ggbfs	50% P + 50% S	CEIII	42.5
Filler	95% P + 5% F	CEI	42.5R

[a] Fly ash near 28% limit for CEIIC [29].

Uniaxial wetting was achieved by placing the single exposed face of the test specimen on a wire grid that was 1 mm below a water surface. Water absorption was measured after 1, 2, 4, 6, 24 and 30 h of wetting. Wetting and weight gain measurements were continued until half of the exposure weight loss was regained. The test specimens were then oven-dried at 105°C for 18 h prior to carbonation measurements. The depth of carbonation was determined by lightly spraying split concrete surfaces with a phenolphthalein pH indicator solution and measuring the average depth of the magenta, uncarbonated region using an illuminated magnifier that was fitted with a measuring graticule. The indicator solution was prepared by dissolving 5 g of phenolphthalein in 950 ml of industrial alcohol (95% ethanol + 5% methanol) and adding 50 ml of distilled water.

3. RESULTS AND DISCUSSION

Some typical plots of water absorbed versus the square root of time are illustrated in Fig. 1. None of the tests yielded a linear relationship and the exponent for a power-law time function averaged 0.32 rather than 0.5. The non-linearity in Fig. 1 may be due to moisture and porosity gradients. Higher moisture contents and lower porosities with increasing distance from the exposed surface have been observed in mature, companion specimens [24,30] and in other studies (e.g. [1,2]). More detailed measurements of porosity gradients are planned in order to clarify their role in controlling the relationship between the weight of water absorbed and the time of wetting. The shape of each absorption curve appeared to be geometrically similar and this observation was supported by the results shown in Fig. 2. The absorption after 4 h of wetting was closely and almost linearly related to the absorption after 1 h regardless of exposure condition, water/cement ratio, curing or cement type. The relationship between the absorption results for 24 and 1 h was more scattered. The range of absorption values in Fig. 2 are comparable in magnitude to those obtained by Torrent and Jornet [3]. It may be noted that the water absorbed after 4 h typically constitutes 15 to 35% of the water lost during exposure. Thus on average the 4 h value represents the absorption characteristics of a surface zone approximately 15 to 35 mm deep, and corresponding roughly to cover concrete. These depths of penetration are consistent with other reported data [12,14–16,32]. Since the role of cover concrete in controlling durability is of prime concern, attention will be focused upon absorption values measured after 4 h of wetting.

Fig. 3 illustrates the effect of water/cement ratio upon the 4 h absorption value. Absorption increased with water/cement ratio in agreement with other data [3,11,22,23] and a similar pattern was observed for the ordinary Portland, pulverized fuel ash and ground granulated blast-furnace slag cements. There was no evidence to suggest that prolonged exposure encouraged microstructural development that was especially beneficial to the absorption characteristics of concretes made with blended cements: the Portland cement concretes generally exhibited the lowest absorption values at a given water/cement ratio. The replacement of 5% of the Portland cement with limestone filler caused a small increase in absorption.

The effect of exposure condition upon absorption is shown in Fig. 4. It was evident that absorption was much smaller in wetter concretes. The effect was particularly significant where rain could fall upon the exposed concrete surface. Outdoor exposure with the concrete sheltered from rain caused only a limited reduction of absorption relative to the values for laboratory exposure. The sensitivity of absorption to the moisture condition of the concrete has also been recognized in other investigations [13,23,32,33].

The beneficial effects of curing upon the resistance of concrete to water absorption are demonstrated in Table 4

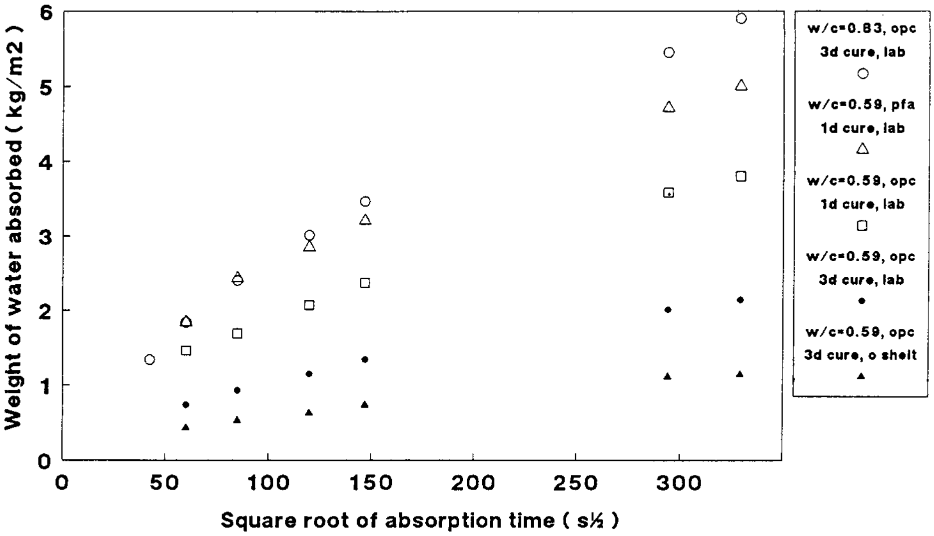

Fig. 1 Examples of water absorption results for a range of experimental conditions.

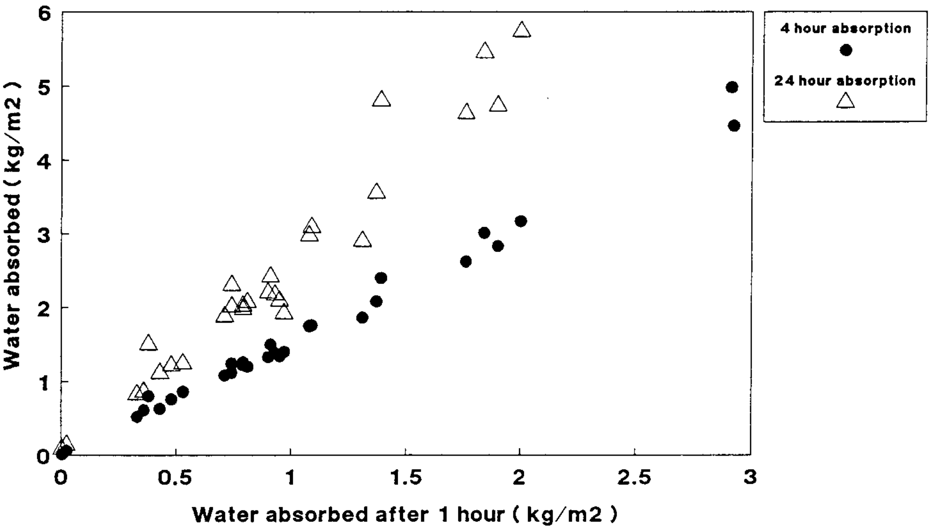

Fig. 2 Water absorption after 1, 4 and 24 h of wetting.

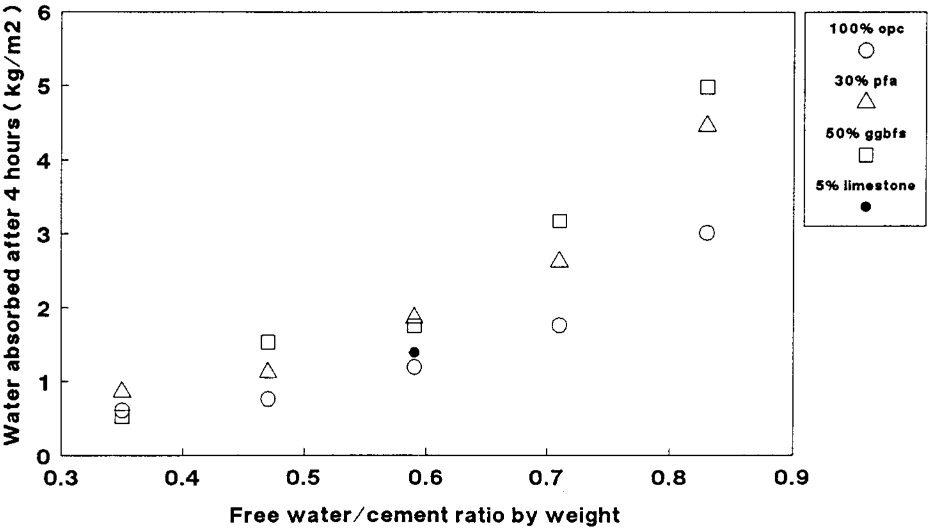

Fig. 3 Effect of water/cement ratio and cement type upon water absorption after 1.5 years of laboratory exposure (3 days moist curing).

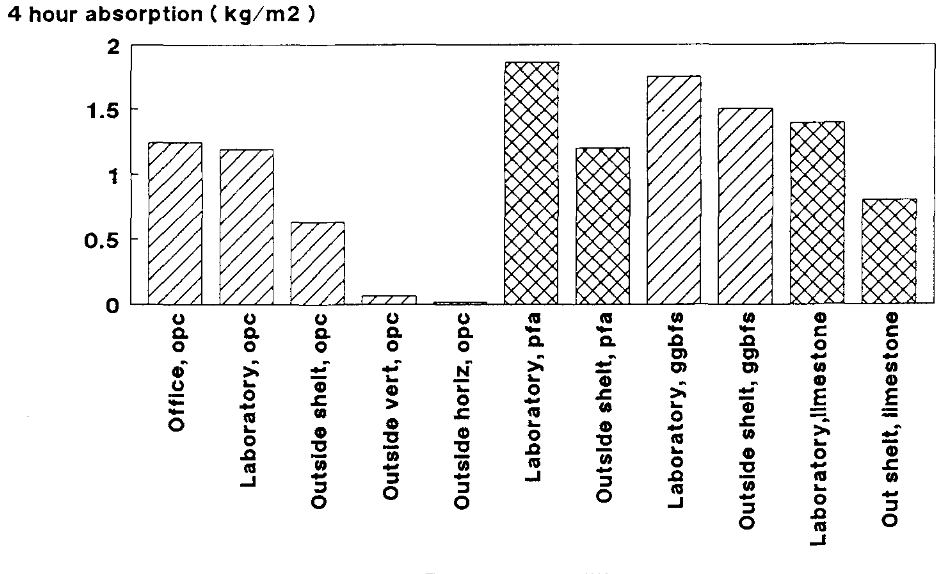

Fig. 4 Effect of exposure condition upon water absorption after 1.5 years of exposure (3 days moist curing, 0.59 water/cement ratio).

Table 4 Effects of curing and Portland cement replacement upon water absorption (kg m^{-2}) after 1.5 years of laboratory exposure and wetting for various times (0.59 water/cement ratio)

Moist cure (days)	100% opc			30% pfa			50% ggbfs		
	1 h	4 h	24 h	1 h	4 h	24 h	1 h	4 h	24 h
1	1.46	2.07	3.58	1.84	2.85	4.71	1.39	2.40	4.70
3	0.77	1.19	1.99	1.31	1.86	2.70	1.08	1.75	2.97
28	0.71	1.08	1.88	0.95	1.34	2.09	0.97	1.37	1.92

and are in good agreement with other data [2,12,14,22]. Similar effects of curing were observed for 1, 4 and 24 h of wetting, even though the different periods correspond to increasing depths of water penetration. Curing beyond 3 days reduced the absorption levels for concretes made with pulverized fuel ash or ground granulated blastfurnace slag but for ordinary Portland cement concrete long-term curing had only a small effect. When Portland cement was partially replaced with pulverized fuel ash or ground granulated blastfurnace slag it was necessary to increase the curing time from 3 to 28 days in order to achieve similar absorption results; this is consistent with European code requirements for longer curing periods when these cements are used at constant water/cement ratio. The sensitivity of absorption to the effects of curing has encouraged its use for evaluating the effectiveness of membranes and sheet materials as concrete curing aids [34].

The rate of water absorption into cover concrete should be less in material with finer pores and the results in Fig. 5 are consistent with this idea if we assume that finer pores are associated with a lower porosity in the cover concrete and a lower weight loss during initial exposure. The results for different water/cement ratios, exposure conditions, cements and curing periods conform approximately to a single relationship with the exception of two results. These two results were for outdoor exposure where rain could fall on the exposed concrete surface. The dry conditions during the initial 4 days of exposure were not representative of the wetter, average conditions during the 1.5 year exposure period. The initial, 4 day weight loss was a more sensitive indicator of long-term absorption performance for the less porous concretes.

Compressive strength is often regarded as a general measure of concrete quality. The standard 28-day strength obviously cannot account for any effect of initial moist curing, but if absorption is plotted against strength at the start of exposure then a broad relationship is obtained (Fig. 6). Analysis of the initial surface absorption results of Dhir *et al.* [22] for oven-dried test specimens also yielded a broad relationship with compressive strength at the start of exposure. Fig. 6 shows that strength is a more sensitive indicator of absorption for the less porous concretes. The results in Figs 5 and 6 indicate that measurements of weight loss during initial exposure or strength at the start of exposure could be used for concrete control purposes in order to avoid concrete with a potential for high levels of water absorption.

Compressive strengths were also determined for unsealed cubes that were exposed in parallel with the partially sealed specimens used for absorption and carbonation tests. To obtain a standard test condition the cubes were resaturated for 30 min prior to crushing at an age of 1.5 years. As shown in Fig. 7 this measure of strength gave a plot against absorption similar in appearance to that illustrated in Fig. 6 although scatter was slightly smaller. Possibly the relatively dry conditions in the unsealed cubes better represented the surface zone penetrated by water in the absorption test. These results, coupled with the data in Fig. 6, suggest that differences of absorption are primarily due to differences between concretes that are present at the start of exposure.

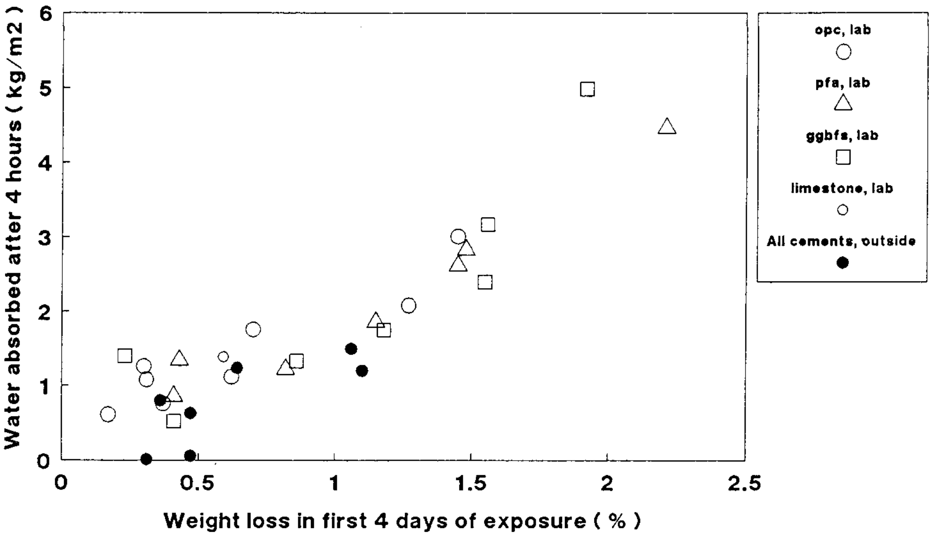

Fig. 5 Water absorption after 1.5 years of exposure versus weight loss during initial exposure.

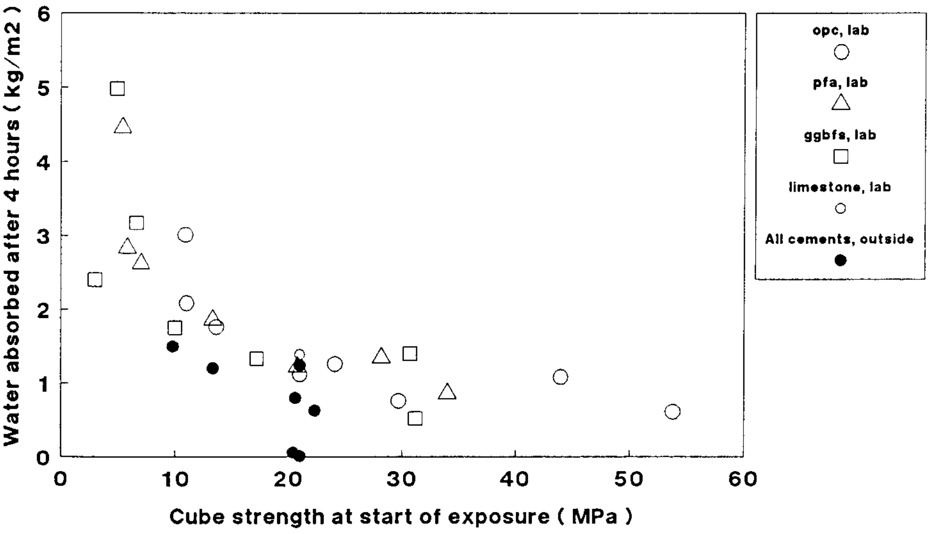

Fig. 6 Water absorption after 1.5 years of exposure versus cube strength at start of exposure.

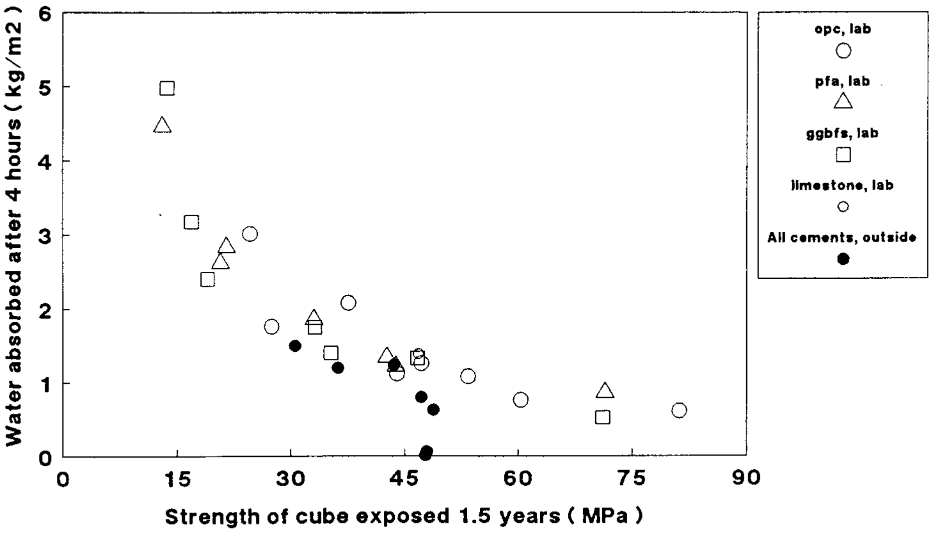

Fig. 7 Water absorption versus cube strength after 1.5 years of exposure.

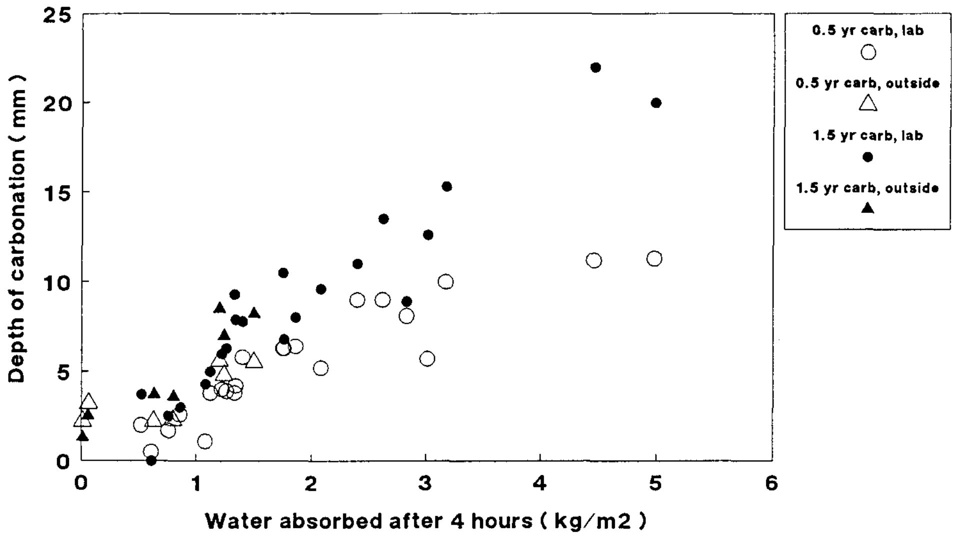

Fig. 8 Carbonation depths at 0.5 and 1.5 years versus water absorption after 1.5 years of exposure.

The results in Fig. 8 show that the relationship between carbonation and absorption, both measured 1.5 years after the start of exposure, is virtually linear and is not affected greatly by exposure conditions or other experimental factors. The results for carbonation measured after 6 months exhibited a non-linear relationship with 1.5 year absorption. Further measurements are required but it seems possible that high water absorption results could be indicative of high rates of long-term carbonation and vice versa. The results at the higher levels of absorption appear to conform approximately to a square-root time function for carbonation. Rostasy and Bunte [4] suggested that field measurements of absorption could be used for the prediction of *in situ* carbonation.

A realistically wide range of experimental conditions was used for the present tests and therefore some practical observations seem warranted:

(a) Indications of long-term water absorption performance can be obtained from rapid and convenient early-age measurements of strength at the start of exposure or weight loss during initial exposure. They both account approximately for effects of water/cement ratio, cement and curing. Clearly the effects of long-term exposure cannot be accounted for with the strength measurements, but weight loss data may be useful in this respect if initial exposure is representative of long-term exposure.

(b) Carbonation depths could be approximated from water absorption data.

(c) Field measurements of water absorption in damp concrete should not necessarily be preceded by attempts at artificial drying: a measured value of absorption associated with naturally occurring moisture conditions seems to be of greater significance for durability assessment. Parallel arguments could be applied to the need for unrealistic pre-drying in laboratory absorption tests.

4. CONCLUSIONS

The water absorption measurements on various concretes exposed for 1.5 years under a range of environmental conditions led to the following conclusions:

1. Water absorption after a given wetting time was increased with an increase of water/cement ratio, a reduction of moist curing time and partial replacement of the Portland component of the cement with pulverized fuel ash or ground granulated blastfurnace slag.
2. The 4 hour absorption after outdoor exposure was less than that after laboratory exposure, especially if rain could fall on the concrete surface.
3. Absorption results correlated approximately with weight losses during initial exposure and with cube strengths at the start of exposure for a wide range of experimental conditions.
4. There was a near-linear relationship between carbonation depths and absorption measured in cover concrete after 1.5 years of exposure for a wide range of experimental conditions, including different exposure conditions.

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RESUME

Absorption d'eau dans le béton d'enrobage

On rend compte de mesures de l'absorption d'eau initiale sur des bétons exposés pendant 18 mois en milieu fermé et en plein air. Après un temps donné d'humidification, l'absorption d'eau augmentait avec l'accroissement du rapport eau/ciment, la diminution de la conservation à l'état humide et le remplacement partiel du composant de clinker Portland du ciment. A la suite de l'exposition à l'air libre, l'absorption, en particulier si la pluie était tombée sur la surface du béton, était moindre qu'en laboratoire. Les résultats de l'absorption correspondaient approximativement avec les pertes de poids durant l'exposition initiale, et aux résistances en compression au début de l'exposition. On a constaté une relation non linéaire entre les profondeurs de carbonatation et l'absorption mesurées dans le béton d'enrobage après une exposition de 18 mois.