Pergamon

Cement and Concrete Research, Vol. 25, No. 6, pp. 1199-1208, 1995

0008-8846/95 $9.50+.00

0008-8846(95)00112-3

WATER-PERMEABILITY MEASUREMENT OF HIGH PERFORMANCE CONCRETE USING A HIGH-PRESSURE TRIAXIAL CELL

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(Refereed)
(Received September 16, 1994; in final form February 21, 1995)

ABSTRACT

Water permeability of concrete is used to indicate its durability. Accurate and reproducible measurement of water permeability is difficult and becomes more difficult as the quality of concrete increases. When high-performance concrete (HPC) is tested, these concerns become more pronounced. HPC is used widely to improve the durability and performance of structures but there are few test procedures able to evaluate its permeability-related properties. In this study the water permeabilities of concretes including HPC were measured using a high-pressure triaxial cell with a sensitive and automated measurement capability. Special analysis procedures were developed to obtain useful data from the extremely low volume of water being measured. This method was able to measure a wide range of permeability values from 10^{-12} m/s to 10^{-16} m/s, with reproducible measurements on replicates.

Introduction

The 28-day strength is the most widely used acceptance criterion for hardened concrete, therefore it has been convenient to classify concrete by its strength. In the past, concretes that have strength higher than 42 MPa (6000 psi) have been classified as high-strength concrete (HSC) [1]. With recent advances in concrete technology, a more suitable lower limit of HSC may be >70 MPa. In fact, the 1994 version of the Canadian CSA A23.1 standard for concrete invokes special testing requirements for concretes >70 MPa. Lately, the use of HSC has gradually shifted from its strength-related applications to other uses where such properties as high modulus of elasticity, low penetrability (permeability, diffusion, and absorption) and improved

durability are important. High-performance, rather than high-strength, better describes such concrete. The production of high performance concrete (HPC) entails the use of very low ratios of water to cementitious materials (w/c typically below 0.35) together with a high cementitious contents (>450 kg/m^3). Supplementary cementing materials (SCM), such as slag, fly ash and silica fume, and the use of high dosages of superplasticizer also contribute to the high performance of HPC.

The durability of concrete structures is always a concern in aggressive environments. Factors to be considered in dealing with concrete durability include the constituent materials, construction processes, physical properties of the concrete, type of loading, and the nature of the environment to which the concrete structure is exposed. The major durability problems, such as the corrosion of steel reinforcement, damage by freezing of water in pores, attack by sulphates and acids, and cracking due to the reaction between alkalis released during the hydration of cement and certain types of aggregates, are caused by fluids penetrating the pore system of concrete. Therefore, permeability of concrete is critical to its durability in many service environments.

Saturated water permeability of concrete is seldom the dominant transport mechanism in practical situations. Real mass transfer takes place by two-phase flow in which the vapour component is dominant [2]. However, saturated permeability has been of great interest since the 1920's and the 1930's [3,4] as it quantifies the connectivity of the pore structure.

Testing of concrete by saturated water permeability has been plagued by variability. Not only is a wide variation noted when test conditions are changed but a large variability exists for a given set of test conditions [5-8]. In addition, many individual test methods have been unable to accommodate a wide range of concrete qualities, and they were unable to measure the very low permeabilities associated with HPC [5,9]. The problems of measuring saturated permeability for high performance concrete (HPC) have become more acute with the increase in use of HPC to improve the durability and performance of structures such as bridges, parking decks, and offshore structures.

The need to improve the range and sensitivities of methods for measuring concrete permeability has been discussed in the literature [10]. The need to have a reproducible permeability measurement is essential for comparison of permeability data from different laboratories. At present, interlaboratory comparison is difficult because of the use of many different non-standard test methods [11, 12, 13]. Even for a single method, variability of test results on replicates is still high [14]. As well, the variability of data increases with a decrease in permeability [15]. Also the use of thin samples, about 6 mm [13], to test the efficiency of a method cannot indicate how the method will perform on thick concrete samples, as thin concrete samples give a higher permeability value than is measured for thick specimens of the same concrete [6]. Also, the direct application of results of studies on bulk cement paste could be misleading, as shown by Diamond [16], because bulk and homogeneous paste such as that produced in laboratories is not likely to be present in concrete. Winslow et al. [17], showed that the pore-size distribution of the paste in concrete and mortar is different than that of plain paste, and the degree of change depends on the amount of aggregate. Also, Sarkar [18], concluded that the characterization of concrete could differ from that of the corresponding mortar or paste.

In previous studies [19,20] a high pressure triaxial cell with an improved measurement and analysis system was developed for measuring the water permeability of a wide range of

concrete qualities. In this study, the sensitivity of the previously described apparatus [19] was evaluated for concretes with different permeability coefficients.

Experimental

Concrete Mixtures and Properties

Three concrete mixtures were designed to have a wide range of permeability values, to evaluate the sensitivity of the test method proposed for measurement of low and high permeability coefficients. The slump was maintained in the range of 50 to 100 mm, for ease of casting and consolidation. Relatively high sand contents were used to minimize bleeding and segregation of the fresh concretes.

For one of the concretes, slag and silica fume were used as partial replacement of the cement, at 25% and 7% by mass respectively, of the total cementing materials. A naphthalated sulfonate-type superplasticizer, Lomar-D powder, was used for two of the mixtures to improve workability. Superplasticizer dosage was calculated as a percentage by mass of the cementing materials. The superplasticizer was added to the mixing water.

Slump, air content, and density were measured for the fresh concrete. The compressive strength was measured at 7, 18 and 91 days based on the average of three 100x200 mm cylinders. Table 1 shows the mixture design (based on dry masses of aggregates) and the properties of the fresh and hardened concrete for the mixtures used.

Preparation of Specimens

Batches were sized to provide enough concrete for 15 cylinders (100x200 mm), 8 slabs of dimensions 500x400x160 mm, and for air content and slump tests.

After casting, concrete specimens were covered with wet burlap and plastic, de-moulded after 1 day, and concrete cylinders were kept in the moist room until the day of the compressive strength test. Two curing regimes were applied to the concrete slabs: **i)** continuous immersion in saturated lime water and **ii)** moist curing for 4 days after stripping then in air at room temperature. The concrete slabs were kept under the specified curing regime until the date of preparing the specimen for testing.

The specimens prepared from the immersed concrete slabs are denoted **(W)** while those from the combination curing regime are denoted **(D)**. For the identification of the different mixes used and the number of the replicate specimens, the curing regime code is followed by the mix number and a letter (A, B or C) showing the number of replicates, for example **(W1 A)** refers to the first replicate for mix number 1 from the immersed slabs.

Cores of nominal diameter 100 mm were taken from the slabs and sliced into discs of approximately 50 mm thick. Only the middle disc, at 50 mm from the cast surface, was used for the permeability tests. The reason for only using the middle slice was to minimize variation of the concrete, and to help ensure that the specimens would be a representative of the bulk concrete. Cores were used rather than cylinders, to avoid any possible "wall effect" on the test results.

Table 1
Concrete Mixture Design and Properties.

	MIX 1	MIX 2	MIX 3
Mix Design: (kg/m^3)			
Cement (O.P.C)	290	350	340
Slag	---	---	125
Silica Fume	---	---	35
Stone (10 mm)	684	820	820
Sand	1205	1085	1009
Water (W/CM)	200 (0.69)	171.5 (0.49)	145 (0.29)
Superplasticizer	---	0.3%	1.0%
Measured Slump (mm)	90 - 100	60 - 70	50 - 60
Air Content %	3 - 3.2	3.3 - 3.5	3.5 - 4.0
Density (kg/m^3)	2371	2414	2455
Compressive Strength (MPa)			
7 days	22.0	38.1	62.5
28 days	29.6	42.0	74.6
91 days	39.3	54.2	81.0

Preparation and testing procedures and conditioning were standardized in this study to minimize variation of the measured permeability on replicates [19,20].

Each sample was prepared by vacuum saturation. The specimen was placed under vacuum for 6 hours, and then covered by de-aired water while it was still under vacuum. The vacuum was maintained for an additional 1 hour and then released. The specimen was then left under water for 18 ± 1 hours prior to insertion into a permeability cell.

The ratio of the triaxial confining pressure to the driving pressure* (P_c/P_d) was maintained at approximately 4, to reduce the sensitivity of the permeability measurement to operating conditions [5]. Also, the ratio of the specimen thickness (L) to the maximum aggregate size was kept constant, L = 5 times the aggregate maximum size [6], to minimize the effect of short circuiting of water along paste-aggregate interfaces.

The permeability coefficients are expressed in (m/s), so that water viscosity, a function of the pore size, is not a factor. Controlling the temperature of the environment surrounding the permeability set-up contributes to pressure stability, so testing temperature was maintained at 23 ± 1.0 °C. Finally, de-aired water is used for the experiment as well as for applying confining pressure, so that air dissolved in water under the pressure does not affect rate of flow and stability of pressure.

* the pressure difference across the specimen.

Test Results

Concrete specimens were tested after 12 to 16 months of either water curing or air curing at 23°C. All the experiments were carried out on three replicates and the average of the three results is reported. Also, the standard deviation and the coefficient of variation (CV) for the test results have been calculated to judge the reproducibility of the test results.

For each specimen the testing procedure involves the measurement of the main experimental parameters such as dimensions of the specimen, the specimen's mass before and after the experiment, temperature of the surrounding environment, the driving pressure and the confining pressure.

Due to the noise from the LVDT output signals, no trend could be detected from the raw inflow and outflow volume rates. Therefore, raw data were analyzed by taking the running average (which is the average of the first n measurements; where n ranges from 2 to total number of measurements) to detect any trend in the outflow and inflow volume rates, so that the onset of equilibrium flow could be defined for calculating the permeability coefficient. Figure 1 shows typical running averages for the inflow and outflow volume rates. Figure 2 shows a typical curve for coefficient of permeability, calculated from the processed outflow-volume data.

Table 2 shows the dimensions of specimens for mixture 3 (diameter D and thickness L), specimen mass before (M_{before}) and after (M_{after}) the experiment, and the temperature of the surrounding environment (Temp). Table 3 is the associated driving (P_d) and confining (P_c) pressures during the experiment, the ratio of confining to driving pressure (P_c/P_d), the time at which the measurement of average coefficient of permeability was initiated (T_i), the time interval of measuring the average coefficient of permeability (ΔT), and the average coefficient of permeability (K_{avg}).

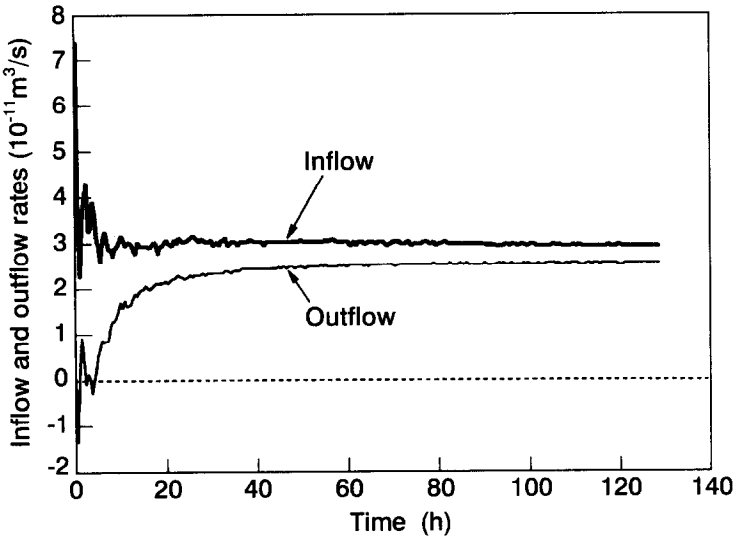

FIG. 1
Running Averages for Inflow and Outflow Volume Rates (Mix 2 Specimen D2B).

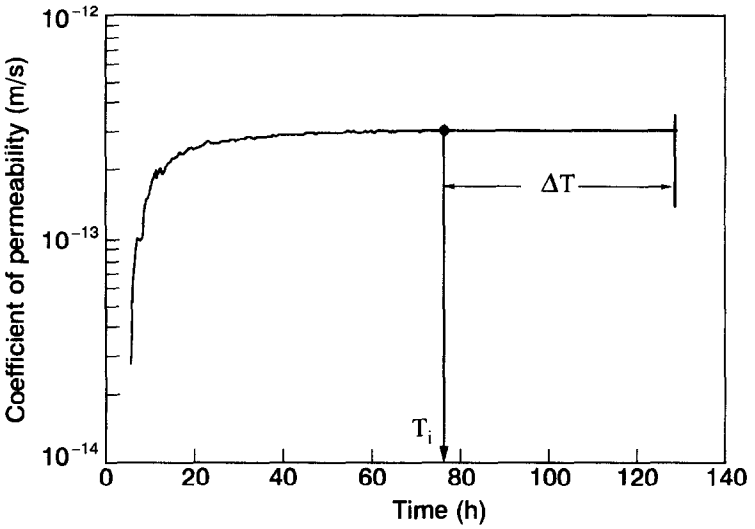

FIG. 2
Coefficient of Permeability (Mix 2 Specimen D2B).

Discussion of Test Results

The equipment was able to measure permeability coefficients in the order of 10^{-16} m/s. Test time varied according to the order of the coefficient of permeability being measured. The total test time for permeability coefficients up to $1x10^{-14}$ m/s was about 160 hours, and for permeability coefficient in the order of $1x10^{-16}$ m/s was about 330 hours. This is expected for low

Table 2
Specimen Dimensions, Mass Before and After the Experiment and Temperature of Surrounding Environment for Mixture 3.

Curing Regime	Specimen #	D (mm)	L (mm)	M_{before} (gm)	M_{after} (gm)	Temp* (°C)
W	W3 A	100.0	50.2	922.39	923.70	23.2 (1.3%)
	W3 B	100.0	50.3	927.00	929.11	23.3 (1.2%)
	W3 C	100.0	50.0	922.79	925.02	22.7 (1.5%)
D	D3 A	100.0	50.2	926.87	930.54	22.8 (2.4%)
	D3 B	100.0	49.9	916.35	919.76	22.9 (1.6%)
	D3 C	100.0	50.0	916.78	918.98	23.2 (1.1%)

* Values in parenthesis are the coefficient of variation of the measured temperature.

Table 3
Experimental Parameters and Coefficient of Permeability for Mixture 3.

Curing Regime	Specimen #	P_d* (MPa)	P_c* (MPa)	P_c/P_d	T_i (hr)	ΔT (hrs)	K_{avg} (m/s)
W	W3 A	6.562 (1.9%)	25.857 (0.5%)	3.94	250	64	1.92E-16
	W3 B	6.598 (1.5%)	25.497 (1.1%)	3.86	250	72	1.72E-16
	W3 C	6.540 (1.3%)	24.917 (0.9%)	3.81	250	83	1.93E-16
D	D3 A	6.501 (2.4%)	24.686 (1.4%)	3.80	250	78	1.86E-16
	D3 B	6.555 (1.7%)	24.266 (0.6%)	3.70	250	84	1.88E-16
	D3 C	6.664 (1.7%)	24.584 (0.5%)	3.69	250	80	2.14E-16

* Values in parenthesis are coefficient of variation for the measured pressures.

permeability measurements due to the longer period required to establish equilibrium flow. Also, the initialization time after which the coefficient of permeability was measured increases as the permeability coefficient decreases. For permeability coefficients in the order of $1x10^{-12}$, $1x10^{-13}$, $1x10^{-14}$ and $1x10^{-16}$ m/s, the initializing times were about 130, 140, 150 and 250 hours respectively. Figure 3 shows the total test time and the initializing time (T_i) versus the different permeability coefficients.

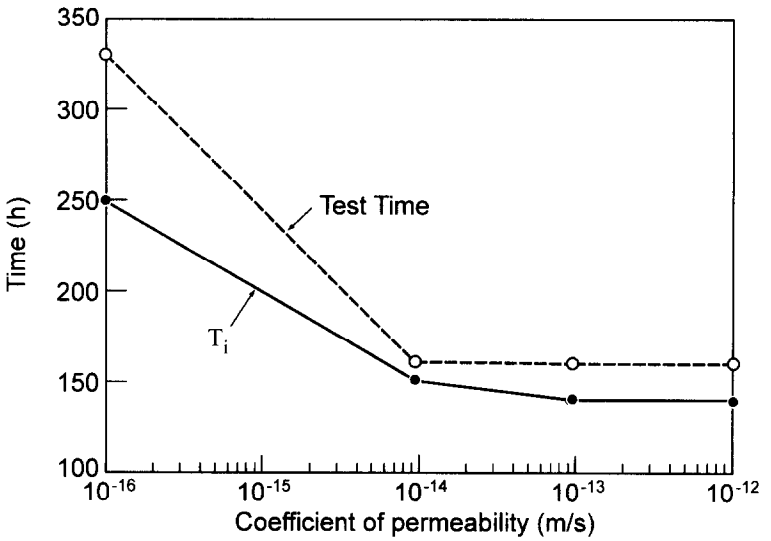

FIG. 3
Coefficient of Permeability Versus Initializing Time and Total Test Time.

The mass of each specimen (saturated surface-dry condition) was recorded before and after the experiment (only for mixture 3) to reveal any change that might have occurred during the test ($\Delta M = M_{after} - M_{before}$). This change was compared to the difference between the cumulative mass of the inflow volume and the cumulative mass of the outflow volume ($\Delta W = W_{inflow} - W_{outflow}$).

The relationship between the change in mass and the difference between the cumulative mass of the inflow volume and the outflow volume is shown in Figure 4. The linear regression analysis of the data shows a linear relationship with a coefficient of correlation (r) of 0.861. Moreover, the intercept of the line is -0.218 (which is close to zero, as it should be) and the slope is 0.905 which is close to unity, or a 45° line (equality line).

This procedure shows that it appears to be possible to quantify the difference between the inflow and the outflow volumes with respect to the change in mass that occurs to the specimen during the test. For the data presented (Mixture 3) most of that difference is accounted for by the increase in the specimen's mass which indicates further hydration or saturation of specimens during the test.

The average values of measured coefficients of permeability (K_{avg}) for the different mixes together with the standard deviations (σ), and the coefficients of variation (CV) are shown in Table 4. The coefficient of variation (CV) for the measured permeability values using the high pressure triaxial cell ranged between 3.7% to 17.1%, and the overall average CV is about 10%. This indicates a very low variation in the test results relative to those published previously [3,4,14,21,22,23], in which the best CV value was 30.6% [22] . Therefore, this equipment and these procedures yielded permeability measurements with improved reproducibility.

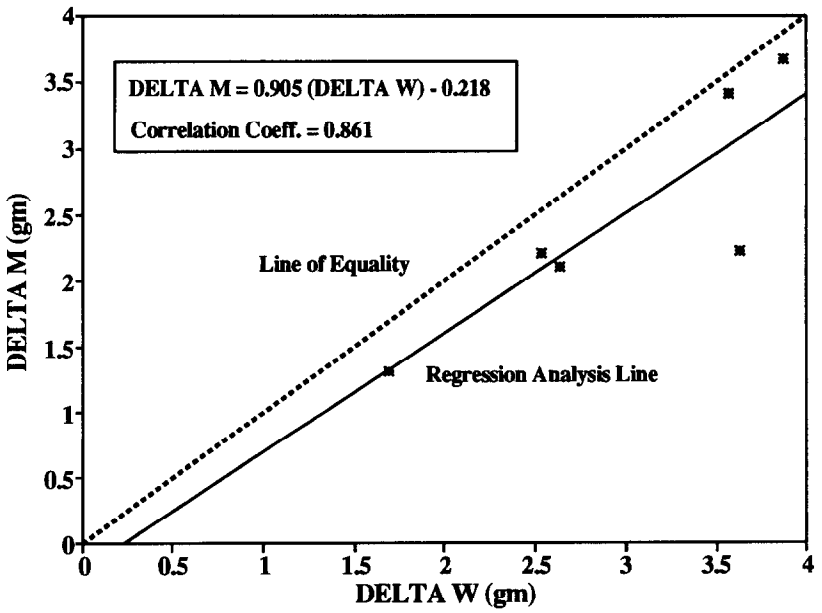

FIG. 4
Relationship Between Change in Specimen's Mass (ΔM) and the Difference Between Cumulative Weight of Inflow and Outflow Volumes (ΔW).

Table 4
Average Values of Measured Coefficients of Permeability, Standard Deviations, and Coefficients of Variation.

Mix #	Curing Regime	K_{avg} (m/s)	σ (m/s)	CV %
1	W	2.04E-12	2.29E-13	11.2
	D	3.66E-12	2.65E-13	7.3
2	W	3.72E-14	1.39E-15	3.7
	D	2.83E-13	4.85E-14	17.1
3	W	1.86E-16	1.19E-17	6.4
	D	1.96E-16	1.56E-17	8.0

Conclusions

Improved measurement of pressure and flow, well controlled testing procedures, and the statistical averaging techniques for data analysis developed in this method enabled the measurement of a wide range of permeability levels from 10^{-12} m/s to 10^{-16} m/s with reproducible measurements on replicates (an average coefficient of variation of 10%). Statistical data analysis provided useful data from measured inflow and outflow volumes, especially in the case of extremely low volumes of water being measured. Changes that occurred to the specimens during the test could be quantified by studying the measured inflow and outflow volumes, and by careful measurement of the specimen mass before and after the test.

This equipment and these procedures, provided reproducible measurement of water permeability for HPC and for a wide range of concrete qualities, by minimizing the causes of variation. It is hoped that this improvement will contribute to a standard permeability testing method and a common base of quantifying concrete durability.

Acknowledgment

The support of the Natural Sciences and Engineering Research Council (NSERC) and the Ontario Centre of Materials Research (OCMR) is gratefully acknowledged.

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