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**Author post-print (accepted) deposited in CURVE June 2010**

**Original citation & hyperlink:**

Claisse, P.A. , Ganjian, E. and Adham, T. (2003) A vacuum-air permeability test for in-situ assessment of cover concrete. Cement and Concrete Research, volume 33 (1): 47-53.

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# **A VACUUM-AIR PERMEABILITY TEST FOR IN-SITU ASSESSMENT OF COVER CONCRETE**

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keywords: C, degradation, C, durability, C, long-term performance, C, permeability,  
C, transport properties

## **ABSTRACT**

The transport properties of fluids in the cover layer are the main indicator of the durability of reinforced concrete structures. Many laboratory tests exist for measuring these properties. However, there are relatively few tests which can be used on site. In this paper the development of a new non-destructive rapid test capable of measuring the air permeability of in-situ concrete is described. The new method measures the movement of gas between different holes drilled into the concrete and gives results for the permeability of the concrete and for the volume of concrete which has been tested.

A pressure measuring method was developed to measure the pressure inside the concrete by using a piezoresistive pressure transducer and a data logger. Four different techniques were investigated and one preparation technique is recommended for in-situ use.

“This new test is a modification of the original Figg test that was introduced in the early 70s. There had been modifications to the original Figg test in order to improve its repeatability and sensitivity, which were not taken into account while carrying out the investigation reported in this paper. Therefore, the proposed test does not necessarily have improved repeatability and sensitivity compared to the modified Figg tests. The primary objective of this investigation was to obtain a coefficient of permeability from the original Figg test.”

## **1. Introduction**

### **1.1 Background**

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 [1-3].

The problem of durability of concrete usually involves movement of aggressive fluids from the surrounding environment into the concrete through the cover concrete followed by physical and/or chemical action in its internal structure, leading to deterioration. The mechanisms of ingress of harmful materials involved are in fluid form or dissolved in water [4-5].

The main agencies of deterioration of concrete require the presence and movement of water through the material [6-7]. A number of different permeation tests described in the literature (e.g. ISAT, Figg permeation method, CAT and AUTOCLAM) [8-11]. This paper describes the development of a new test which is proposed as an improvement to the Figg method.

### **1.2 Drilled-hole tests in concrete.**

The measurement of transport to or from a drilled hole is the alternative to surface measurements for insitu assessment of concrete durability [12]. A convenient way of carrying out these tests is to drill a hole, seal the top of it, evacuate the space below the seal and measure the time taken for the vacuum to decay. This is the basis of the Figg test [9]. The problem of moisture in the concrete affecting the test results may be overcome by vacuum drying prior to the test [12]. The test is well established and has been shown to give a good measure of the relative performance of different mixes, but it has been shown [12] that it

cannot give any indication of the volume of concrete that it is testing. The Figg test also cannot be used to calculate values of concrete permeability. In order to overcome these difficulties a new test is proposed which uses additional holes in the concrete. In this paper a number of different methods which were assessed for the new test are compared and results from the test are reported.

The new test is shown in figure 1.

## 2. Theoretical Analysis

The volume of concrete that is being tested is measured by the distance  $X$  at which the pressure returns to atmospheric. To calculate this the steady state is considered in which a constant vacuum is applied to the centre hole.

The modelling is based on the Darcy equation for pressure driven flow [13]

$$F = \frac{KA}{E} \frac{dp}{dx} \quad (1)$$

where

$F$  = flow rate ( $m^3/s$ );

$K$  = intrinsic permeability ( $m^2$ );

$E$  = viscosity of the fluid ( $Pa \cdot s$ );

$p$  = pressure ( $Pa$ ) at a distance  $x$   $m$  from the high pressure reservoir; and

$A$  = area ( $m^2$ ) across which the fluid is flowing.

In this test the permeating fluid is compressible and the observed flux  $F$  ( $m^3/s$ ) will therefore change with pressure. The flow is therefore best expressed as molecular flow where  $N$  is the total flux ( $mol/m^2/s$ ) and  $dn/dt$  is the flow rate of the gas ( $mol/s$ ). Both  $N$  and  $dn/dt$  are approximately constant across the sample (assuming a steady state within it) [12].

$$N = \frac{1}{A} \frac{dn}{dt} = -\frac{Kp}{RTE} \frac{dp}{dx} \quad (2)$$

where  $R$  = gas constant ( $8.31 \text{ J / mol/}^{\circ}\text{K}$ );

$T$  = temperature ( $^{\circ}\text{K}$ ); and

$t$  = time from the start of the test ( $s$ ).

Considering the radial flow into the curved surface of the drilled hole, the area  $A = 2\pi xl$ .

where  $l$  is the length of the evacuated volume (m).

Eq. (2) therefore becomes:

$$\frac{1}{2\pi l} \int \frac{dn}{dt} \frac{dx}{x} = -\frac{K}{RTE} \int P dp \quad (3)$$

This flow passes through the region in which the side holes are located.

Integrating from  $X \rightarrow x_1$

where:

$X$  = the distance from the centre of the main hole to a point where the pressure is atmospheric ( $m$ ), and

$x_1$  = the distance from the centre of the main hole to the centre of the side hole ( $m$ ),

$$\frac{dn}{dt} \text{Ln} \left( \frac{X}{x_1} \right) = -\frac{K}{RTE} (P_a^2 - P_1^2) \quad (4)$$

where

$P_a$  = atmospheric pressure ( $Pa$ ). and

$P_1$  = the pressure at the side hole ( $Pa$ ),

integrating from  $x_1 \rightarrow x_0$

where  $x_0$  = the radius of the main hole ( $m$ ),

$$\frac{dn}{dt} \text{Ln} \left( \frac{x_1}{x_0} \right) = \frac{K}{RTE} (P_1^2 - P^2) \quad (5)$$

Where

$P$  = the pressure at the main hole ( $Pa$ )

Dividing Eq. (4) by Eq. (5) gives:

$$\frac{\text{Ln}(X/x_1)}{\text{Ln}(x_1/x_0)} = \frac{(P_a^2 - P_1^2)}{(P_1^2 - P^2)} \quad (6)$$

Eq. (6) may be used to calculate  $X$  from experimental observations of  $P_1$ .

The intrinsic permeability is obtained from an analysis of the decay transient when the Figg test is applied in the normal way, i.e. a vacuum is applied to the centre hole and then the inlet is sealed and the vacuum decays. An initial analysis of this has been published by the authors [12] and the result is in equation 7. It may be seen that the distance  $X$  must be known in order to calculate the permeability  $K$ .

$$\frac{(P + P_a)(P_i - P_a)}{(P - P_a)(P_i + P_a)} = \exp \left[ \frac{2KP_a t}{E x_0^2 \text{Ln}(X/x_0)} \right] \quad (7)$$

When analysing the transient, however, the total flow into the centre hole must be considered. The above analysis takes no account of the flow into the base of the drilled hole. To improve the approximation a second region has been added to the model to include flow into the base of the hole as shown in Figure 2. The drill bit used produced an approximately hemispherical inner surface to this region.

By including the hemispherical area and following through the integration equation (7) becomes

$$\frac{(P + P_a)(P_i - P_a)}{(P - P_a)(P_i + P_a)} = \exp \left\{ \left[ \frac{2KP_a t}{E x_0^2} \right] \times \left[ \frac{1}{\ln \left( \frac{X}{x_0} \right)} - \frac{1}{L \left( \frac{1}{X_s} - \frac{1}{x_0} \right)} \right] \right\} \quad (8)$$

Where  $X_s$  is the radius of the hemispherical region below the base of the hole and  $L$  is the length of the evacuated volume. In order to estimate  $X_s$  the authors suggest that it is best to assume that the flow rate ( $N$ ) per unit area at the boundaries of the two regions is the same.

Equating the two flow rates and solving the equations gives:

$$-X \ln \left( \frac{X}{x_0} \right) = X_s - \frac{X_s^2}{x_0} \quad (9)$$

Equation (9) may be used to calculate values of  $X_s$  from measured values of  $X$  (from equation (6)) and these may then be used in equation (8) to calculate the permeability. Trial calculations using these equations have indicated that  $X_s$  is approximately  $0.5X$  and approximately 30% of the flow into the hole comes from the hemispherical region.

### 3 Casting And Curing Of Specimens

#### 3.1 Mortar Mixes

Mortar mixes were made by using a linear horizontal pan type mixer of  $0.04m^3$  capacity, throughout the study. The mixing of mortar was done according to BS 5075 (14). The mix design is shown in table 1.

All the samples were cured in water at  $20^{\circ}C$  for 7 days and then oven-dried at  $105^{\circ}C$  to constant weight and kept in the laboratory until tested.

#### 3.2 Concrete Mixes

Three different concrete mixes were designed and made as shown in table 2.

Three different mould sizes i.e. (100 *mm* cube, 150 *mm* cube and a prism of 400 x 400 x 100 *mm*) were cast for each concrete mix. All the specimens were air cured at laboratory temperature for 28 days until tested.

## **4 Investigation Of Methods**

### **4.1 The different methods**

The new test requires the measurement of pressure in the "side holes". These holes are different from the centre hole in that they are only used for measuring pressure (not applying it) and their diameter is as small as possible to prevent disturbance of the pressure decay. Tests were therefore carried out to see if the method of preparing the holes should be different from the normal method for the Figg test which was used on the centre hole.

The four methods for preparing the holes are given in Table 3.

### **4.2 Experimental procedure**

Pressure measurements were made using piezoresistive pressure transducers and a data logger. The different methods were tested by applying a vacuum to the centre hole and then sealing it and letting the vacuum decay. 100mm mortar cubes were used with a standard centre hole (13mm diameter by 50mm deep). The side holes were 6mm diameter and 30mm deep with a 5mm deep void space. This diameter would be insufficient for measurement of flow rates because a significant proportion of the surface of the void could be obstructed by a single aggregate particle. These holes are, however, only used for observation of pressure and the risk of the entire surface of the void being sealed by an uncracked aggregate particle is not seen as significant. A larger hole could cause significant disturbance to the air flow.

### **4.3 Selection of experimental method**

The graph of pressure against time for each preparation technique is presented in figs. 3 to 6.

Comparison of the graphs of the four preparation techniques reveals that and all the pressure decay curves for the different techniques were almost the same. This gives considerable



confidence in all of the methods used and indicates that a selection may be made based on practical considerations.

Method 4 is ideal for use on site because method 1 cannot be used on site and method 2 is much more time consuming than method 4. In method 3 it is difficult to inject the liquid silicon where the flexible tube limits the remaining space. This action also limits the diameter of the side hole in this technique.

For these reasons the selected technique is method 4 i.e. drill a hole fill it with silicon and insert the hypodermic needle.

## **5. Determination Of Pressure Decay Profile**

### **5.1 Experimental procedure**

The distance  $X$  at which the pressure returns to atmospheric was determined by applying a constant pressure to the centre hole and measuring the pressure in the side hole. It was found that the piezoresistive pressure transducers could be conveniently assembled directly onto the hypodermic needles thus minimising "dead volume" which would have affected the readings. 4mm diameter side holes were used. In order to minimise the effect of the 20mm aggregate these were drilled to 40mm deep with a 20mm deep void space. Before applying the vacuum three readings of pressure were taken at 10 seconds intervals in order to zero the pressure sensors.

### **5.2 Results**

For each concrete mix the pressure values were measured for all the three holes. A typical graph of vacuum pressure against time is shown in figure 7. The distance  $X$  was derived by substituting the value of the applied constant vacuum pressure and the resulting vacuum pressure in the side holes in Eq. 6.

The distance  $X$  for each concrete studied is in table 4 and plotted in figures 8 to 11 with regression lines to the data (where there are only 2 values of the dependant variable this becomes a line through the average values of  $X$ ).

## 6. Discussion

It may be seen that this technique gives realistic values for the distance  $X$ . From figure 8 it may be seen that the distances lie within the specimen width, except the 100 mm cube specimen in cast number 3. The increase in specimen size shows a minor increase in  $X$  which was expected from the closeness of the radius  $X$  to the edge of the 100mm cubes. The averages from the 150mm and 400mm samples are similar. The use of these larger samples gives confidence that the observed values of approximately 50mm were not a product of edge effects. From figures 9 and 10 it may be seen that increasing the separation of the holes or the vacuum pressure only had a very minor effect on  $X$  giving confidence in the modelling method. Figure 11 shows that there was very little change in  $X$  with w/c ratio. This does not indicate that the permeability did not change because a more permeable sample will have a higher rate of extraction of air from the side hole but it will also have a higher rate of replenishment.

The following method is proposed for testing concrete:

1. Prepare for the Figg test using the standard method but with an additional hole 4mm diameter, 40mm deep at a distance of 30mm from the centre hole.
2. Set up a data logger to take pressure readings in both holes at 10 second intervals.
3. Apply a constant vacuum to the centre hole until a stable pressure is recorded in the side hole and then seal the input and let the vacuum decay.
4. Calculate the distance  $X$  from equation 6 and then calculate the permeability by fitting equation 7 to the vacuum decay transient. This may be done by applying the equation at two different times and subtracting.

It may be seen that in this study the distance  $X$  was typically 50mm. In order to calculate the permeability without drilling the second hole this value might be used but all of the samples

tested in this study had low moisture contents and a higher moisture content could reduce X. If the vacuum preconditioning [15] is used to standardise the moisture content this would be unlikely to have any effect at less than 0.5 atmospheres of vacuum, i.e. more than approximately 20mm radius.

This method has been applied to a range of different samples and the permeability has been calculated [16]. Figure 12 shows the results in which the permeability is plotted against the Figg permeability index which is obtained directly from the transient. These show that this new method demonstrates the great changes in permeability indicated by small changes in Figg index time at short times.

## **7. Conclusions**

1. A new test method is proposed which is derived from the Figg test but uses additional holes drilled into the concrete. This new method reveals the volume of concrete that is being tested and permits calculation of the permeability.
2. Comparing various techniques has revealed that the method used for the standard Figg test is the best method to use for measurement of pressure in small diameter holes drilled into concrete samples.
3. The comparison of techniques has also given confidence in the results obtained for the pressure measurements.
4. The volume of concrete tested in the Figg test on a dry sample has a radius of approximately 50mm. The test should therefore be reliable in concrete with 20mm aggregate.
5. The new test shows the very large changes in permeability corresponding to small changes in the Figg index.

“This new test is a modification of the original Figg test that was introduced in the early 70s. There had been modifications to the original Figg test in order to improve its repeatability and sensitivity, which were not taken into account while carrying out the investigation reported in

this paper. Therefore, the proposed test does not necessarily have improved repeatability and sensitivity compared to the modified Figg tests. The primary objective of this investigation was to obtain a coefficient of permeability from the original Figg test.”

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Figure 1. The drilled hole test

Figure 2. The developed model for the vacuum decay test.

Figure 3. Pressure decay curves for method 1 (pipe cast into concrete)

Figure 4. Pressure decay curves for method 2 (epoxy seal)

Figure 5. Pressure decay curves for method 3 (silicon rubber seal around pipe)

Figure 6. Pressure decay curves for method 4 (hypodermic through silicon rubber)

Figure 7. Pressure curves for a concrete specimen using the new method

Figure 8. Effect of sample size on distance X

Figure 9. Effect of distance between holes on distance X

Figure 10. Effect of vacuum pressure on distance X

Figure 11. Effect of w/c ratio on distance X

Figure 12. Relationship between Permeability and Figg index.

Constituent materials (Kg/ m <sup>3</sup> )			
OPC	Water	Sand	W/C
350	245	1400	0.7

Table 1: Mortar Mix Design

Mix Number	Cement (Kg/m <sup>3</sup> )	Water (Kg/m <sup>3</sup> )	Coarse Aggregate 20 mm (Kg/m <sup>3</sup> )	Sand (Kg/m <sup>3</sup> )	W/C
1	395	225	800	980	0.57
2	520	240	1050	590	0.46
3	410	250	1100	625	0.61

Table 2: Concrete Mix Design

Method number	Method	Comments
1	6mm plastic pipes cast in wet concrete. Metal rods inside the pipes to keep them clear	Cannot be used on existing structures.
2	Hole drilled in set concrete and filled with epoxy. Plastic pipe inserted into wet epoxy. Hole drilled through to the concrete when the epoxy had set.	
3	Hole drilled in set concrete. Plastic pipe set into hole with liquid silicon rubber. Sponge to keep silicon out of pipe.	Difficult to inject the silicon to full depth.
4	Silicon rubber placed in hole to 25mm depth. Hypodermic needle inserted through set silicon	This is the standard Figg method This method selected for the investigation

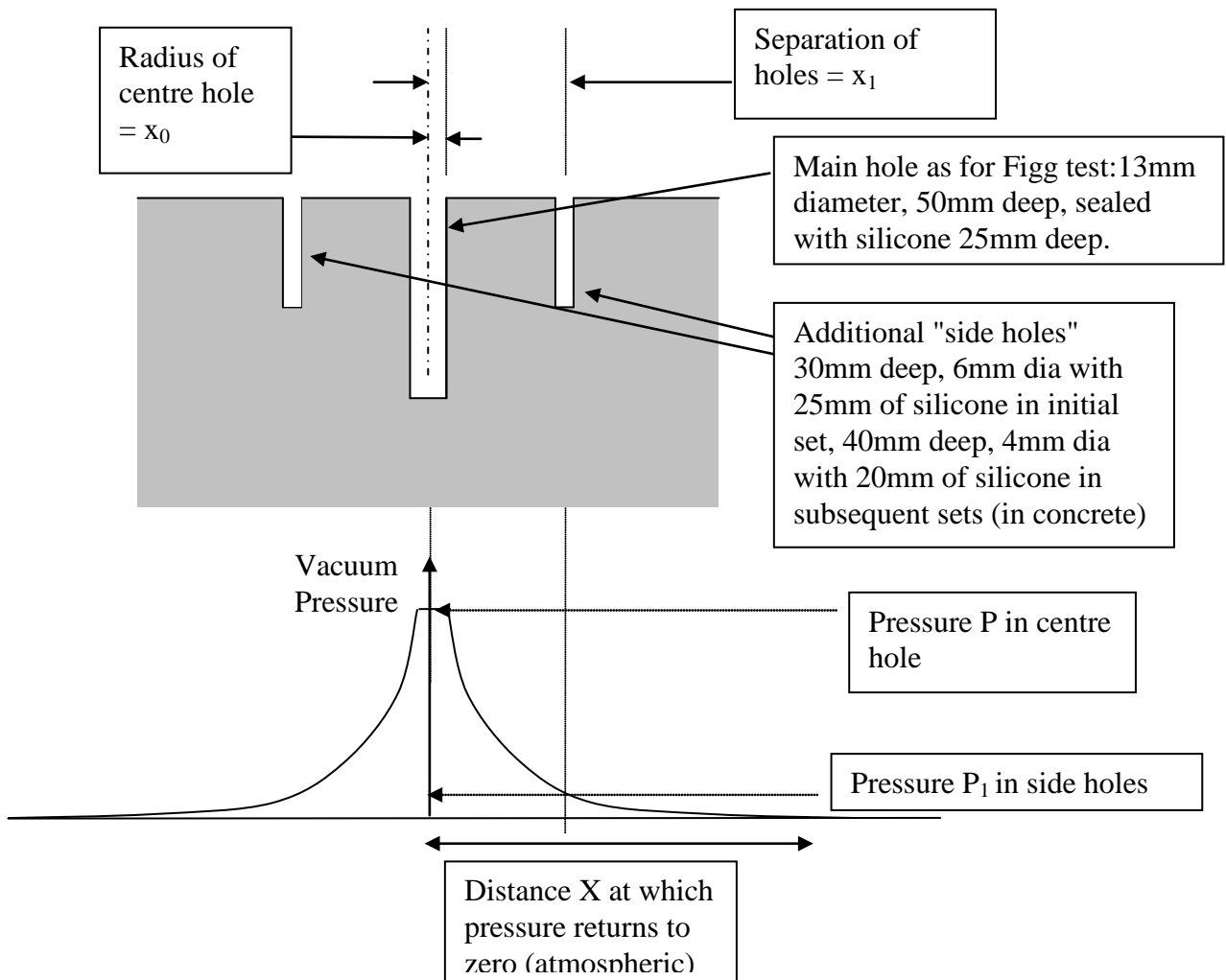
Table 3. The methods for preparing the side hole

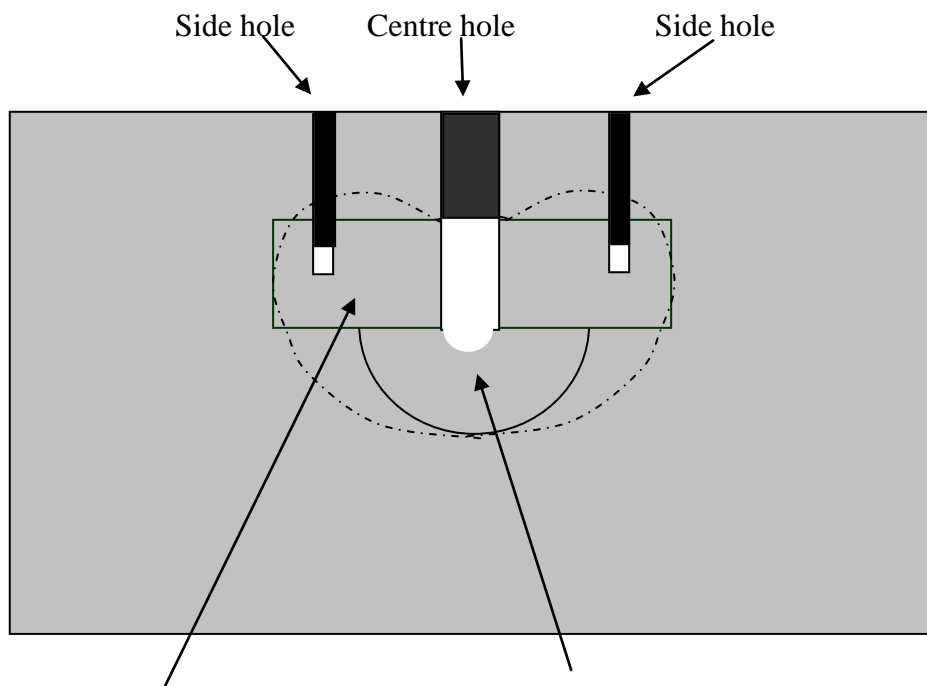


Mix No.	W/C	Sample Size mm	Distance x <sub>1</sub> mm	Pressure P at main hole mm Hg of vacuum	Pressure P <sub>1</sub> at Side hole mm Hg of vacuum	X mm	Pressure at P main hole mm Hg of vacuum	Pressure P <sub>1</sub> at Side hole mm Hg of vacuum	X mm
1	0.57	100x100	30	742	57	38.7	633	56	38.9
		100x100	40	742	33	47.2	633	32	47.3
		150x150	30	770	117	54.6	656	110	53
		150x150	40	770	31	46.8	656	30	46.7
		400x400	30	755	158	73.9	640	149	70.9
		400x400	40	755	32	46.9	640	31	46.9
2	0.46	100x100	30	760	85	44.9	652	83	44.9
		100x100	40	760	31	46.7	652	30	46.7
		150x150	30	760	92	46.8	646	90	46.9
		150x150	40	760	53	52.9	646	52	52.9
		400x400	30	736	110	52.2	650	100	49.8
		400x400	40	736	81	62.9	650	55	53.9
3	0.61	100x100	30	749	129	59.2	636	120	57.2
		100x100	40	749	34	47.5	636	15	43.1
		150x150	30	745	127	58.4	633	116	55.6
		150x150	40	745	55	53.5	633	51	52.7
		400x400	30	756	104	50.2	640	98	49.3
		400x400	40	756	45	50.5	640	42	49.9

Table 4 Results

Figure 1





Cylindrical region radius  $X$

Hemispherical region radius  $X_s$

The solid lines show the pressure fronts used in the idealisation for the model.  
 The dashed lines show possible location of the actual pressure front.

Figure 2

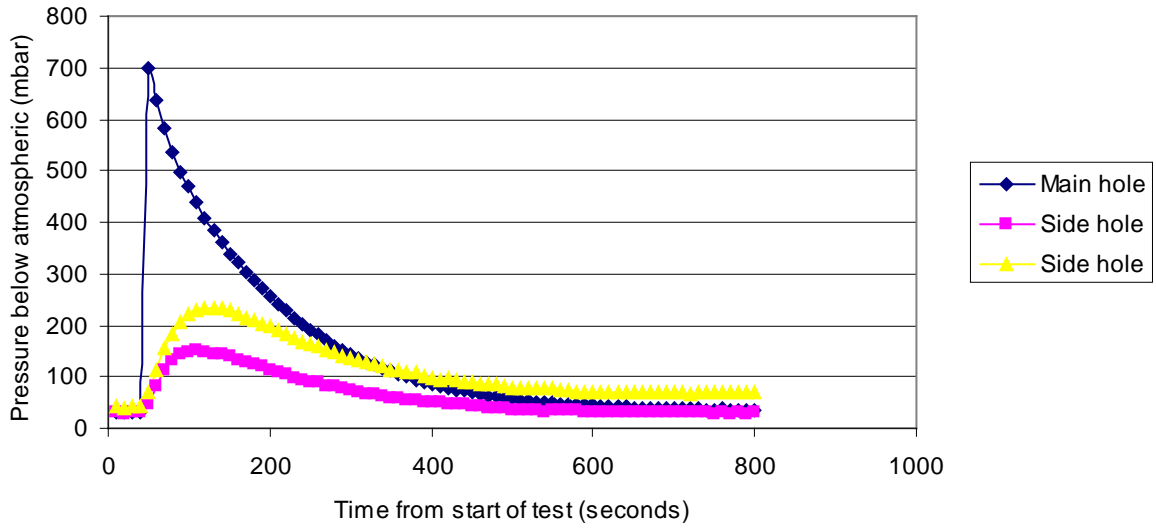


Figure 3

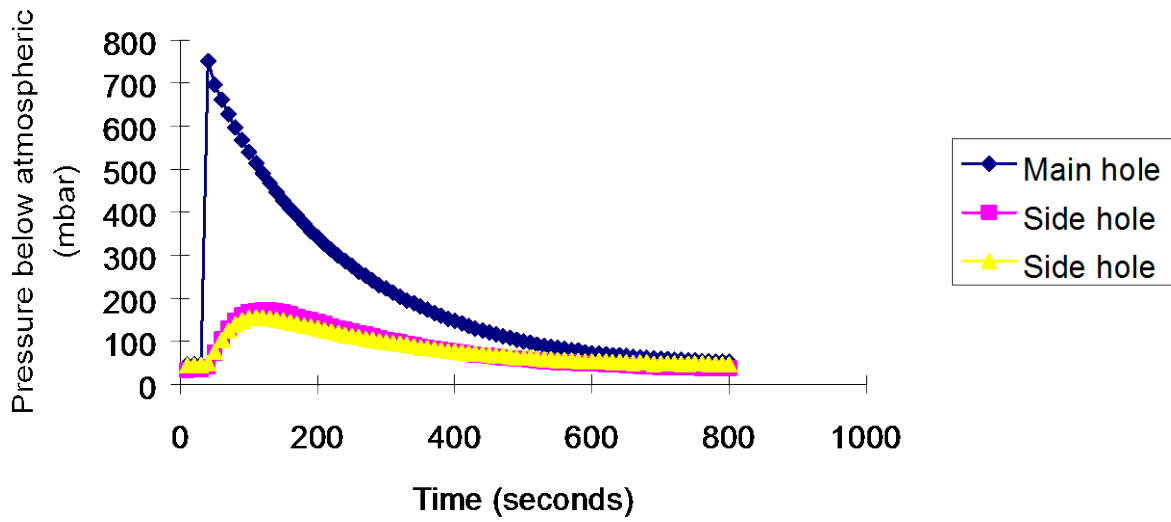


Figure 4

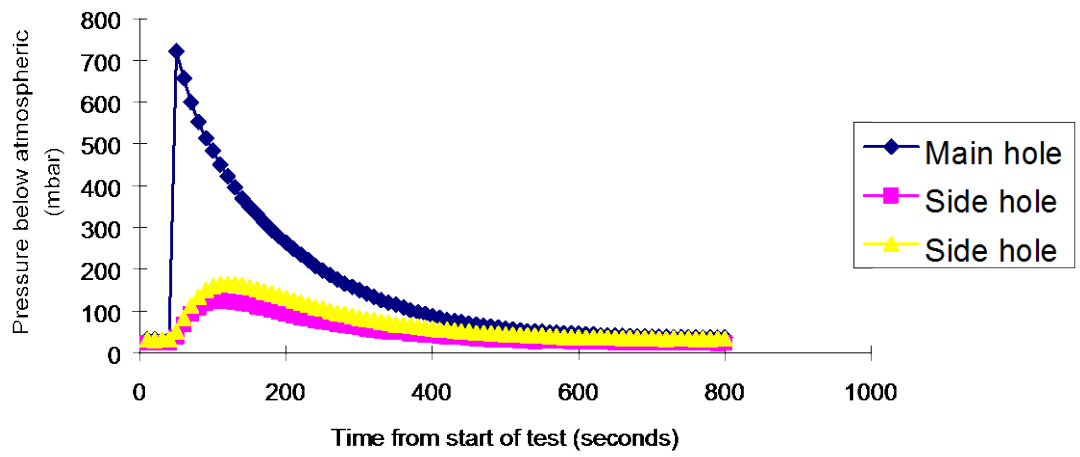


Figure 5

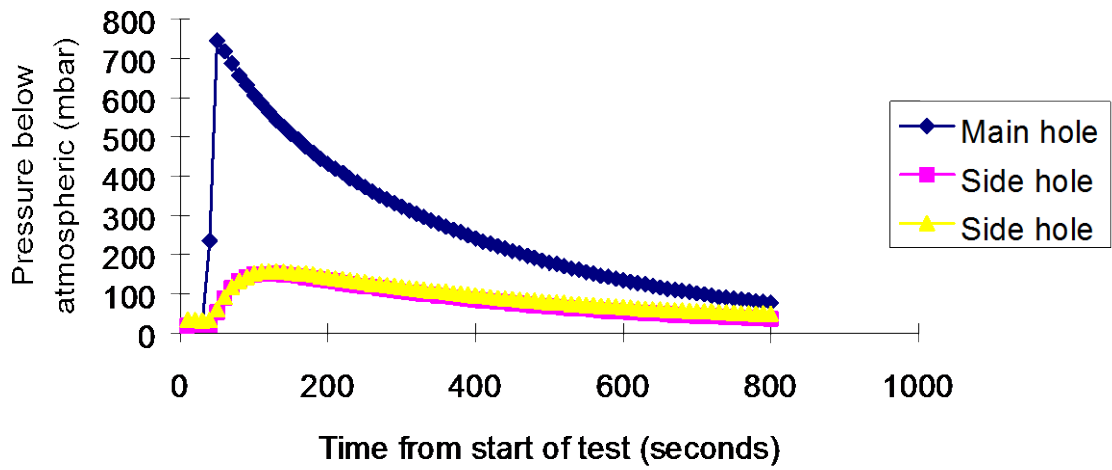


Figure 6

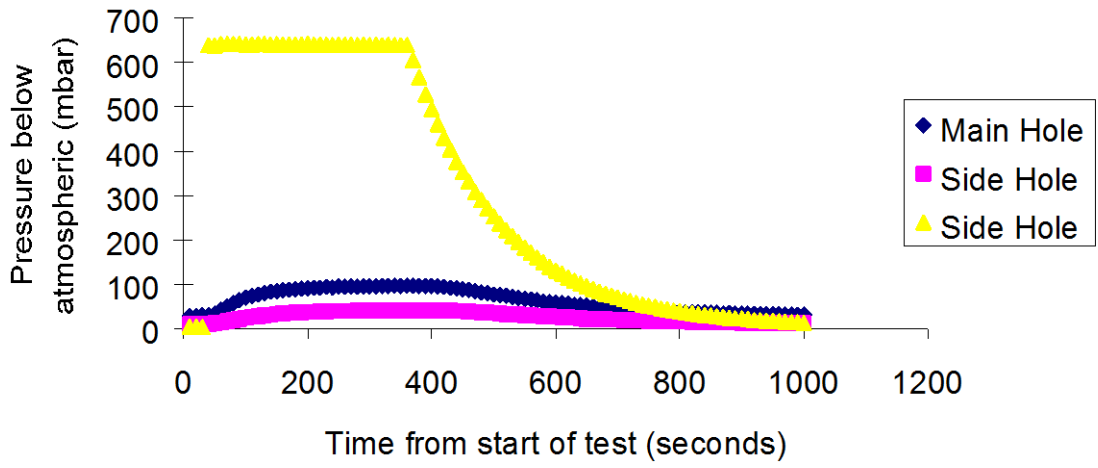


Figure 7

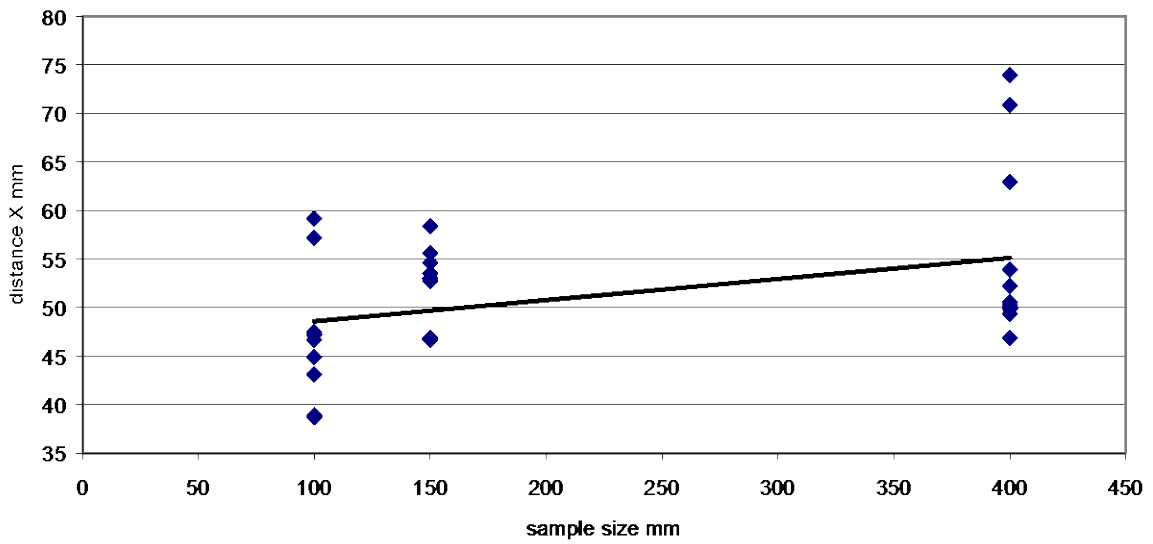


Figure 8

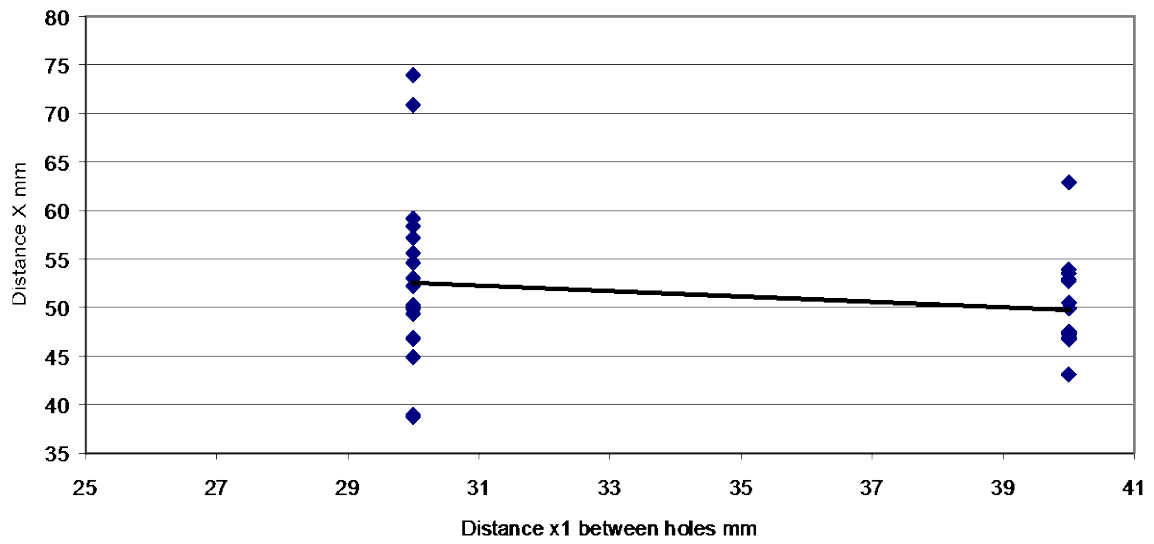


Figure 9

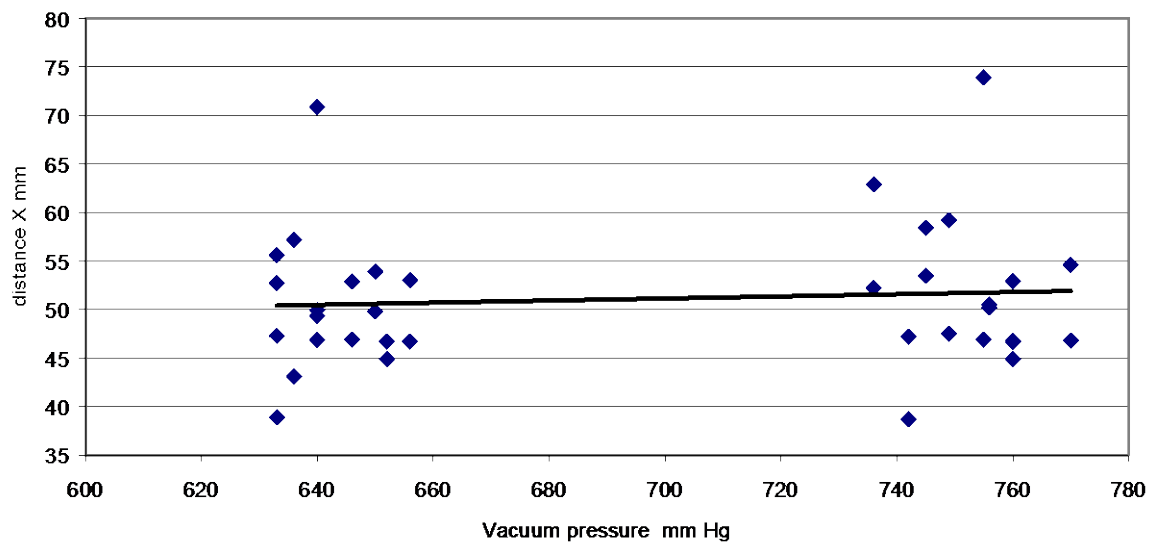


Figure 10

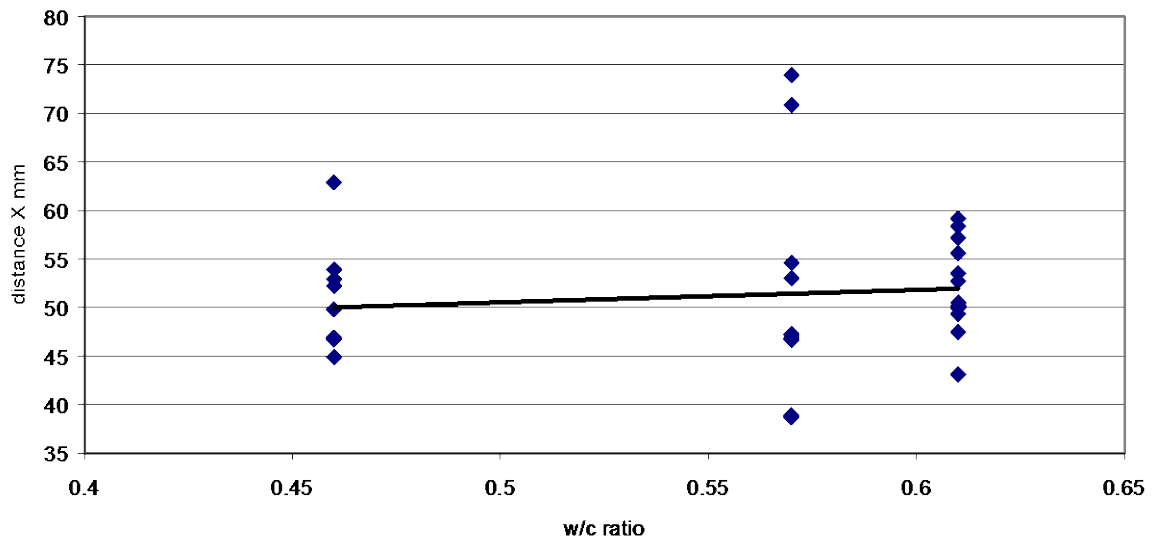


Figure 11

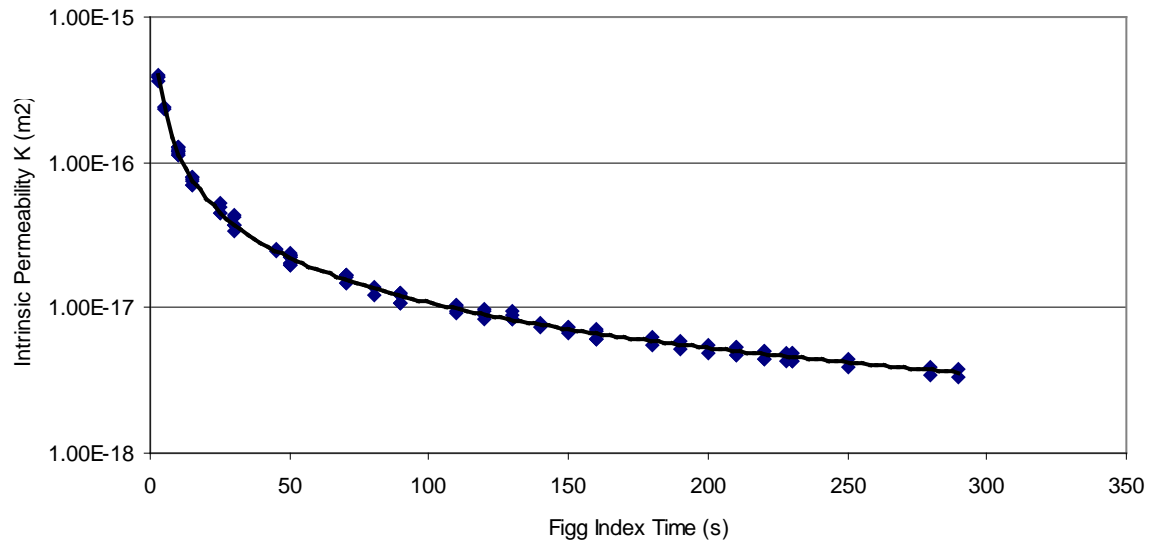


Figure 12