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In this paper test methods that could be used on in situ concrete are used to obtain values for the permeability of concrete. The permeability is of interest because it significantly affects the ability of the concrete to prevent corrosion of embedded reinforcement. The important feature of the tests in this paper is that they yield values for permeability that are expressed in fundamental units and therefore have a better foundation in materials science than tests which only yield comparative data. The two in situ tests used are a new vacuum–air test using drilled holes[1] and a surface absorption test. Results from these tests are compared with direct measurements of permeability obtained in a high pressure through flow cell. The results show strong correlations but some differences in absolute values are noted.

Introduction and research significance

The surface skin of concrete is the first line of defence against the ingress of aggressive agents such as chlorides, sulphates and carbon dioxide. For this reason, there is an increasing awareness of its importance for durability of concrete.[2–4]

The durability of concrete primarily depends on the permeation properties of the surface layer.[5] Durability problems usually involve the movement of aggressive agents from the surrounding environment into the concrete through the cover concrete followed by physical and/or chemical reaction in its internal structure, leading to deterioration. Therefore, the in situ assessment of permeation characteristics of concrete cover is important for the assessment of durability.[6,7]

A number of different permeation tests are available in the literature.[8–13] These tests can be used for quality control and compliance testing, during and immediately after construction, or to check the residual durability of existing structures.[1]

The theoretical analysis of this paper expresses the results in fundamental units of permeability. This permits real comparison of results between the tests in addition to correlation, which would otherwise be the only analysis possible. The ultimate aim of this type of work is to develop the materials science of the measurement of processes such as permeation, diffusion, electromigration and capillary suction, which limit the life of concrete structures. If these processes could be measured in detail and their relative contribution to deterioration could be determined, scientifically based durability assessments of proposed or existing structures could be made.[13]

The specific objective of this paper is to calculate the intrinsic permeability from three different tests in order to compare the different observations of the same physical property of the concrete.

Test methods

Sample preconditioning

One of the major obstacles to applying these tests is the variation of moisture content in concrete, which leads to poor reproducibility of results.[14–16] To overcome this problem a vacuum drying pre-conditioning technique has been used.[17] In this method, a vacuum of 10 mbar absolute pressure is applied to the concrete prior to testing. A silica gel indicator placed at the surface is used to monitor the progress of extracting moisture. As the concrete dries the silica gel changes colour from pink to blue, which means that the moisture content of the near-surface region has reached a standard level.

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The three-hole test

This test is shown in Fig. 1 and its development has been previously reported.[1] The test was developed from the Figg test[11] with the additional holes being used to calculate the distance (X) over which the vacuum decays. This distance is then used to calculate the permeability in fundamental units from the decay times obtained from the standard test.

The testing procedure is as follows.[1]

(*a*) Prepare for Figg test using the standard method but with two additional holes either side of the centre hole.

(*b*) Set up a data logger to take pressure readings in all holes at 10 s intervals.

(*c*) Apply a constant vacuum to the centre hole for 6 min until a stable pressure is recorded in the side hole and then seal the input and let the vacuum decay.

(*d*) The distance X is obtained from applying equation (1) to the results obtained in the steady state with a constant vacuum applied to the centre hole[1]

$$\frac{ln(X/x_1)}{ln(x_1/x_0)} = \frac{(P_a^2 - P_1^2)}{(P_1^2 - P^2)} \tag{1}$$

where X = the distance from the centre of the main hole to a point where the pressure is atmospheric (m); x_1 = the distance from the centre of the main hole to the centre of the side hole (m); x_0 = the radius of the main hole (m); P_a = atmospheric pressure (Pa); P_1 = the pressure at the side hole (Pa); and P = the pressure at the main hole (Pa).

(*e*) The intrinsic permeability is obtained from an analysis of the decay transient, i.e. a vacuum is applied to the centre hole and then the inlet is sealed and the vacuum decays. The analysis of this

has been published by the authors[1,16] and the result is in equation (2). It may be seen that the distance X must be known in order to calculate the permeability K.

$$\frac{(P + P_a)(P_i - P_a)}{(P - P_a)(P_i + P_a)} =$$

$$\exp\left\{\left[\frac{2KP_a t}{ex_0^2}\right] \times \left[\frac{1}{\ln\left(\frac{X}{x_0}\right)} - \frac{1}{L\left(\frac{1}{X_s} - \frac{1}{x_0}\right)}\right]\right\} \tag{2}$$

where P_i = initial pressure; K = intrinsic permeability (m^2); e = viscosity of the fluid (Pa s); t = time from the start of the test (s); L = length of the evacuated volume (m); X_s = radius of a hemispherical region of reduced pressure below the base of the hole. In order to calculate X_s it is assumed that the flow rate, N, per unit area at the boundaries of the two regions is the same.[1]

Initial surface absorption test (ISAT)

This test is well known as described in BS 1881.[18] A cap is sealed to the concrete surface. The system is filled with water, and the rate of flow into the surface is measured by observing the movement of a water meniscus in a capillary tube. The initial surface absorption (ISA) is defined as the rate of flow at stated intervals after the start of the test.

A theoretical analysis of the ISAT has been published by the authors.[19] The derived equation for the flow is

$$F = A\left(\frac{Ks\alpha}{re}\right)^{1/2} t^{-1/2} \tag{3}$$

where F = flow rate (m^3/s); A = cap area (m^2); s = surface tension of water (N/m); α = porosity;
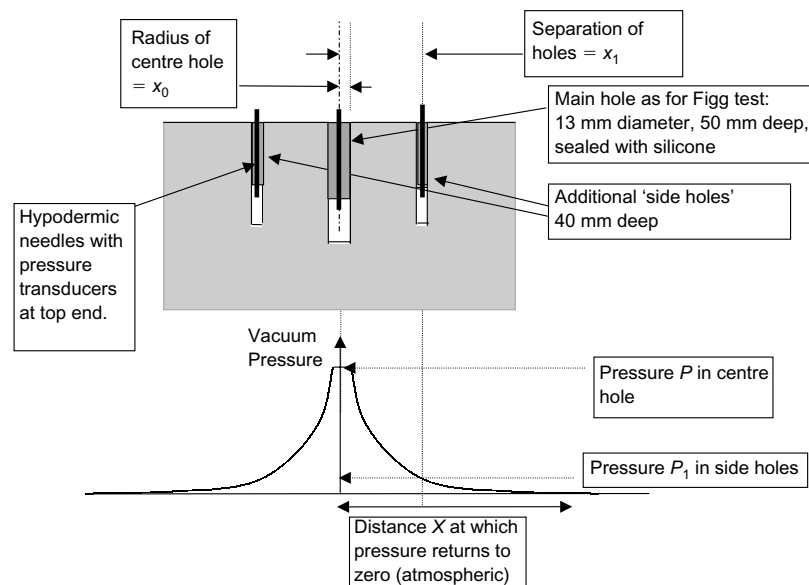

Fig. 1. The three-hole test

r = radius of largest pores (m); t = time after start of test (s).

High pressure permeability apparatus

The apparatus for this test is shown in Fig. 2 and is a modified Hoek cell originally designed for rock testing. The cell is designed to operate at working pressures up to 15 MPa. The cell is connected with hoses to a water pump and a pressurised oil supply. The water pump is operated by a pressurised air supply.

The sample (100 mm diameter) is placed inside the cell on top of the bottom drainage plate. The perforated plate is placed on top of the sample, to prevent mechanical failure of the sample, and then the upper drainage plate is place on top.

The cell is assembled, the pressure applied and the system is left on to reach steady state. Water is collected to approximately equate to one sample volume, then the time required to collect 10 ml of water is recorded to calculate the intrinsic permeability as follows

$$K = \frac{vxe}{P} \tag{4}$$

where v = velocity of flow (m/s), obtained as volume/(cross section area × time); x = sample thickness (m); P = applied water pressure (N/m^2).

Relationship between water permeability and gas permeability

Bamforth[20] reported that gas permeability measurements were higher than those for water permeability. The difference increases as the concrete permeability reduces. The major reason for the differences between water and gas permeability is the theory of gas slippage. The difference is explained by slip in the flow of gas; the gas close to a wall has a finite velocity. The theory suggests that the flow of gas will be affected by pressure (which will affect the mean free path).

Fig. 2. The high pressure test cell

Klinkenberg derived an equation relating water and gas permeability to the mean pressure, for oil sands, as follows

$$K_l = \frac{K_g}{\left(1 + \dfrac{b}{p_m}\right)} \tag{5}$$

where K_l = water intrinsic permeability of concrete (m^2); K_g = gas intrinsic permeability of concrete (m^2); P_m = the mean pressure at which gas is flowing (atmospheres).

Values of b were calculated by Bamforth for concrete from the average values of water and gas permeability as follows

$$b = 1 \cdot 635 \times 10^{-8} K_l^{-0 \cdot 5227} \tag{6}$$

Substituting value of b in equation (5), a relationship between water permeability and gas permeability is derived. Bamforth reported that the gas permeability values may be one or two orders of magnitude higher and the largest difference would occur when testing using a partial vacuum. It is therefore important to consider the effect of slippage when interpreting results obtained from gas measurement as a means of assessing concrete quality.

Experimental programme

Mix designs

Two different concrete mixes and one mortar were designed and made as shown in Table 1. The cement was Portland class 32·5R from Rugby Cement and the aggregates were quartzitic uncrushed from a quarry in Nottinghamshire, UK.

Casting of samples

Mortar mixes were made by using a linear horizontal pan type mixer of 0·04 m^3 capacity, throughout the study. The mixing of mortar was done according to BS 5075.[21] The concrete was mixed in the same mixer. The aggregates were first mixed with half the mixing water for two minutes and permitted to stand for eight minutes. The cement and remaining water were then added and mixed for a further three minutes. Three different mould sizes (i.e. 100 mm cube, 150 mm cube and a prism of 400 × 400 × 100 mm) were cast for each mix.

Curing regimes

Three curing regimes were followed in this study.

(a) Air curing for 28 days in the laboratory at approximately 20°C and 50%RH.
(b) Water curing in tanks at 20°C for 7 days then air cured to 28 days age.
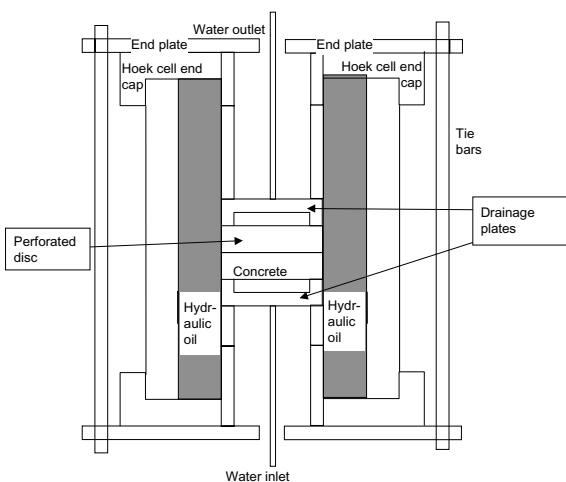(c) 28 day water curing in tanks.

Table 1. Mix designs

Mix number	Cement: kg/m³	Water: kg/m³	Coarse aggregate: 5–20 mm kg/m³	Sand: kg/m³	W/C
1	400	230	810	990	0·58
2	400	190	810	990	0·47
3	400	230	–	1800	0·58

Schedule of testing

The programme of tests is shown in Table 2.

Three-hole test

Three holes were drilled in each sample. The main hole (13 mm diameter, 50 mm depth) was drilled at the centre of the cube surface opposite to the as cast surface. Two side holes (4 mm diameter, 40 mm depth) were drilled at 30 mm and 40 mm distance from the centre of the main hole. When the holes had been drilled the sample was vacuum dried as described above. Testing was carried out immediately after vacuum drying. For the main hole, a 15 mm sponge disc was inserted in the base of the hole and the top 20 mm was blocked with a liquid rubber silicone. For the two side holes, a 5 mm sponge disc was inserted below 20 mm of liquid rubber silicone. A period of 24 h was allowed for silicone to cure.

The main hole was connected to the vacuum pump by inserting a hypodermic needle through the silicone fixed to a flexible tube. It was found that the piezoresistive pressure transducers could be conveniently assembled directly onto the hypodermic needles thus minimising 'dead volume' that would have affected the readings. Before applying the vacuum three readings of pressure were taken at 10 s intervals in order to zero the pressure sensors.

A constant vacuum pressure of 35 kPa absolute pressure was applied to the main hole for 6 min then the vacuum pump was disconnected. Readings were collected using a data logger, until the pressure returned to atmospheric. The pressures in the steady state and the time for the pressure in the main hole to rise from 45 to 55 kPa were recorded.

ISAT

This test was carried out to BS1881.[19]

High pressure permeability test

Cylindrical samples (100 mm diameter, 200 mm length) were cast from each mix as shown in Tables 1 and 2. Samples were cured as described above. Two discs of 50 mm thickness were cut from the central portion of each cylinder for testing.

The applied oil pressure was 10 MPa on the rubber membrane around the curved surface of the sample. The water pressure was 6 MPa. The difference between the oil and water pressure was enough to produce a proper seal to the sample curved surface and stop any water passing around it.

Results

Results from the three-hole gas test

For each sample, the pressure values were measured for all the three holes. A typical graph of vacuum pressure against distance is shown in Fig. 1. The distance X (the distance from the main hole at which the applied vacuum pressure effect reached atmospheric) was derived by substituting the values of the applied constant vacuum pressure and the resulting constant vacuum pressure value in equation (1). Average values of the X distance for replicate samples are shown in Fig. 3.

The intrinsic permeability was obtained from equation (2) using the time Δt for the pressure in the centre hole to rise from 45 to 55 kPa. By applying the equation at both pressures and subtracting the following relationship was obtained
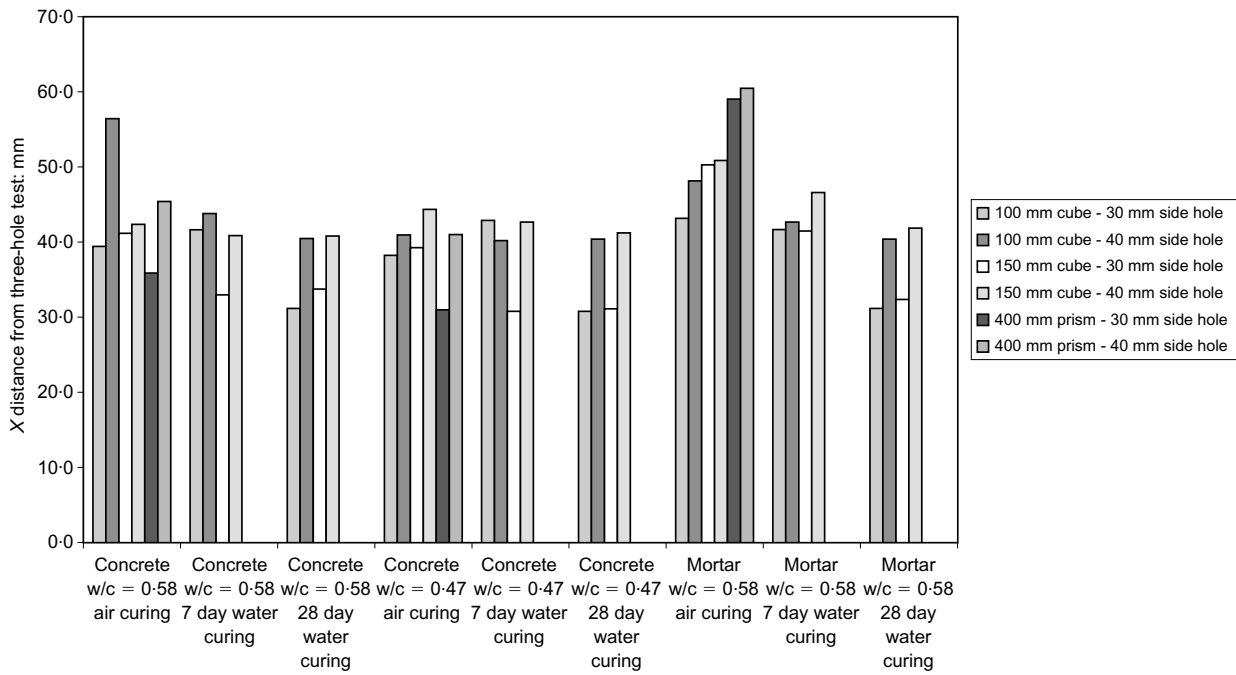
Table 2. Programme for each test

	Three-hole test	ISAT	High pressure water test
Air curing	3 × 100 mm cubes 3 × 150 mm cubes 2 × 400 mm prisms	2 × 100 mm cubes 2 × 150 mm cubes	2 × cores
7 day water curing	3 × 100 mm cubes 3 × 150 mm cubes	2 × 100 mm cubes 2 × 150 mm cubes	2 × cores
28 day water curing	3 × 100 mm cubes 3 × 150 mm cubes	2 × 100 mm cubes 2 × 150 mm cubes	2 × cores

Fig. 3. *Distance x over which the vacuum decays in three-hole test*

$$K = \frac{e x_0^2}{2 P_a \Delta t \left[\dfrac{1}{\ln\left(\dfrac{X}{x_0}\right)} - \dfrac{1}{L\left(\dfrac{1}{X_s} - \dfrac{1}{x_0}\right)} \right]}$$

$$\times \ln\left[\frac{(55 \times 10^3 + P_a)(45 \times 10^3 - P_a)}{(55 \times 10^3 - P_a)(45 \times 10^3 + P_a)} \right] \quad (7)$$

The value used for the viscosity of air, *e*, was 1.8×10^{-5} Pa s.

The resulting values for the permeability, *K*, are shown in Fig. 4.

Results from initial surface absorption test

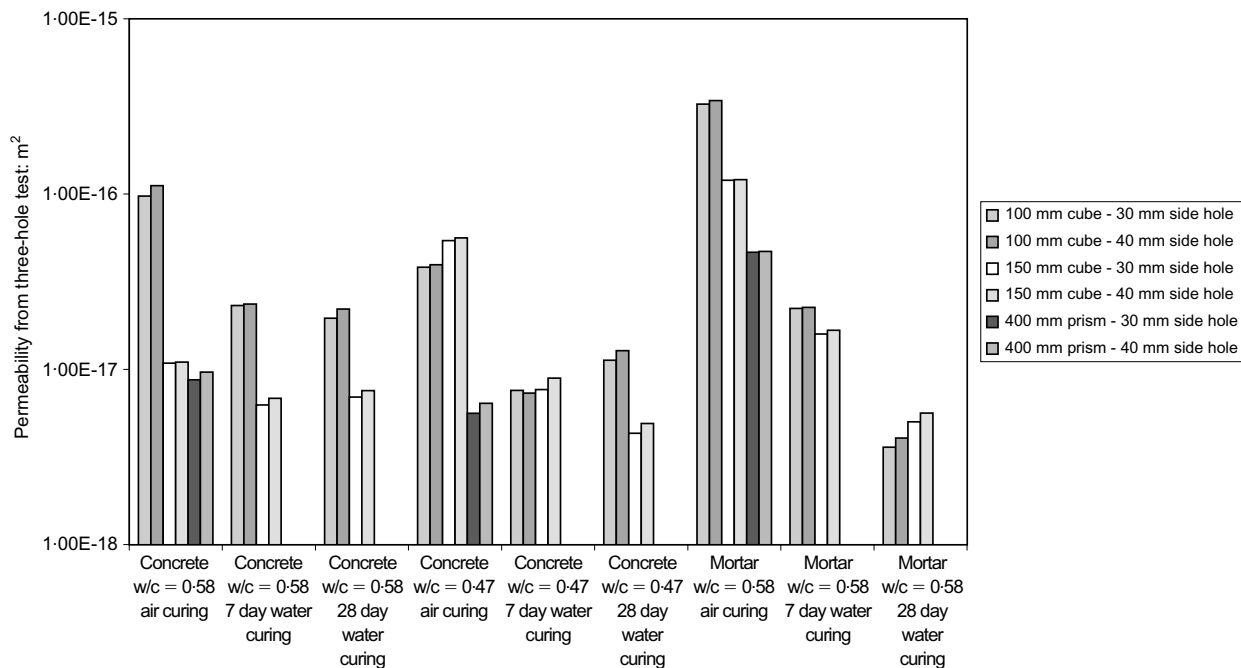The initial analysis of the results was carried out by assuming a relationship of the form

Fig. 4. *Intrinsic permeability calculated from the three-hole test*

$$F = at^{-n} \tag{8}$$

where a and n are constants. From equation (3) it may be seen that

$$a = A\left(\frac{Ks\alpha}{re}\right)^{0.5} \tag{9}$$

The constant a was obtained from the intercept of the relationship of the logarithm of the flow rate against the logarithm of time and K was obtained from it. This analysis has been used previously[17,18] but it gave widely varying results. The reason for this was found to be that it does not assume any value for the constant n that may be seen from equation (3) to have a value of 0·5.

A simpler analysis was therefore carried out by applying equation (3) directly to the individual data points and obtaining an average result. The porosity of the concrete was assumed to be 10 and 7% for mixes 1 and 2 respectively and the mortar 18%. The radius of the largest pores was assumed to be 0·6 μm. These are typical values for mixes of this type.[16] The values for surface tension and viscosity of water were 0·073 N/m and 10^{-3} Pa s respectively. Fig. 5 shows the average values and also the separate values for 100 mm and 150 mm cubes from which the averages were obtained.

Results from the high pressure permeability test

The time required to collect 10 ml of water was recorded and the flow velocity was computed. The values were substituted in equation (4) to obtain the intrinsic permeability. The results are shown in Fig. 6.

Discussion

Results for the individual tests

Figure 3 shows that, as previously reported,[1] the vacuum–air procedure gives realistic values of the distance X which represents the extent of the lowered pressure in the sample. The only exception is the 100 mm cubes in air for which the calculated distance lies outside sample indicating that the test was affected by air entering from the edge. Fig. 4 shows, however, that the calculated permeability from the test decreased substantially with increasing sample size. This indicates that these tests should not be used on small samples or near an open edge if used in situ.

The ISAT results in Fig. 5 show good agreement between tests on the two different sample sizes and a clear effect of reducing permeability with improved curing.

The results from the high pressure water test in Fig. 6 show an unexpected increase in permeability for the mortar samples when cured in water. The pressures used in this test are high (typically 60–100 atmospheres) and it is suggested that some pathways through the pore structure were created.

Comparison of permeability values

Figure 7 shows the comparison between the three different experiments. The calculated relationship between gas and water permeability taking account of gas slippage (equation (5)) is shown on the graph and the line of equality is also shown. It may be seen that the ISAT values show a good correlation ($R^2 = 0.97$) with the results of the three-hole test and all lie between the
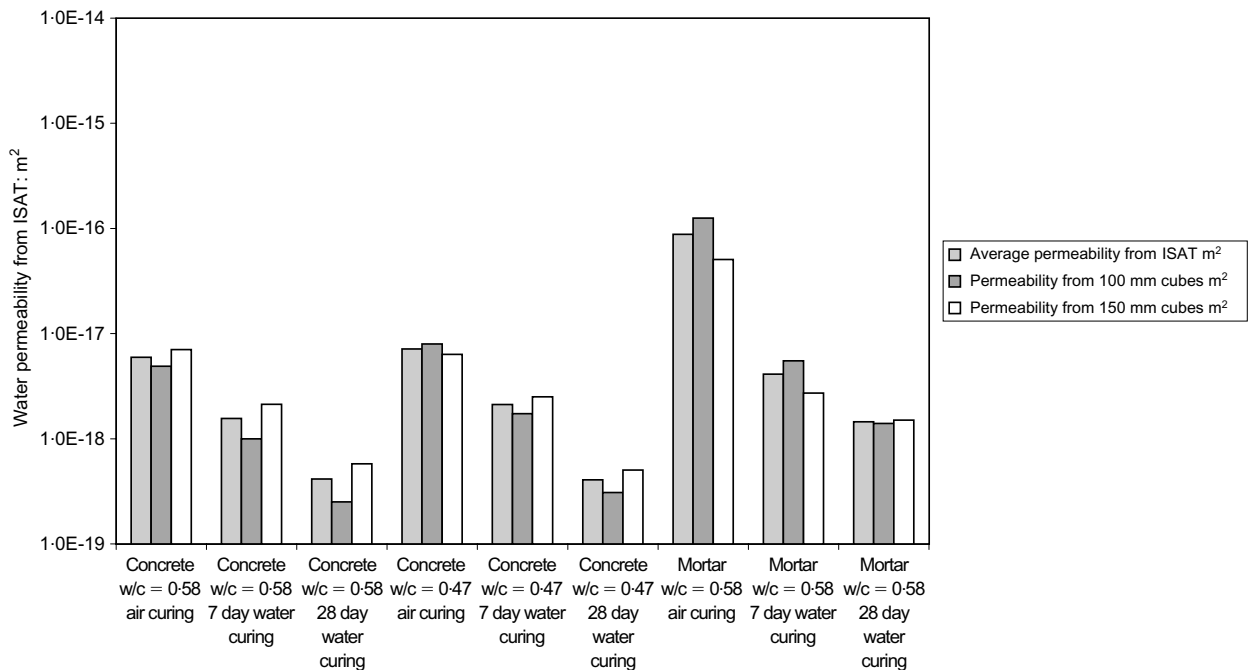

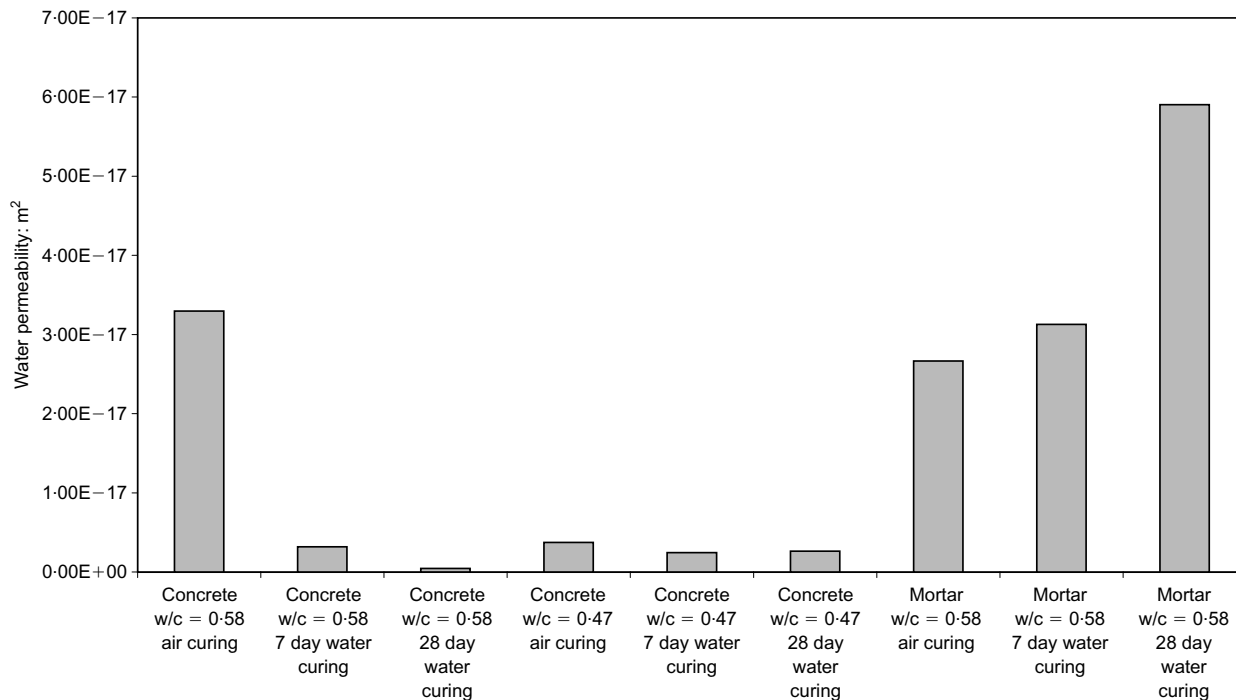*Fig. 5. Intrinsic permeability calculated from ISAT*

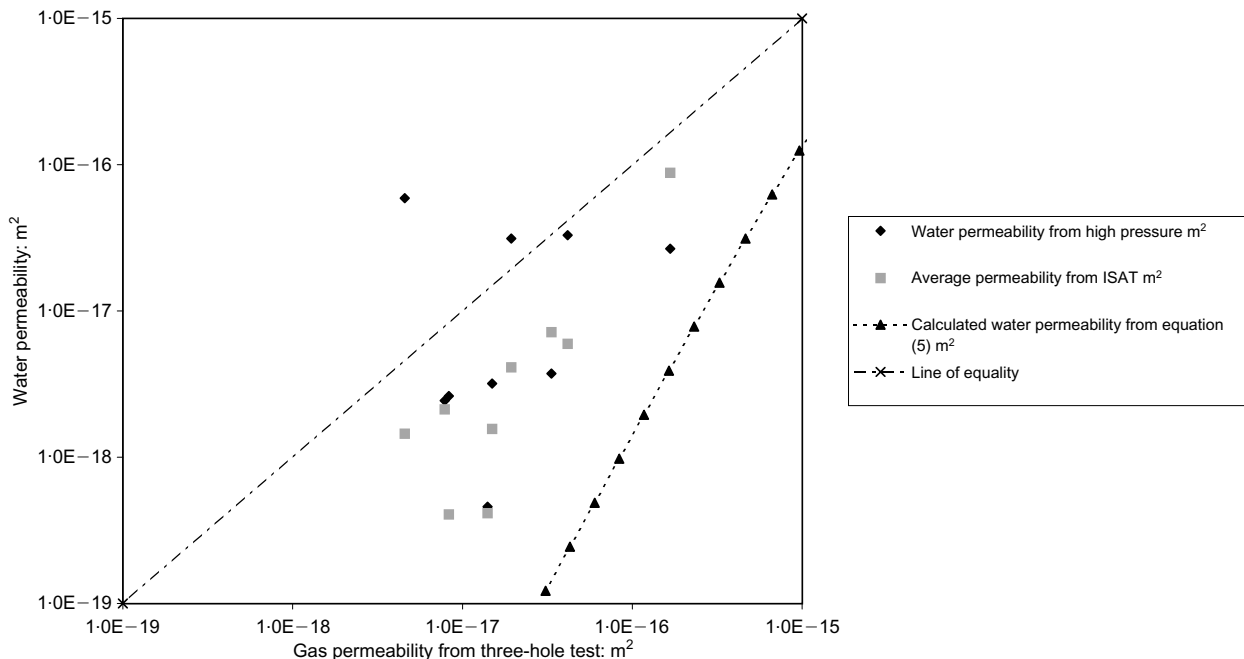Fig. 6. *Water permeability from high pressure test m²*

Fig. 7. *Comparison of permeabilities*

two lines, i.e. the ISAT values are above those predicted by the gas slippage theory but below the line of equality.

The only two points for the high pressure test which do not lie between the two lines are the two results for wet cured mortar which are noted above as outliers. These two points lie on and above the line of equality.

With these exceptions the high pressure test results lie in the same region as the ISAT results and show a correlation coefficient $R^2 = 0·59$ with the results of the three-hole test confirming the validity of the analyses for the non-destructive tests.

Some change in permeability measured from the ISAT might be expected because it is a surface meas-

urement and the other two tests measure bulk properties. At the surface poorer curing and a higher paste content could increase the permeability but carbonation might reduce it. The present results do not indicate any systematic effect.

It may also be noted that the intrinsic permeability should be an absolute property of the material and should not depend on the fluid used to derive it. The existence of the discrepancies quantified in equation (5) highlight the limitations of the Darcy equation (4). By replacing the analytical solutions presented in this work with numerical simulations containing corrections for gas slippage and other factors it should ultimately be possible to derive permeability values which are the same for all fluids.

Conclusion

(*a*) The three-hole test is derived from the Figg test with additional holes drilled into the concrete. This new method reveals the volume of concrete that is being tested and permits calculation of the permeability in absolute units.

(*b*) The volume of concrete tested in the Figg test on a dry sample has a radius of approximately 50 mm. The test should therefore be reliable in concrete with 20 mm aggregate.

(*c*) The three-hole test gives a good correlation with the ISAT test and direct measurements of permeability.

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