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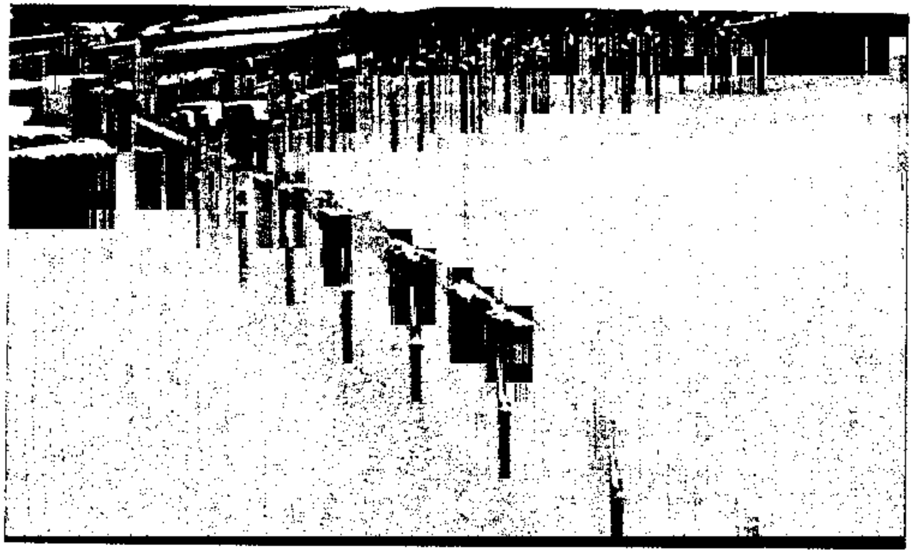

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Editor

Specifying Concrete for High Performance and Long Term Durability

by J.G. Cabrera

Synopsis: Although most researchers and engineers agree that the performance of concrete is better quantified by measuring its transport properties, most of the current specifications across the world do not directly include measurements for the evaluation of these properties and instead, rely heavily on the doubtful premise that controlling the strength of concrete is indirectly sufficient to guarantee high performance, thus confusing high strength with high performance concrete.

The study presented here discusses the causes for which direct measurement of transport properties, i.e., permeability and diffusion, do not form part of the standard specifications. It describes the development of testing procedures carried out at the laboratories of CEMU in Leeds, especially oriented towards their application for the control of concrete during production and construction.

Keywords: Concrete performance, durability, permeability, diffusion, specifications

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INTRODUCTION

The proportioning of concrete mixtures and their control of quality is largely based on the attainment of a target compressive strength which is achieved by limiting the maximum water-cement ratio (W/C) and the minimum cement content. The British Standards, for example, relate the values of minimum cement content and maximum water cement ratio to the environmental conditions of exposure of the structure for which the concrete has been proportioned. Although these criteria are adequate for compliance with the structural requirements they fall short of the requirements for adequate performance and long term durability, especially if the concrete is exposed to aggressive environments. Most researchers and engineers agree that the performance of concrete is better quantified by measuring its transport properties, however most of the current specifications across the world do not include directly measurements for the evaluation of these properties and instead rely heavily in the control of strength of the concrete.

Transport properties which characterise a porous solid are quantified by measuring its permeability and diffusion coefficients. Although, in theory these properties are easily measured in the laboratory, they are time consuming and very difficult to repeat and more so to reproduce. Because test methods for adoption in National Standards demand as basic requirement reasonable repeatability , reproducibility and short time to obtain the results particularly for control during the construction of structures, tests have not been included , although recognising the need for evaluating directly some property related to performance the European Standards and the new CEB-FIP Code which is supported by a separate Design Guide for Durable Concrete Structures have included a test procedure to measure a parameter related to permeability (1,2).

The Civil Engineering Materials Unit (CEMU) of the Department of Civil Engineering, University of Leeds has for many years been working in the development of concrete performance models which may be used for mixture proportioning ,field control and assessment of built concrete structures. For this purpose a number of test procedures and equipment have been developed and eventually simplified for practical use.

This paper describes some of these methods, and in particular the equipment and methods to obtain data on gas and liquid permeability. The equipment described in this paper was used to develop the mix proportioning for the concrete used on the construction of precast tunnel segments for the Jubilee Line in London UK.

THE REQUIREMENTS TO PRODUCE HIGH PERFORMANCE CONCRETE

In the context of this paper high performance concrete is defined as a concrete which is suitable for resisting deterioration in aggressive environments were water and chloride ions are freely available, and a concrete which will not require major repairs during its service life. Because resistance to the ingress of fluids and ions is a function of the pore volume, pore structure and nature of the hydration products of the cementitious binder, proportioning high performance concrete requires careful selection of the binder composition, the w/c and the curing regime which determines, in the long term the moisture content of the concrete. A low w/c is most effectively achieved by using chemical admixtures, particularly superplasticisers. Its use is now recognised as imperative for maintaining a workable fresh concrete mix with a low w/c which greatly reduces the water which contributes to the increase of capillary porosity. Although the quantity of binder per unit volume of concrete is important for attainment of the required strength, in terms of permeability and diffusion properties the nature of the binder is far more important than its quantity. It has been shown that by using pozzolanic additions like fly ash (fa), microsilica (ms) or metakaolin (mk) and by using hydraulic additions like ground granulated glass furnace slag (ggbs) the resistance of concrete to penetration of fluids and ions can be enhanced far more than by increasing the quantity of Portland cement (3,4,5).

A practical illustration of the selection of materials and proportioning of a high performance concrete mix was the one which the author helped to produce for the precast concrete tunnel segments for the construction of the Jubilee Line in London UK. The specifications for this project were the first to be used in the UK for controlling concrete quality as a guarantee of its suitability for the required service life.

CONTRACT SPECIFICATION

Although the initial contract specification stated the basic requirements, after consultations this was amended and written with more details particularly with respect to the frequency of testing. The specification stated that:

"The Contractor shall submit details of his proposed concrete mix including any proposed cement replacement materials. Cored samples for testing will be required prior to an during production. Samples will be tested to obtain the coefficient of **permeability to water which shall be a maximum of 1 x 10^{-13} m/s**, using test procedures and equipment supplied by Leeds University or Imperial College London or similar approved. The test samples shall be obtained from concrete which has undergone the proposed curing regime for production and shall include the cured surface. For the water permeability test, samples shall be conditioned at 75% Relative Humidity and 20^0 C and tested at 35 days. Samples shall also have an oxygen diffusion coefficient value not greater than 5 x 10^{-8} m^2/s. For oxygen diffusivity, samples shall be conditioned at 55 % Relative Humidity and 20° C and tested at 28 days. Other tests may be required by the Engineer if necessary".

This clause was further amended by the addition of a detailed testing regime giving frequency and timing of testing:

"The testing for permeability to water (K) and oxygen diffusion coefficient (O) shall be carried out as follows:

1. All sampling will based on sets of three cores. Core size may be quite small, e.g. 50 mm diameter x
 40 mm deep to allow for coring of segment into cover concrete.

2. Four batches of 3 cores required for K and for O from the original test mix These may be cast "cores". If the results are satisfactory then production may begin.

3. Four batches of 3 cores for K and O from the first ring of production. One batch from one segment.

4. Four batches of 3 cores for K and O from the 5th ring of production and then from the 100th, and every further 100th ring (i.e. 200th, 300th, etc.)

The firm supplying the precast tunnel elements worked closely with the author in the laboratories of CEMU. The first part of the investigation was to produce matched laboratory and production samples particularly for evaluating the production methods. A range of segments were produced in order to assess the effects of different curing regimes and mixture composition. These have been reported by Billington and Smith (6).

It was the view of the producer that the concrete mix should be, if possible, made up of traditional materials. The initial investigation included Rapid Hardening Portland cement/ggbs, normal Portland cement/fa, Normal Portland cement/fa/ms. An extensiv laboratory programme was carried out to evaluate the mixes produced. A number of these mixes were selected for full scale manufacture simulating actual production conditions so that all aspects of practical importance could be evaluated.

The concrete mix made with Rapid Hardening Portland cement and ggbs was discarded due to its low strength at 24 hours which could result in damage to the segments during demoulding and lifting. The mix containing microsilica was considered unsuitable due to the difficulties experienced in finishing the segments because the cohesive nature of the mix and the cost of the microsilica. Consideration was also given to the type of aggregate; for example crushed granite coarse aggregate was rejected due to higher water demand which resulted in unacceptable high permeability values (6).

From practical constructional considerations and the attainment of the required permeability values the mix selected was the one containing Normal Portland Cement and Fly Ash. This mix gave a concrete with good finishing characteristics, sufficient early strength and low permeability.

To maintain the programme of testing during the time requirements it was necessary to increase the number of permeability an diffusion cells. The following section describes the apparatus and the procedures used highlighting the most important variables which were found to affect the measurement of permeability.

THE LEEDS MODIFIED PERMEABILITY CELL

The Leeds modified permeability cell is similar to the one developed by Cabrera and Lynsdale (7) with some modification which allow the measurements of water permeability. The cell consists of four parts; a sample holder, accurate pressure gauge, stable gas supply and flowmeter at the downstream side. A schematic diagram of the cell is shown in Figure 1. The cell has been designed to test either mortar specimens of 25 mm diameter and 10 to 50 mm height or concrete specimens of 50 mm diameter with the same heights.

The concrete specimen (B) is placed in the rubber cylinder (A) inside a PVC taped collar (E). A vertical threaded shaft is designed to apply and maintain a pressure over the cell cap (H), which sits freely on the top of the O-ring (G). This pressure forces the rubber cylinder inwards against the sample and thus provides a seal.

Leakage between the sample and the rubber cylinder is checked by using a metal cylinder as the sample under a gas pressure similar to that used for testing. Because the surface texture of the concrete sample is not perfectly smooth a thin layer (approximately 0.5 mm) of a soft silicon rubber compound is applied to the curved surface of the specimens and left to cure at the desired environmental condition for at least 12 hours before testing. This layer provides a smooth surface and achieves perfect interface seal with the rubber cylinder.

Measurements of Oxygen Permeability

Oxygen is applied at a desired pressure through the gas inlet valve (J) and the flow rate at the downstream (L) is measured using a bubble flowmeter. Different diameter flowmeters are used depending on the permeability of the sample. The measurements of flow rate are carried out once a steady state flow has been reached. This period varies between 15 minutes to several hours, depending on the pore structure and the degree of saturation of the specimen under test.

The flow, through a specimen, of a non-compressible fluid (such as water) can be determined according to D'Arcy's law as follows:

$$K = \frac{v\eta L}{A\Delta P} \qquad (1)$$

Where:

K = intrinsic permeability (m^2)
v = flow rate (m^3/sec)
η = viscosity of the fluid ($N.s/m^2$)
L = length of the specimen (m)
A = cross-sectional area of the specimen (m^2)
ΔP = fluid pressure head across the specimen (bar $\cong$ 105 N/m^2)

However, when a compressible fluid, such as oxygen, is used, D'Arcy's equation should be modified to calculate the volume of fluid at the average pressure within the specimen (8).

$$K = \frac{2v\eta L P_2}{A(P_1^2 - P_2^2)} \tag{2}$$

where:
P_1 = inlet absolute applied (gauge) pressure (bar)
P_2 = outlet pressure at which the flow rate is measured, usually 1 bar

Knowing that the viscosity of oxygen at 20°C is equal to 2.02×10^{-16} ($N.s/m^2$), the intrinsic oxygen permeability (K_o) can be calculated according to the following equation:

$$K_o(m^2) = \frac{4.04vL \times 10^{-16}}{A(P_1^2 - 1)} \tag{3}$$

Measurements of Water Permeability

On completion of the measurement of oxygen permeability, the pressure is released to atmospheric by opening valve (M). Water is then introduced at the top of the specimen through the same valve. The valve (M) is then closed again and pressure is applied to force the water to penetrate into the same specimen.
The coefficient of water permeability can be calculated either by flow as explained before (D'Arcy's Equation) or by penetration depth. The penetration depth method is relatively faster and convenient because it greatly reduces the time to produce results.

According to Valenta (9), the water permeability coefficient can be calculated as follows:

$$k_w = \frac{d_p^2 \delta}{2ht} \tag{4}$$

where:

k_w = coefficient of water permeability (m/s)
d_p = depth of water penetration (m)
δ = porosity of the specimen (as a fraction)
h = head of water (m)
t = time to penetrate to depth d_p (s)

The coefficient of water permeability (k_w m/s) can also be calculated according to the empirical equation of D'Arcy:

$$k_w = \frac{vL}{Ah} \tag{5}$$

where:
h = water head expressed in (m)

To convert the coefficient of water permeability k_w (m/s) into intrinsic water permeability value K_w (m^2), which is independent of the liquid properties, use can be made of equations (1) and (5) to calculate the conversion coefficient as follows:

$$K_w(m^2) = \frac{v\eta L}{Ah\rho g} = k_w \frac{\eta}{\rho g} \tag{6}$$

where:
η = viscosity of water is 1 centipoise = 10^{-3} $N.s/m^2$ at 20°C
ρ = density of water is 1000 kg/m^3
g = gravity is 9.81 m/s^2

Substituting these values:

$$K_w(m^2) = 1.02 \times 10^{-7}\ kw\ (m/s) \tag{7}$$

It is important to highlight here the difficulty of measuring the water penetration depth into a concrete specimen which is not completely dry as the boundary between the penetrated water and the actual water within concrete is not easy to differentiate. At CEMU, it has been found that a water solution which produces a change in colour is adequate to clearly see the boundary of the water advancing front. The solutions which are used in the CEMU test are:

I) phenolphthalein solution - which gives a purple colour upon contact with concrete materials with pH over 9 (uncarbonated concrete)

ii) sodium chloride solution - which when sprayed with silver nitrate, gives a white colour for the penetrated depth and dark brown for the unpenetrated depth of the specimen.

The conversion factors for these two solutions were calculated and found to be:

For phenolphthalein: $K_w(m^2) = 1.3 \times 10^{-7}\ k_w\ (m/s)$ (8)

For sodium chloride: $K_w(m^2) = 1.0 \times 10^{-7}\ k_w\ (m/s)$ (9)

FACTORS AFFECTING PERMEABILITY

The main factors which strongly influence the permeability of concrete are the total pore volume, the pore size distribution of the concrete and the degree of pore saturation.

Porosity

The porosity of a material is normally described by its total pore volume and the pore size distribution which constitutes the total volume. The rate of penetration of fluids and ions is related to both parameters which described the porosity of a material.

Although the pore size distribution of concrete covers a- wide range of pores from the large >1 mm diameter pores to the gel pores <0.01 µm, the pores which influence the permeability and diffusion of fluids into concrete are those pores which are classed as capillary pores i.e. >0.01 µm. Many investigations have proposed correlations between permeability and pore structure in terms of a range of pore sizes (10-14), however there is no full agreement with relation to which, if any, is a better description of the pore volume characteristics which can be used to predict, or at least estimate permeability.

Degree of Saturation

Moisture within the pores of concrete has a noticeable effect on its permeability. Dry concrete is more permeable than wet concrete, even if the pore structure is identical. Furthermore, moisture in the concrete has a large effect on the degree of hydration of cement which in turn affects the pore structure of concrete and hence its permeability. The moisture in concrete which is here expressed as the ratio of the volume of water over the total volume of pores multiplied by 100 i.e. the degree of saturation is determined by the concrete pore structure and the environmental conditions.

Measurements of Porosity and Degree of Saturation

A simple and easy technique is used in CEMU to determine the porosity of concrete and the degree of pore saturation which is based on vacuum saturation. The apparatus and test procedures have been explained in details elsewhere (14).

A brief description of the procedure is as follows: the concrete specimens are initially weighed in air (W_o) after conditioning in the desired environments. The specimens are then sealed in an air tight container and subjected to a pressure of -1 bar for 3 hours. De-aired water is then introduced into the container until the samples are completely immersed, keeping the negative pressure for an additional 3 hours. After this period the pressure is increased to atmospheric leaving the specimens still submerged overnight to ensure full saturation. The specimens are then weighted in air (W_s). The total porosity (P) and the degree of saturation (DS) are then calculated as follows:

$$\text{Porosity (P\%)} = \frac{W_s - W_d}{W_s - W_w} \times 100 \qquad (10)$$

$$\text{Degree of saturation (DS\%)} = \frac{W_o - W_d}{W_s - W_d} \times 100 \qquad (11)$$

From equations, 10 and 11 the volume of pores which are not occupied by moisture can be determined using the following expression:

$$\text{Volume of open pores } (V_e\%) = (P\%)\left[1 - \frac{(DS\%)}{100}\right] \qquad (12)$$

The volume of open pores V_e in this paper corresponds to the "empty porosity" used by Ujike and Nagataki (15) and it will be used here as a parameter to correct the permeability value to a desired degree of saturation.

THE EFFECT OF VOLUME OF OPEN PORES ON CONCRETE PERMEABILITY

Oxygen Permeability

The concrete samples used in this study were obtained from the concrete segments (rings) used in the Jubilee Line Extension Project, London, UK. This is probably one of the largest and most prestigious projects of the 1990s in the UK. The core specimens were obtained from ring segments and were conditioned at different relative humidities and tested for permeability at the age of 35 days. The calculated volume of open pores was then correlated to oxygen permeability. The results are presented graphically in Figure 2.

Examination of Figure 1 illustrates clearly the dependence of permeability on the volume of open pores within concrete. The permeability increases with higher volume of open porosity, confirming that permeability is affected not only by porosity but particularly by the degree of saturation. The results show that a concrete with volume of open pores of less than 4% exhibits low permeability value, while above 5% V_e there is a very rapid increase in permeability. This appears to be an indication that an interconnected system of pores is established when the value of V_e exceeds 4%. Powers (16) proposed the well known relationship between capillary porosity and permeability for hardened cement pastes. Figure 3 shows this relationship indicating that capillary porosity above 20% probably results in an interconnected pore structure which increases the value of permeability very rapidly. The relation obtained by Powers is not of course applicable to concrete but his concept has been shown to be adequate by the analysis presented in this paper.

Water Permeability

Because the time required for reporting results was very short i.e. test measurements made at the age of concrete of 35 days, the method of testing for water permeability was to measure the penetration front. In most cases 3 days under pressure of 4 bar was sufficient to obtain a penetration which was easily measured. Since specimens were not saturated, the real value of the permeability coefficient was difficult to determine due to the nature of the gas/liquid mixture in the concrete while water was advancing into the concrete. The boundary of the water already in the concrete determined the effective thickness of the concrete and this was used to calculate the values of k_w. However, a correction was necessary so that k_w could be reported at the required degree of saturation which in theory should be equal to the value of relative humidity.

Figure 4 shows that low water permeability is achieved by controlling the concrete total volume of open pores. This as in the case of gas permeability should be less than 4%. Cabrera and Hassan (13) showed that the degree of saturation at the surface of concrete is the same as the environmental relative humidity after equilibrium has been attained. By assuming that the degree of saturation is uniformly distributed within the pore structure of concrete, a desired V_e value can be obtained from Equation 12 and used as a target value when designing concrete mixes.

The most important aspect arising from the results reported here is that oxygen and water permeability are affected by the volume of open pores in the same manner, thus it should be possible to measure only oxygen permeability (which is a very rapid test) and convert this value into a water permeability value as required by the specifications. For example, the permeability requirements of the Jubilee Line Extension Project could be achieved by specifying an oxygen permeability value of 1×10^{-18} m^2 at a V_e value which gives the relative humidity shown in Figure 2. This value of oxygen permeability has been determined using a statistical correlation obtained from more than 2000 measurements. Figure 5 shows this relationship and Equation 13 gives its numerical expression

$$y = 2.53 + 1.12x \qquad r^2 = 0.95 \qquad (13)$$

Where:
$y = \text{Ln } K_w$ = Water permeability (m^2)
$x = \text{Ln } K_o$ = Oxygen permeability (m^2)

During the extensive testing carried out under actual production conditions it was found that the repeatability of both, oxygen and water permeability was better than initially expected particularly considering that the specimens were obtained from the production of the actual tunnel segments in two factories. The results confirmed not only the goodness of the equipment and testing procedures but also the excellent quality control established in the factories producing the segments.

The values of standard deviation for the two tests obtained from more than 2000 measurements were:

Standard Deviation for Oxygen permeability = 0.9×10^{-8} m/s

Standard Deviation for Water permeability = 3.9×10^{-14} m/s

CONCLUSIONS

The development of equipment and test procedures discussed in this paper have been shown to be practical and adequate for controlling the permeability of concrete produced industrially and for acceptance of concrete on the basis of performance. Particularly the procedures described show that:

1. Porosity as described by pore volume and degree of saturation i.e. the parameter V_e influence strongly the value of permeability measured. At a value of V_e greater than 5% the pores appear to be interconnected. This is reflected on the very rapid increase of the permeability value above the 5% V_e value.

2. Oxygen and water permeability are correlated by a valid statistical equation obtained with more than 2000 measured values. This equation has been effectively used to convert the values of oxygen permeability to water permeability as normally specified.
3. Because the measurement of oxygen permeability is easier to carry out it is more repeatable and takes a very short time, its adoption is recommended for use as a tool for control of the quality of concrete in industry.

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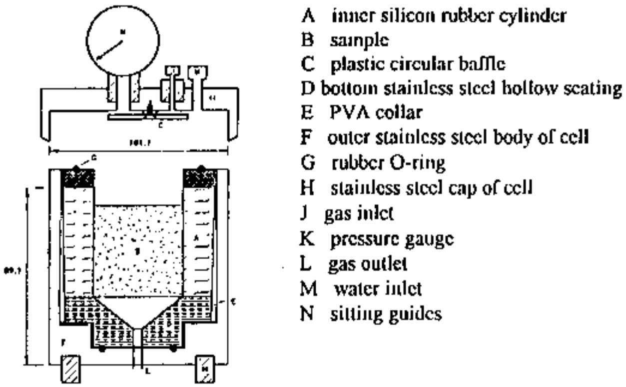

Figure 1. Schematic diagram of the Leeds permeability cell

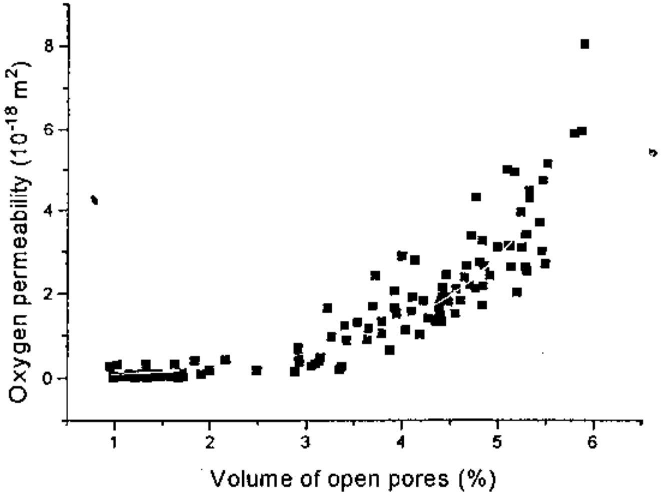

Figure 2. The effect of open pores on oxygen permeability

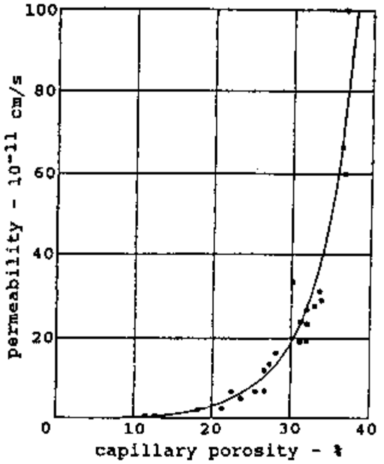

Figure 3. The dependence of permeability on the capillary porosity (16)

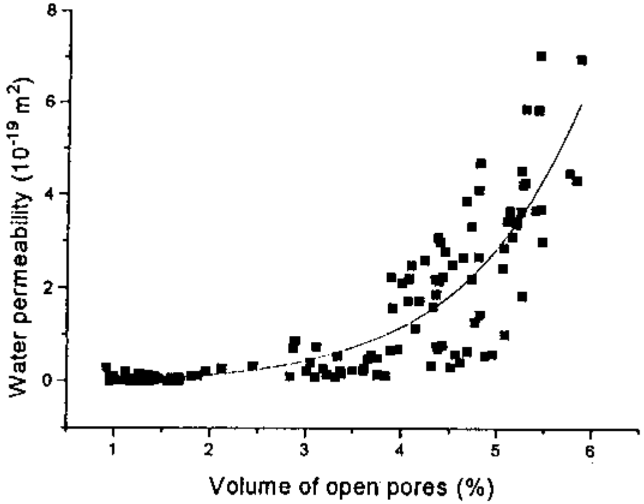

Figure 4. The effect of open pores on water permeability

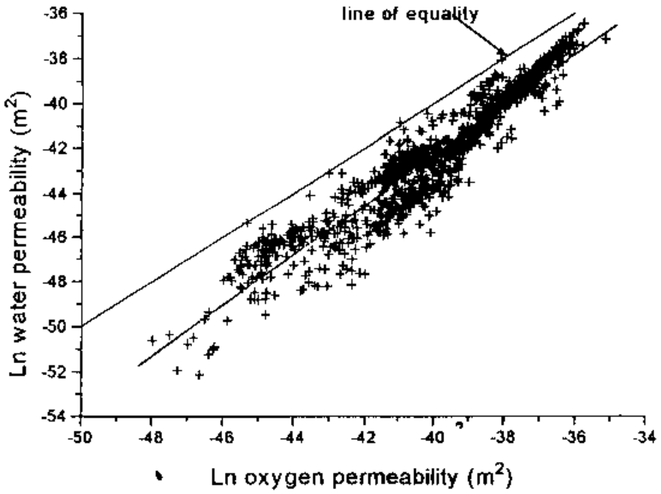

Figure 5. Relationship between oxygen and water permeability