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Gas permeability coefficient of cover concrete as a performance control

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ABSTRACT

A simple and practical gas permeability measurement method, known as the overpressure method, was used to assess the quality of cover concrete. This method enables distinguishing the quality of cover concrete both qualitatively and quantitatively, under laboratory conditions and/or *in situ*. The gas permeability values obtained are sensitive to changes in curing duration, water/cement ratio, age of testing and moisture history of the concrete. It has been confirmed from the test results that compressive strength alone cannot be a good indicator of concrete durability. It has also been observed that sorptivity and gas permeability values are linearly proportional to each other.

RÉSUMÉ

Une méthode simple et pratique pour mesurer la perméabilité au gaz, appelée la méthode de surpression, a été utilisée pour déterminer la qualité de l'épaisseur d'enrobage du béton. La méthode permet une détermination qualitative et quantitative, en laboratoire et/ou in situ. *Les valeurs de la perméabilité au gaz obtenues sont sensibles aux variations de la durée de cure, du rapport eau/ciment, de l'âge de l'essai et de l'historique de l'humidité du béton. Les résultats des essais confirment que la résistance à la compression seule ne peut être un bon indicateur de la durabilité du béton. Il a également été constaté que les valeurs d'absorption et de perméabilité au gaz présentent une corrélation linéaire.*

1. INTRODUCTION

Concrete is a heterogeneous material consisting of aggregates bound with cement paste. Its performance properties are thus influenced by the properties of its constituent materials, its mixing, placement and curing, and its environmental exposure. It is an established fact that differences in relative humidity and temperature in both curing and storage conditions result in noticeable variations in concrete properties due to the fact that environmental exposure determines the moisture content and moisture distribution in a concrete specimen. Thus, the determination of moisture content of test specimens at the time of testing is vital for the correct interpretation of test results.

It has been generally understood that in the study of the durability properties of concrete, the topmost concrete cover, which is about 30-50 mm, requires more attention than the inner section, since nearly all transport mechanisms in concrete are influenced by the quality of this layer. Consequently, the gas permeability measurement of concrete cover is considered to be more suitable in assessing the performance properties of concrete than diffusivity, sorptivity or water permeability measurements for various reasons: *e.g.* gas permeability values are more sensitive to changes in the pore

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structure; gas permeability measurements are relatively simple, take only a short time and produce repeatable test results. In this respect, the tendencies of current research work are aimed at relating measured gas permeability coefficients of concrete to performance properties of concrete in order to make a prognosis of durability [1, 2].

Table 1 - Mix composition and fresh concrete properties

Mix type	w/c	Cement [kg/m^3]	Cement type	Aggregate size [mm]	Workability (1)	Density [kg/dm^3]
A	0.47	360	CEM I 32.5R	0/32	365	2.39
B	0.52	320	CEM I 32.5R	0/32	370	2.40
C	0.60	280	CEM I 32.5R	0/32	450	2.41
D	0.65	260	CEM I 32.5R	0/32	425	2.38
E	0.46	369	CEM I 32.5R	0/16	360	2.34
F	0.56	300	CEM I 32.5R	0/16	365	2.34
G	0.63	270	CEM I 32.5R	0/16	380	2.35
H	0.50	340	CEM I 42.5R	0/16	355	2.36
I	0.63	270	CEM I 42.5R	0/16	360	2.34
J	0.51	340	CEM II/A-V32.5R	0/16	355	2.33
K	0.64	270	CEM II/A-V32.5R	0/16	370	2.33
L	0.51	340	CEM III/A32.5	0/16	415	2.34

(1) = workability [mm] measured using flow table test.

Despite the existence of numerous gas permeability test methods [3-12], there is still a lack of general agreement in standardizing gas permeability measurement. A majority of the existing gas permeability test methods are destructive and suitable under laboratory conditions primarily. In most cases, they require pre-conditioning of the test specimens before testing and therefore, test results do not represent the actual situation. For instance, drying concrete in an oven at a temperature of over 100 °C results in micro-cracks, while complete saturation results in changes in the pore structure of test specimens due to possible rehydration. Therefore, it is difficult to compare gas permeability values obtained by using different test methods and various test procedures. In the case of unconditioned specimens, the effect of moisture present in the test specimens on the gas permeability of concrete is not given adequate attention. Instead of test specimen conditioning, the best alternative should have been to assess or determine the moisture content of test specimens just before gas permeability testing, for instance by measuring the relative humidity in the cover concrete and considering the measured relative humidity value in the analysis of gas permeability coefficients. If proper relative humidity measurement methods are incorporated, such steps are believed to reduce the effort involved in conditioning specimens in the laboratory and to give the actual material property.

In this paper, results of gas permeability coefficients obtained by using the overpressure test method are discussed. A practical means of moisture content assessment in concrete specimens is described. The compressive strength, depth of carbonation and sorptivity values of various concrete mixes were determined, and are discussed herein in relation to the gas permeability coefficients.

2. EXPERIMENTAL DETAILS

2.1 Materials, mix proportions and curing

The fine and coarse aggregates used for the concrete mixes were rounded quartzite aggregate obtained from the upper Rhine valley; they were dried, cleaned and stored at room temperature in the laboratory. Cements were supplied by the Schwenk cement producers from Ulm in south-western Germany.

Twelve different concrete mixes, as shown in Table 1, were prepared for this investigation. The concrete cubes (150 × 150 × 150 mm^3) were demoulded 24 hours after casting and were cured for 1, 3 or 7 days in a humid room at a temperature of 20 °C and at 100% relative humidity. The specimens were then stored in a controlled room at a temperature of 20 °C and at 65% relative humidity until the day of testing.

2.2 Determination of gas permeability coefficient

The gas permeability of the concrete specimens was determined by using the overpressure method [7], which has been modified in the present investigation [14] and is schematically shown in Fig. 1. The principle of the measurement is basically to inject nitrogen gas at high pressure (11 bar) through a hole of 14 mm in diameter and 45 mm in depth, to wait for a few seconds until stability, and then to measure the rate of pressure decay as demonstrated schematically in Fig. 2. Recording of the pressure decay starts when the pressure reaches 10 bar and continues at a pressure interval of 0.5 bar for normal concrete and at an interval of 0.1 bar for very dense concrete, until it reaches 7.5 bar and 9.0 bar, respectively.

Considering the rate of pressure decay, it is possible to distinguish concrete quality qualitatively. For instance, using a reservoir volume of 94 cm^3 and a pressure decay range of 11-10.5 bar (absolute), a qualitative concrete

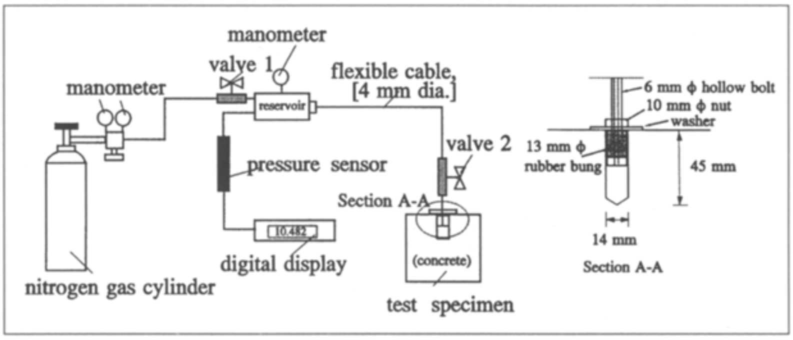

Fig. 1 - Schematic arrangement of the overpressure method.

Table 2 - General concrete quality classification		
Absolute test pressure [bar]	Time [sec]	Concrete quality
11 - 10.5	$t \leq 50$	High-permeable concrete
11 - 10.5	$50 \leq t \leq 150$	Average-perm. concrete
11 - 10.5	$t \geq 150$	Low-permeable concrete

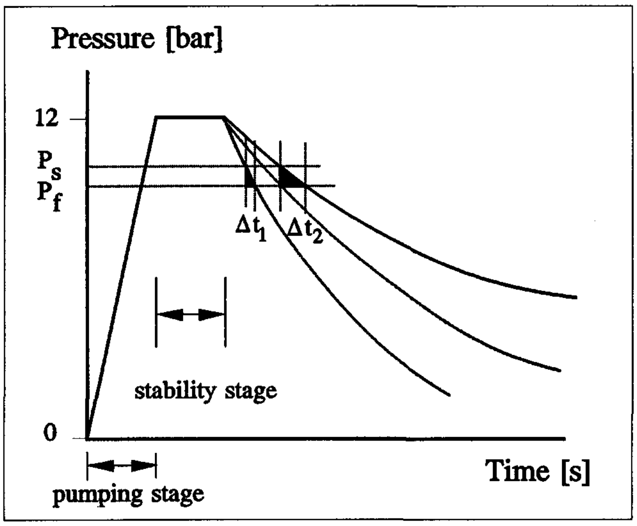

Fig. 2 - Schematic pressure decay measurement.

classification, as shown in Table 2, is established for various concrete mixes tested at the age of 1 year. Although this classification is based on the volume of the reservoir, it does provide a general idea about the concrete quality and can be used for routine performance assessment.

According to Table 2, high-permeable concrete includes those concretes having a w/c ratio ≥ 0.60 (*e.g.* B 15, B 25 and only 1-day cured B 35), while low-permeable concrete contains specimens having a w/c ratio ≤ 0.50 and having been cured for a minimum of 3 days after casting (*e.g.* B 45, B 55). For a general interpretation of test results, a permeability index, K_{indx}, is established as given in equation (1):

$$K_{indx} = \frac{V_{res}}{t} \tag{1}$$

where:

K_{indx} = gas permeability index [m³/sec]

V_{res} = reservoir volume [m³]

t = pressure decay time [sec]

The permeability index, K_{indx}, can be used as a technological index to the gas permeability of concrete since it accounts for the reservoir volume. Using equation (1) and substituting it into Table 2, the following qualitative classification can be made:

if $K_{indx} \geq 1.88$ m³/s	high-permeable concrete
if 0.63 m³/s $< K_{indx} < 1.88$ m³/s	average-quality concrete
if $K_{indx}x \leq 0.63$ m³/s	low-permeable concrete.

The specific gas permeability coefficient of the concrete specimens was determined using the Hagen-Poiseuille relationship for the laminar flow of a compressible fluid in a steady-state condition by using equation (2):

$$K = 2 \cdot \eta \cdot \frac{L}{A} \cdot \frac{V}{t} \cdot \frac{P_2}{P_1^2 - P_2^2} \tag{2}$$

where:

K = specific gas permeability coefficient [m²]

η = viscosity of nitrogen gas at room temperature [17.6x10⁻⁶ Ns/m²]

V = volume of gas passed through the concrete surface during the testing time [m³]

A = cross-sectional area in the flow direction [m²]

L = length of flow [m]

P_2 = atmospheric pressure, usually 1 bar

P_1 = average overpressure, $(P_s + P_f)/2$ [bar]

t = time [sec].

The volume of gas passed through the concrete surface, V, during the testing time interval was obtained using equation (3):

$$V = \frac{(P_s - P_f) \cdot V_{res}}{P_{atm}} \tag{3}$$

where:

P_s = absolute starting pressure [bar]

P_f = absolute final pressure [bar]

V_{res} = volume of the nitrogen gas reservoir, [94x10⁻⁶ m³]

P_{atm} = P_2 = atmospheric pressure [1 bar].

The values of A and L are difficult to determine exactly under test conditions. However, they can be approximated as being constant due to the fact that they are more geometrical factors than the material property, and that the same test method and test procedure were employed throughout the investigation. Accordingly, the value of A was taken as the area enclosed within a radius of 35 mm from the centre of the bore hole, and L was taken as 28 mm as an effective pressure drop, as shown in Fig. 3. Similar approximations of area A have been suggested in the literature [9, 12, 13].

Inserting the values of η, V_{res} (94 cm³), A and L into equation (2) and using P_s and P_f as 11 and 10.5 bar, respectively, a simplified equation for determining the gas permeability coefficient is obtained as:

$$K = 105.09 \cdot 10^{-17} \cdot t^{-1} \quad [\mathrm{m}^2] \tag{4}$$

Similar expressions can be derived for different reservoir volumes and for various starting and finishing pressures.

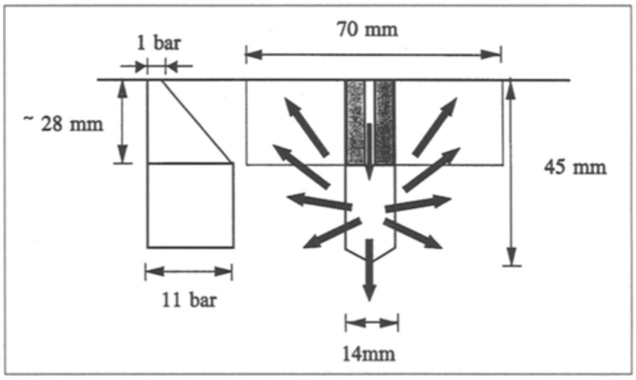

Fig. 3 - Gas flow and pressure distribution in a test hole.

The moisture content in the test specimens was assessed by measuring the relative humidity in the test holes drilled for the gas permeability measurement using a relative humidity sensor. The measurement of relative humidity enables distinguishing between the effects of porosity and of moisture content on the gas permeability coefficients; it can also be used to check the repeatability of the test methods [9, 14].

2.3 Determination of sorptivity

The water sorptivity of the concrete test specimens was determined using the capillary suction method. Before the test, the cylindrical specimens were dried in an oven at a temperature of 65 °C to a constant mass. The circumference of the specimens was coated with transparent epoxy resin in order to allow flow only in one direction. The measurement of sorptivity values can require more time depending on the specifications and the test method used. Some investigators have suggested taking the early hours of absorption values to calculate the sorptivity. For instance, Parrot suggested the 4-hour sorptivity values to be ideal as an indicator of durability [15, 16]. Without specifying the testing time, Hall pointed out that a minimum of 5 points is essential to define a good sorptivity plot [17].

In this investigation, the 24-hour sorptivity values are considered, and data points are fitted using linear regression in the form of equation (5):

$$i = A + S \cdot t^{1/2} \tag{5}$$

where:

i = volume of water absorbed per unit area [m^3/m^2]

S = a material constant called the sorptivity [m/sec$^{1/2}$]

A is an intercept that takes into account the effect of initial filling of the open surface porosity, and its values were nearly zero for good quality concrete and around 1.0 mm for poor-quality concrete.

Table 3 – The effects of curing duration on the mean compressive strength, gas permeability, depth of carbonation and sorptivity of the test specimens

Mix type	Curing days	$f_{c,28}$ [N/mm^2]	$K_{90\ days}$ [10^{-17}m^2]	$K_{1\ year}$ [10^{-17}m^2]	1-yr. carb. depth [mm]	$S_{24\ hr.}$ [mm/√h]
A	1	49.1	1.251	–	6.0	$1.00^{(2)}$
	3	54.4	0.693	0.907	4.0	$0.95^{(2)}$
	7	55.0	0.493	0.861	3.0	$0.95^{(2)}$
B	1	47.6	2.817	–	6.5	–
	3	47.7	1.681	–	5.0	–
	7	52.6	1.325	–	3.5	–
C	3	41.0	5.126	–	–	–
	7	43.5	5.530	2.144	4.0	–
D	1	33.0	4.203	–	9.0	$1.23^{(2)}$
	3	37.3	2.060	4.705	6.5	–
	7	37.1	1.585	3.702	5.5	$1.08^{(2)}$
E	1	54.9	1.360	1.04	5.5	$0.98^{(3)}$
	3	56.3	1.250	0.633	3.5	–
	7	60.2	0.953	0.613	2.0	$0.83^{(3)}$
F	1	43.3	1.890	2.280	7.0	$1.35^{(3)}$
	3	46.0	0.557	0.682	5.0	–
	7	48.0	0.381	0.391	3.5	$1.07^{(3)}$
G	1	36.7	2.610	2.920	8.0	$1.40^{(3)}$
	3	38.3	0.914	0.968	6.0	–
	7	42.8	0.513	1.356	4.5	$1.09^{(3)}$
H	1	52.9	1.171	0.968	4.5	–
	3	56.0	1.080	0.560	2.5	–
	7	55.6	0.816	0.516	2.0	–
I	1	40.2	1.900	3.336	7.5	$1.16^{(2)}$
	3	47.6	1.946	2.563	5.5	–
	7	46.7	1.114	1.025	5.0	$1.10^{(2)}$
J	1	49.4	0.500	–	$5.0^{(1)}$	–
	3	52.0	0.472	–	$2.0^{(1)}$	–
	7	54.8	0.204	–	$1.8^{(1)}$	–
K	1	39.7	1.834	–	$4.0^{(1)}$	–
	3	41.9	0.893	–	$3.0^{(1)}$	–
	7	45.6	0.731	–	$2.0^{(1)}$	–
L	1	35.5	4.325	–	$6.5^{(1)}$	–
	3	40.0	1.289	–	$5.5^{(1)}$	–
	7	44.4	0.401	–	$5.0^{(1)}$	–

(1)= Carbonation depth measured at an age of 6 months.
(2) = Sorptivity values determined at an age of 90 days.
(3) = Sorptivity values determined at an age of 1 year.

3. RESULTS AND DISCUSSION

3.1 Compressive strength

The compressive strength of the test specimens was determined using 150-mm cubes at an age of 28 days. The mean value of three concrete cubes was considered to represent each concrete quality, and the mean compressive strength values are given in Table 3. The test results indicate that compressive strength values are generally more sensitive to changes in w/c ratios than they are to changes in curing duration.

3.2 Sorptivity

The results of water absorption tests show that, under similar curing durations, concrete specimens with higher w/c ratios absorb more water than those with relatively lower w/c ratios. This is explained by the fact that concretes made using high w/c ratios are more porous and therefore absorb more water than denser concretes. In addition, the sorptivity values are sensitive to curing duration, as shown for the typical case in Fig. 4.

3.3 Depth of carbonation

The depth of carbonation of the test specimens was determined by spraying phenolphthalein solution onto the freshly-split concrete specimens, and values measured at an age of 1 year are displayed in Table 3. Fig. 5 shows

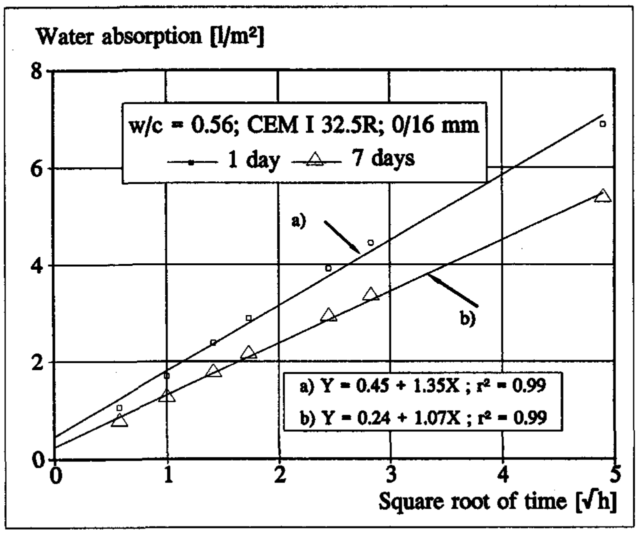

Fig. 4 - Effects of curing on the sorptivity of concrete specimens tested at the age of 1 year.

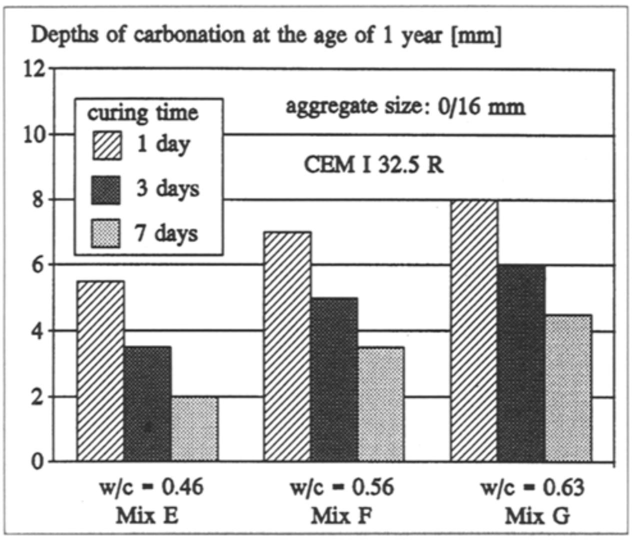

Fig. 5 - Effects of w/c ratio and curing duration on the depths of carbonation for OPC specimens stored in 20 °C and 65% relative humidity.

the typical effects of curing duration and w/c ratio on the depths of carbonation when tested at an age of 1 year. The test results clearly indicate that longer curing durations and decreased w/c ratios are important in reducing the depths of carbonation of concrete specimens.

3.4 Gas permeability coefficient

The specific gas permeability coefficient, K, was determined using equation (4) and values are given in Table 3. A minimum of three freshly-bored holes was considered for the gas permeability measurement, and the mean value was taken to represent the particular concrete quality. When the flow rate, Q (=V/t), is plotted against the squared difference between P_1 and P_2, where P_1 is the average absolute pressure and P_2 the atmospheric pressure, straight lines are typically obtained as shown in Fig. 6, thereby assuring that the theory, *i.e.* Darcy's law, and the experimental results are compatible [5].

The gas permeability coefficients are sensitive to changes in curing duration, test age and concrete composition. An increase in curing duration from 1 to 7 days results in reductions in gas permeability values that are more significant than the improvements in compressive strength values. Similarly, the test results demonstrate that under similar curing durations, a reduction in the w/c ratio results in improvements in gas permeability values greater than the increase in compressive strength values. The basic relationship between gas permeability and compressive strength values is shown in Fig. 7. It can be observed from Fig. 7 that compressive strength alone cannot be a good indicator of concrete quality. Similar target compressive strength values can be derived in alternative ways by varying the concrete composition, w/c ratio and curing duration at the expense of increased gas permeability coefficients. This would mean that concrete specimens with similar compressive strength values do not necessarily exhibit similar performance properties. Furthermore,

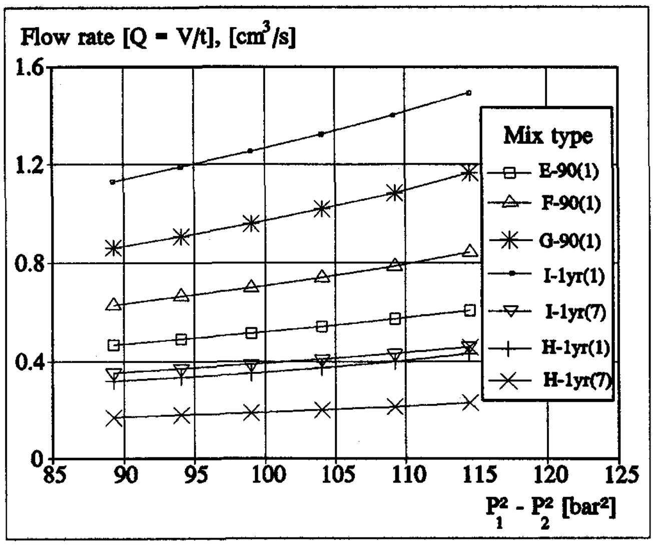

Fig. 6 - Typical relationship between gas flow rate and respective pressure drop.

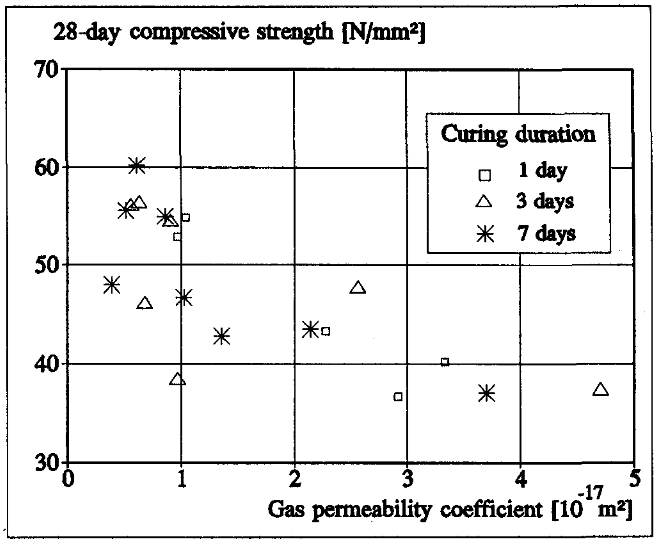

Fig. 7 - The relationship between 28-day compressive strength and 1-year gas permeability coefficients for OPC concrete.

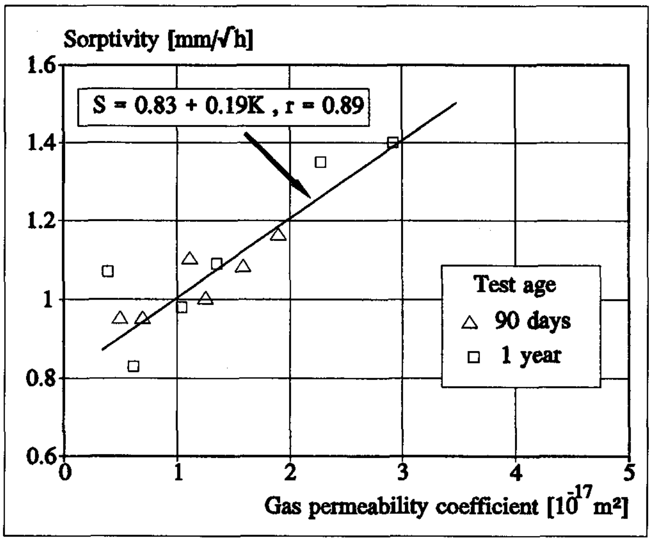

Fig. 8 - The relationship between sorptivity and gas permeability of OPC concrete.

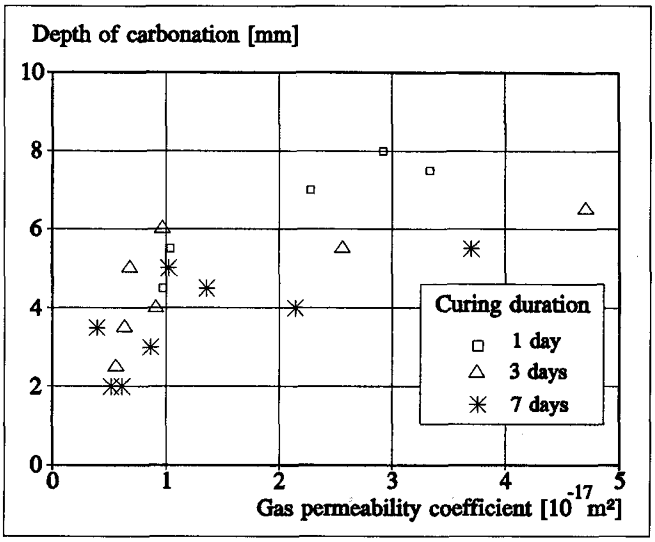

Fig. 9 - The relationship between depths of carbonation and gas permeability of OPC concrete tested at the age of 1 year.

higher compressive strength does not necessarily mean less permeability. For instance, a dried and cracked concrete can have high compressive strength yet a high gas permeability coefficient as well.

The effects of curing on the performance properties of concrete cannot be assessed using the traditional compressive strength tests. Such an assessment can only be conducted by relying on other test methods, which consider the pore structure of the test media. In this respect, sorptivity, diffusion and permeability measurements are more appropriate. The obtained test results highlight the need for a simple and practical performance testing method, which can be used to assess the quality of concrete both in the laboratory and *in-situ*, without significant destruction and at a minimum cost.

Fig. 8 shows the relationship between sorptivity values and gas permeability coefficients. It can clearly be observed from the test results that, within the range of testing, the two values are linearly proportional to each other. However, gas permeability coefficients are more sensitive to variations in curing duration and w/c ratio than are sorptivity values, as shown in Table 3. Nevertheless, if further investigations were incorporated, it would be possible to predict the gas permeability from the sorptivity measurements or vice versa.

Fig. 9 displays the relationship between depths of carbonation and gas permeability coefficients determined at an age of 1 year. Though non-linear, the general tendency is that increased curing duration reduces both the gas permeability coefficients and the depths of carbonation of concrete specimens.

3.5 Effects of moisture

The moisture content of the concrete specimens was assessed by measuring the relative humidity in the test holes just before gas permeability testing using a relative humidity sensor. All of the specimens used for this investigation were stored in a controlled room at a temperature of 20 °C and at 65% relative humidity until the day of testing, and therefore a generally-uniform moisture distribution/content would be expected at similar test ages, especially after 90 days of storage. Accordingly, a relative humidity value in the range of 74-85% and 68-76% was recorded at the ages of 90 days and 1 year, respectively. These relative humidity values (*i.e.* 68-85%) correspond to a moisture content of 2.4-3.7% by weight [14, 18].

An investigation carried out to study the influence of moisture content on the gas permeability coefficient indicated that the effect of moisture is highly significant for wet concrete specimens with relative humidity ≥ 75% and for dried concrete with relative humidity ≤ 40% at the time of testing [14]. Therefore, it is reasonable and practical not to consider correction factors to the calculated gas permeability values when the relative humidity is between 40 and 75%. However, one should be careful when interpreting test results obtained from wet and dried concrete specimens. Wet specimens produce very low gas permeability values since part of the capillary pores is filled with water and thus hinders the free transport of gases, while dried specimens yield unrealistically high permeability values due either to microcracks initiated during drying or to shrinkage.

4. PRACTICAL APPLICATIONS OF RESULTS

It has been observed from the test results that specifying only the compressive strength and w/c ratio is not sufficient in producing durable concrete. A longer curing duration is very important in producing good quality concrete. Test results have indicated that increasing the curing duration from 1 day to 3 or 7 days reduces the gas permeability coefficient by at least one half. In this regard, a minimum of three days of wet curing is suggested in order to meet a sufficient performance requirement.

Based on the test results, it is as easily possible to specify a minimum gas permeability value as it is a performance compliance. For instance, according to Table 2 and equation (4) (see also Fig. 7), for normal OPC concrete, a good quality concrete has a gas permeability coefficient of less than $0.7 \cdot 10^{-17}$ [m^2], while a poor quality concrete has a gas permeability coefficient higher than $2.5 \cdot 10^{-17}$ [m^2]. These values can be used as a basis for concrete mix design focused on performance criteria.

The gas permeability values determined using the overpressure method are generally compatible with the compressive strength, sorptivity and depth of carbonation of similar specimens. The overpressure test method is simple to operate, relatively non-destructive and yields reliable test results (quality indication) quickly. This method can be used to assess a greater number of specimens simultaneously from a single gas cylinder by using extra reservoirs and pressure sensors.

The overpressure test method is very practical since the moisture content is considered in the test result interpretation. Under normal exposure, the effect of moisture is negligible in that the applied test pressure is high, *i.e.* for concrete specimens having a relative humidity of between 40-75%, the pore radius range included in the gas permeability determination at a pressure of 11 bar (absolute) represents the majority of the pores responsible for the transport of gases in concrete. This would have certainly not been possible at very low test pressures. For practical purposes, it is therefore not recommended to test specimens which have been exposed to rain 48 hours before testing. Besides, as has been mentioned in the work of another investigation [9], the measurement of relative humidity enables distinguishing between the effect of porosity and moisture content. For instance, if a very wet concrete specimen were to result in high gas permeability values, the effect would mainly be due to porosity, *i.e.* the specimen would be highly porous. Had the concrete been dense and wet, and saturated with capillary absorption, the result would have been the reverse.

5. CONCLUSIONS

The performance properties of concrete can be both qualitatively and quantitatively assessed by using the *overpressure* test method. Test results obtained by using the overpressure test method are compatible with the other durability parameters, such as sorptivity and depth of carbonation. In an effort to produce durable concrete, in addition to specifying target compressive strength and maximum w/c ratio, it is equally as essential to prescribe gas permeability boundary values which satisfy specific requirements. The measurement of relative humidity in concrete specimens gives information about the moisture content in the concrete, helps in checking the repeatability of a test method, and enables distinguishing between the effect of porosity and that of moisture content on gas permeability.

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