Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 57/1/57/2 (1989)

Artikel: Porosity and permeability as indicators of concrete performance

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DOI: https://doi.org/10.5169/seals-44220

Porosity and Permeability as Indicators of Concrete Performance

Porosité et perméabilité comme indicateur de comportement du béton

Porosität und Durchlässigkeit als Indikatoren des Betonverhaltens

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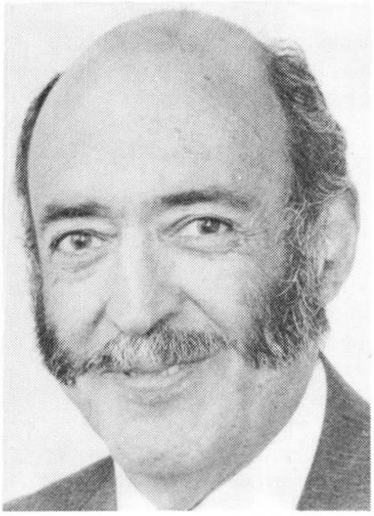

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SUMMARY

Based on the results of an extensive laboratory study, this paper proposes statistical models which link numerically oxygen permeability to pore structure characteristics, total porosity and compressive strength, water/cement ratio, air content and age. The models are used to predict adequate levels of performance for concrete in bridge structures.

RÉSUMÉ

Fondé sur les résultats d'un essai étendu de laboratoire, cet article offre des modèles statistiques qui lient numériquement la perméabilité à l'oxygène aux caractéristiques de la structure des pores, à la porosité totale, à la résistance à la compression, au rapport eau-ciment, à la teneur en air et à l'âge. Ces modèles sont employés pour prédire des niveaux de comportement suffisants pour le béton dans la construction des ponts.

ZUSAMMENFASSUNG

Basierend auf den Resultaten von umfangreichen Laboruntersuchungen werden statistische Modelle vorgeschlagen, welche die Sauerstoffdurchlässigkeit mit der Charakteristik der Porenstruktur, der Gesamtporosität, der Druckfestigkeit, dem Wasser/Zement-Verhältnis, Luftgehalt und Betonalter verknüpfen. Die Modelle werden zur Prognose des Verhaltens von Betonbrücken verwendet.

1. INTRODUCTION

It is now accepted that the performance of concrete under a particular environment cannot be solely related to its strength but that it is a function of its pore structure and permeability [1, 2]. The new British code of practice for the structural use of concrete [3], for example, specifies strength, cement content and water/cement ratio as criteria for design. This, although not satisfactory, is an attempt to control performance by indirectly controlling porosity. The new draft for the Eurocode [4] in concrete has, however, proposed the measurement of permeability as a sole criterion for durability. Notwithstanding the fact that in recent years a large amount of work has been devoted to this problem [5, 6, 7], there is no accepted method for measuring permeability.

This study presents empirical statistical models which relate the oxygen permeability of concrete to other intrinsic and compositional properties of the material. The models are used as an aid to understanding which properties of concrete have a relevant effect on its permeability and also to predict long-term permeability from measurements made at early ages. The paper proposes the use of these models to set criteria for the design of durable concrete mixes.

2. MIX DESIGN AND MATERIALS

The mix design used in this investigation is based on the criterion of "minimum porosity" [8] which involves the selection of the components of concrete to achieve maximum packing.

The composition of the mix designed by the method indicated gave a mix of the following proportions: 1 part of cement, 2.33 parts of sand and 3.5 parts of gravel. The ordinary Portland cement (opc) content of the mix was 325 kg/m^3. This composition was used to prepare three "control" concretes by varying the water/cement ratio (see Table 1).

Table 1: Mixes investigated and their fresh properties

Mix	w/c ratio	Superplasticiser Type	Superplasticiser Dosage*(%)	PFA (%)	Slump (mm)	Flow Table (mm)	Air Content (%)
A	0.65	None	None	None	215	580	0.6
B	0.55	None	None	None	55	390	1.65
C	0.40	None	None	None	0	-	2.8
BN2	0.55	SNFC1	0.2	None	172	550	1.2
BN3	0.55	SNFC1	0.4	None	240	690	0.9
CN2	0.40	SNFC1	1.2	None	50	350	2.6
BM2	0.55	SMFC	0.2	None	155	500	1.3
BM3	0.55	SMFC	0.4	None	225	650	0.9
CM2	0.40	SMFC	1.4	None	50	305	1.60
BP2	0.55	Co-Po	0.08	None	200	545	3.25
BP3	0.55	Co-Po	0.16	None	230	600	5.70
CP1	0.40	Co-Po	0.19	None	50	320	3.9
BSF2	0.55	SNFC2	0.3	None	210	555	3.4
BSF3	0.55	SNFC2	0.45	None	220	600	2.7
CSF1	0.40	SNFC2	0.70	None	50	310	5.4
BLS2	0.55	MLS	0.2	None	200	560	3.5
BLS3	0.55	MLS	0.4	None	215	615	4.3
CLS2	0.40	MLS	0.45	None	65	345	8.4
PFA1	0.50	None	None	30	60	360	1.3
PFA2	0.55	None	None	30	160	485	1.2
PFN	0.40	SNFC1	1.0	30	45	310	2.2
PFM	0.40	SMFC	1.2	30	45	300	1.9
PFL	0.40	MLS	0.45	30	45	320	6.3
PFS	0.40	SNFC2	0.6	30	50	320	4.3
PFH	0.40	Co-Po	0.15	30	50	310	7.0

*Dosage is based on solid/solid weight/weight of cement

Five superplasticisers (see Table 2) were added to the control mixes at different dosages to obtain concretes with a wide range of workabilities up to flowing concrete (see Table 1).

Code	Superplasticiser Description
MLS	Modified lignosulphonate
SNFC1	Sulphonated naphthalene formaldehyde condensate (Powder)
SNFC2	Sulphonated naphthalene formaldehyde condensate (Liquid)
SMFC	Sulphonated melamine formaldehyde condensate
CP	Co-polymer based on acrylic acid and hydroxy-propyl-methacrylate

Table 2: Superplasticisers used in the investigation

Some mixes were also prepared by substituting 30% of the opc with pulverised fuel ash (pfa).

3. PROPERTIES AND METHODS

Air content, slump, flow table (see Table 1) and cube compressive strength were measured according to the relevant parts of BS 1881 [9]. The porosity was obtained by helium pycnometry using a Micromeritics Autopycnometer. Oxygen permeability was measured using the Leeds cell [7].

Although some of the hardened concrete properties were monitored for ages of up to one year, the results used in this paper correspond to ages of 1, 3, 7, 28 and 90 days. The samples were cured in a fog room kept at 20°C and 100% relative humidity. Prior to testing for porosity and oxygen permeability the samples were dried in an oven at 105°C. This method of drying was found not to affect the order of ranking of oxygen permeability values [10, 11].

4. RESULTS AND DISCUSSION

The abundance of data from the 25 mixes studied required the use of statistical techniques for interpretation and evaluation of the effects of the various parameters measured. The data was therefore analysed using a standard statistical package (Statistical Analysis System, SAS). The models presented have a confidence limit of 95%.

4.1 Parameters affecting permeability

Pore structure characteristics directly affect the permeability of concrete, therefore any parameters influencing these characteristics should have an effect on the resistance of concrete to penetration of gases, liquids and ions.

The statistical analysis allowed the evaluation of a large number of properties of concrete with regard to their effects on permeability. From this analysis the most important properties and the extent to which they affected oxygen permeability (K, m^2) were: water/cement ratio (w/c), age (t, days), air content (a, %) and porosity of the fraction of cement paste of concrete (Pp, %). The statistical model (coefficient of correlation $R^2 = 0.80$) which relates these parameters to permeability is:

$$\text{Log } K = -16.853 + 0.077(a)\,(w/c) - 0.012(t)^{0.66} + 0.037(Pp)(w/c)$$

In this model, the air content and the water/cement ratio are considered interactively since (a) is inversely related to (w/c) and its effect on permeability depends on the value of (w/c), i.e. the lower the value of (w/c) the smaller the effect of (a) on the oxygen permeability (10, 12).

4.2 Relation between permeability, strength and porosity.

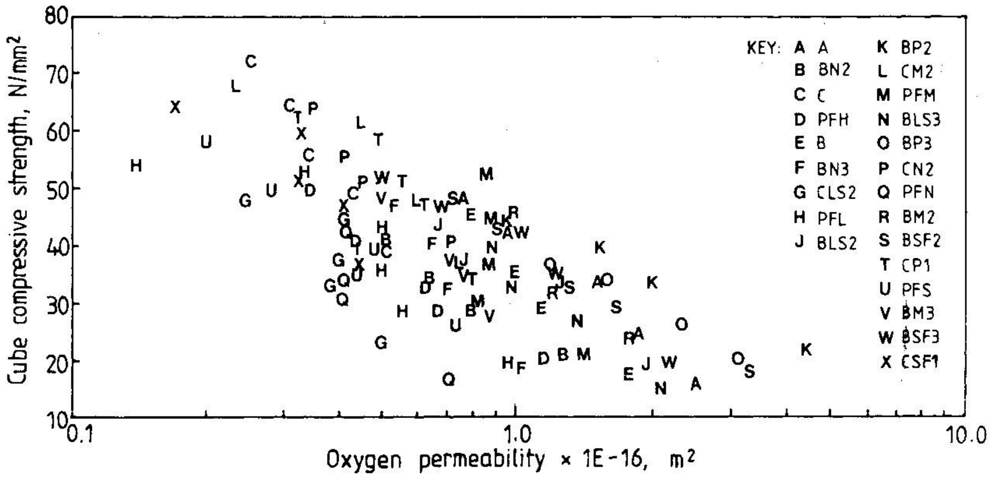

Figure 1: Cloud diagram relating compressive strength to permeability

The compressive strength of concrete is, in most specifications, the dominant parameter used to "control" the quality of concrete. Although there is a good relation between permeability and strength for a particular concrete, the relation cannot be generalised for concretes where the composition is varied either by changing the aggregate-cement ratio or by changing the type of cement or using chemical additives. The results of this investigation confirm the fact that permeability is related to compressive strength for any one mix but when a relationship is attempted for all mixes the result is a cloud diagram as shown in Figure 1. Results reported by Lawrence [13] for concrete mixes made with opc, opc/pfa and opc/slag cured in water at 20°C show similar trends to those shown in Figure 1, i.e. a series of permeability-strength curves within a wide band. Lawrence, [13] however, concludes that there is a single relationship between oxygen permeability and cube strength, despite the fact that his results indicate that at a particular permeability concrete strength varies between 30 and 60 N/mm^2 depending on the mix.

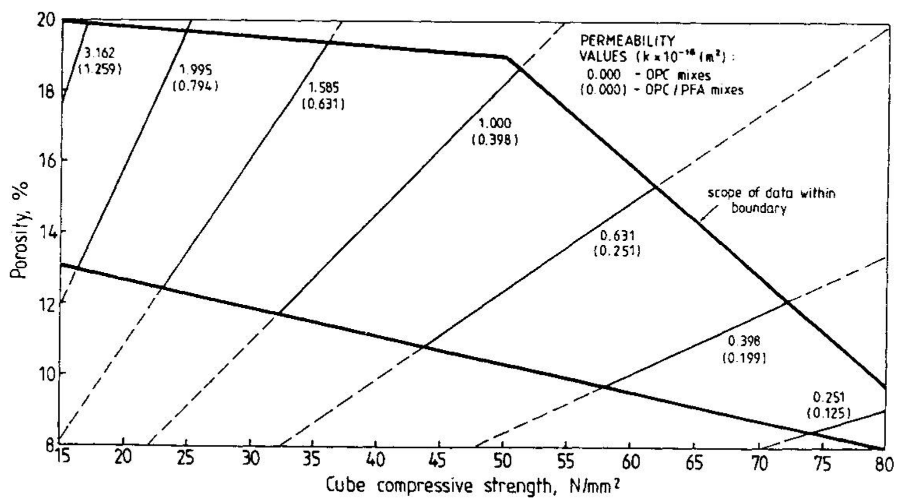

Figure 2: The porosity-strength-permeability model

Statistical analysis of the data gathered in this investigation indicates that oxygen permeability (K) is directly related to porosity (P, %) and inversely related to strength (fcu, N/mm^2). The analysis also revealed that the statistical validity improved by separating the data into two groups; one for opc mixes and one for mixes made with opc/pfa. The models are shown below:

(a) opc concretes:

$$\log K = -15.54 + 1.114 \log \left(\frac{P}{fcu}\right), \ R^2 = 0.71$$

(b) opc/pfa concretes:

$$\log K = -15.95 + 1.01 \log \left(\frac{P}{fcu}\right), \ R^2 = 0.85$$

These models are presented in Figure 2, where the cartesian co-ordinates correspond to porosity and compressive strength and parametric space is divided by contour lines of equal permeability.

4.4 Prediction of long-term permeability from early age values

The use of a permeability test as a quality control test would require measurements at early ages during the mix design stage; therefore relations to predict the long-term permeability of concrete from values at early ages would be very useful. From the data collected in this work, a statistical model to predict the permeability of concrete samples up to the age of 90 days from its one-day value (K_1, m^2) has been obtained. The model is:

$$\log K = -3.688 + 0.789 \log K_1 + \frac{0.356}{t} \ ; \ R^2 = 0.89$$

This model can be used to establish tentative one-day permeability values as a criterion for designing for durability at the stage of trial mixes for a particular job, from the knowledge of the permeability of 'good' and 'bad' in-service concrete. In this investigation, oxygen permeability values of in-service 30 year old concretes, both 'good' concrete and 'bad' concrete showing signs of distress and cracking have been obtained; these were 5×10^{-17} (m^2) and 190×10^{-17} (m^2) respectively. If these values are used in the models as the target permeabilities (i.e. K) then the one-day values will be:

For 'good' concrete $K_1 = 1.02 \times 10^{-16}$ m^2

For 'bad' concrete $K_1 = 1.02 \times 10^{-14}$ m^2

These values can be used as a guide to design for durable concrete. It has, however, to be mentioned that for this model to be of general use, the data base has to be expanded to cover a wider range of concrete mixes.

Similar analysis was carried out on chloride permeability and statistical models have also been developed for its prediction [10]. This will be published elsewhere.

5. CONCLUSIONS

(a) The parameters affecting the oxygen permeability of concrete are: air content, water/cement ratio, porosity and age.
(b) Oxygen permeability is related to the porosity/strength ratio. This relationship is influenced by the presence of pfa in the concrete.
(c) Oxygen permeability, porosity and strength influence the performance of concrete in a particular environment, and at least two of these three parameters are required to predict the performance of concrete.
(d) It is suggested that the target value for oxygen permeability, at one day, for design should be 1×10^{-16} m^2.

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