PERMEABILITY TESTING OF PLASTIC CONCRETE

Osondu J. Uzomaka, Department of Civil Engineering, University of Nigeria

Conventional permeability tests on hardened concrete suffer some limitations such as uncertainty of the physics governing the flow. These tests are painstaking and expensive and yield inconsistent results. Testing concrete at the plastic stage is proposed as a way of rationalizing and accelerating the test. As a first step toward full realization of this concept, the permeability characteristics of retarded plastic concrete have been investigated by using a specially designed cell and a falling-head permeameter. During this investigation, particular attention was paid to (a) elimination of the effect of boundary flow on the true values of the coefficient of permeability of the permeate; (b) verification of the validity of Darcy's law for flow-through plastic concrete; and (c) evaluation of the effects of variation in water-cement ratios and the hydration process on values of the coefficient of permeability of the permeate. Results so far available confirm that the Darcy flow is applicable to plastic concrete. The Darcy coefficient of permeability of the mixes used in this project is generally of the order of 10^{-5} cm/s and increases exponentially as the water-cement ratio increases. The effect of addition of sugar, as a retarder, is to reduce values of the coefficient of permeability of the permeate. Similarly, hydration reduces the coefficient of permeability of the permeate, which decreases with time.

•THE determination of the coefficient of water permeability of hardened concrete involves complicated and expensive test preparation, and the test itself is time consuming. In addition, there appears to be no consensus of opinion on the physics governing the migration of water through hardened concrete. Flow of water through hardened concrete has been variously conceived. Hughes (1) and Murata (2, 3, 4, 5), for example, favor an absorption process, and others conceive the problem as a flow process conforming to Darcy's law. The above limitations are further compounded by the large discrepancy that can occur between permeability test results for apparently identical specimens.

I have postulated that a departure from the convention, by carrying out permeability tests on the fresh mix rather than on the hardened concrete, would, if successfully developed, overcome some of the previously mentioned weaknesses of the conventional test. From theoretical considerations, this unconventional approach should overcome the fundamental issue regarding the pertinent physics governing flow through the material. Plastic concrete has a structure that is similar to a cohesive-frictional soil (6), and the movement of water through such porous media is a flow process.

From a methodological standpoint, the proposal will yield savings in both time and effort. When combined with the fact that the proposed test has to be undertaken on a freshly mixed concrete, the new test qualifies as an accelerated form of permeability testing on concrete. Full realization of this concept requires the establishment of either or both of the following:

1. A correlation between the permeability of plastic concrete with that of the hardened concrete; or
2. A correlation between the permeability of plastic concrete with relevant performance characteristics of concrete, e.g., durability and development of interstitial pressures in dams.

However, the prerequisite to these steps must be a thorough investigation of the methodology of permeability testing of plastic concrete and the permeability characteristics of the material itself. When these have been established, the vital, but secondary, stage of correlating the relevant parameters can then proceed.

In this paper, an investigation into the permeability of plastic concrete is discussed that is aimed at studying the permeability characteristics of concrete mixes at zero time, i.e., just after mixing before any significant setting of the mix takes place. So that this can be achieved, the mixes have been retarded by addition of a small dose of sugar. Particular attention has been paid to the common problem of the boundary flow that occurs during permeability tests. The effect of changes in the water-cement ratio, which is the most crucial of concrete mix variables, and the effect of setting due to cement hydration on the permeability values have also been investigated.

The following notation is used in the paper:

A = cross-sectional area of permeate,
A_c = cross-sectional area of the core of the permeate,
A_p = cross-sectional area of the periphery of the permeate,
a = cross-sectional area of standpipe or manometer tube in the permeameter,
B = constant,
C = constant,
H = height of water in the standpipe above the top surface of the permeate at any time,
H_o = initial height of water in the standpipe above the top surface of the permeate,
H_t = final height of water in the standpipe above the top surface of the permeate,
dH = drop in height of water in the standpipe in time dt,
i = hydraulic gradient,
k = coefficient of permeability of the permeate,
k_c = coefficient of permeability of core of the permeate,
k_p = coefficient of permeability of periphery of the permeate,
L = thickness of the permeate,
Q = quantity of flow through the permeate,
Q_p = quantity of flow through periphery of permeate,
Q_c = quantity of flow through core of permeate,
$\beta = Q_p/Q_c$,
t = time interval, and
v = discharge velocity.

THEORETICAL BASIS FOR PERMEABILITY CELL DESIGN

Pilot tests showed that the boundary flow between the mix and the wall of the cell was significant despite various contrivances that were devised to arrest it. It was therefore decided to tolerate boundary flow and then to modify both the theory and design details of the permeability cell accordingly. Two flow regimes were distinguished (Figure 1): (a) core flow, from which the true k-values were computed, and (b) periphery flow, which included boundary flow. The final design of the cell achieved isolation of these two regimes.

The fundamental law defining macroscopic permeation through a porous medium was established by Darcy in 1856. The law states that

$$V = ki \tag{1}$$

Equation 1 may be rewritten as

$$Q = Aki \tag{2}$$

The falling-head permeability test is usually adopted for materials whose k-values are anticipated to fall below 10^{-1} cm/s (7). On this basis, equation 2 has been developed to simulate the design features of the cell. The basic theoretical approach is available elsewhere (8).

If the level of water in the standpipe fitted above the cell falls by dH in time dt, then

$$\int \frac{H}{L} dt(A_p k_p + A_c k_c) = -a \int dH \tag{3}$$

In any interval of time,

$$\frac{Q_p}{Q_c} = \frac{A_p k_p}{A_c k_c} \tag{4}$$

Substituting equation 4 into equation 3 and evaluating and rearranging the integrals give the true permeability of the material:

$$k_c = \frac{2.3\ aL}{A_c\, t(1 + \beta)} \log_{10}\left(\frac{H_o}{H_t}\right) \tag{5}$$

Every term on the right side of equation 5 can easily be determined, except the effective core area A_c. It should be emphasized that this is not equal to the area bound by the imaginary demarcation lines, i.e., the broken vertical lines in Figure 1. The effective core area is the area at the top of the concrete specimen from which the quantity of water collected via the central outlet has actually emanated. This is better explained by reference to flow nets, the principles of which are outlined by Harr (9). The effective core area is shown at the top of Figure 2; the flow channels from this area cover the core area at the base.

The flow-net technique was used to determine A_c. Based on the observation that each flow channel conveys the same quantity of water, the ratio of the number of channels terminating over the core zone at the base to the total number of flow channels gives the ratio of core flow to the total flow. The effective core area contributing this proportion of flow is then computed from the flow-net analysis shown in Figure 2. Several flow nets were drawn, and an empirical relationship between quantity ratio and area ratio was established.

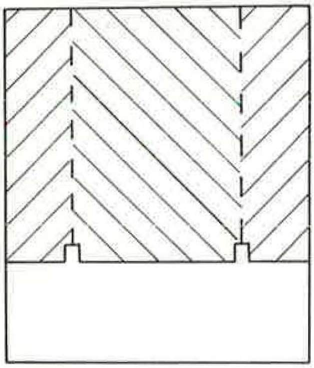
Boundary conditions can also be defined from theoretical considerations and for the particular cell used in this project. They are as follows:

1. The minimum flow ratio is zero, and the corresponding area ratio is zero.
2. The maximum flow ratio is 0.36, and the corresponding area ratio is 0.36.

Data obtained from the flow-net analysis are plotted with the boundary values in Figure 3. Nonlinear regression analyses were carried out in an attempt to fit either a polynomial or an exponential curve to all the points, but the outcome seemed improbable. However, if the upper boundary value was discarded, albeit theoretically plausible, a linear correlation became apparent. The theoretical points, i.e., the upper and lower bound values, were next ignored, and a regression line was fitted to the flow-net points only. The correlation coefficient for this regression line is 0.99.

Given any value of flow ratio determined from tests based on this particular cell, the corresponding area ratio can then be interpolated from the correlation. The effective core area A_c can therefore be calculated and then substituted into equation 5.

Figure 1. Flow regimes.



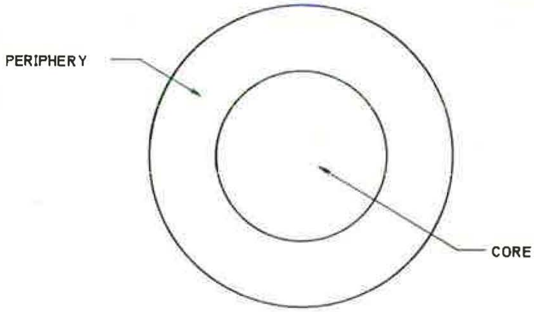


Figure 2. Flow net for test systems.

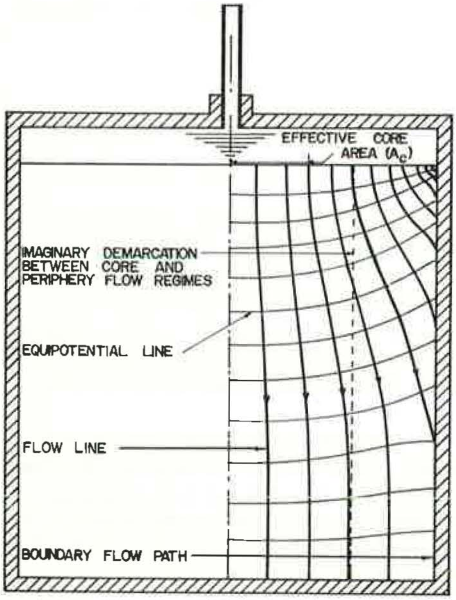
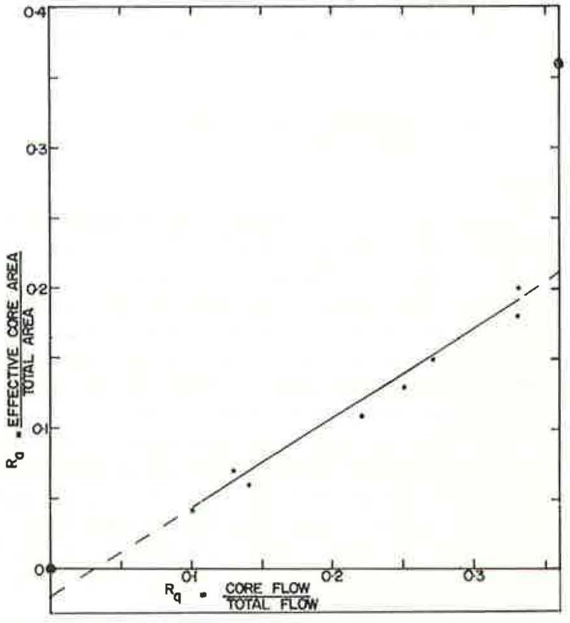


Figure 3. Correlation between flow ratio and area ratio.



APPARATUS

Permeability Cell

Details of the final design are shown in Figure 4. The cell was constructed from cast aluminum to limit rusting. The contact time between each mix and the cell was short, and, consequently, the effect of any reaction between the concrete and the aluminum was considered to be negligible. The three cell components, top, body, and base, are held together with brass screws. Rubber O-rings that are housed in grooves are used to prevent leakage at the joints.

Inlet and bleed valves are provided at the top, and the inside of the upper face is domed to facilitate air bleeding. Perforated aluminum and porous plastic (Vyon) discs sit on a recess at the upper end of the body. The porous plastic prevents any possible upward migration of concrete fines, while the aluminum enhances the flexural rigidity of the porous plastic. The inside wall of the body is machined to produce a continuous fine spiral groove from top to bottom; this aims at improving the keying of the mix to the cell and lengthening the boundary flow path. The combined effect was to minimize the severity of boundary flow. The base has a central depression, 44.5 mm in diameter and 3.2 mm deep, and a central tapping leading to an outlet valve. An annular ridge, 3.2 mm wide and 3.2 mm deep, separates the central depression from an annular groove that collects the peripheral flow.

Permeameter

The permeameter, shown in Figure 5, is similar in principle to conventional falling-head permeameters. However, the design satisfies two specific requirements:

1. Reversible flow can be obtained; therefore, both upward and downward flow tests can be done.
2. A wide range of initial hydraulic heads can also be obtained. High pressures are achieved by coupling to a standard Bishop pressure apparatus (10).

TEST DETAILS

Specification of Concrete Mix and Materials

Budgetary constraints limited the number of mix variables to be investigated to one: the water-cement ratio, which is the most crucial to the characteristics of concrete. The water-cement ratios were chosen to give the following mix consistencies:

Compacting Factors	Water-Cement Ratio
0.78	0.40
0.85	0.43
0.92	0.47
0.95	0.50

Ordinary portland cement and river sand and gravel were used. The aggregate was separated into single sizes before it was recombined to exactly produce grading curve (11). The laboratory air-dried aggregate was soaked for 24 hours before mixing. The total water-cement ratio mentioned earlier included the moisture absorbed by the

Figure 4. Permeability cell.

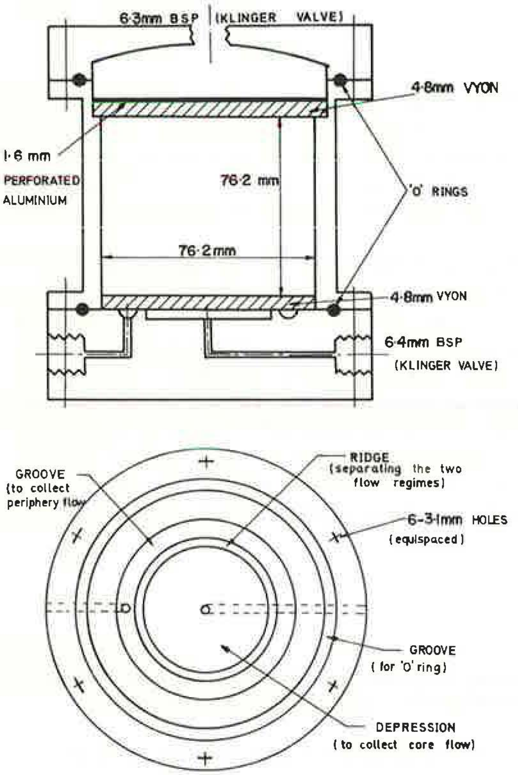


Figure 5. Permeability test equipment.

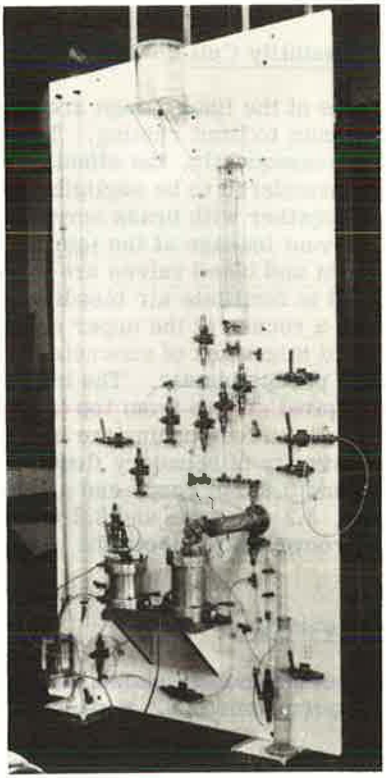
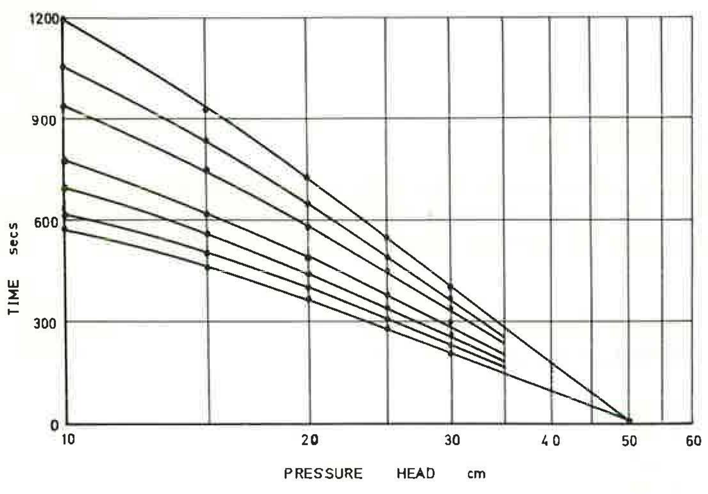


Figure 6. Time versus pressure head.



aggregate. The specific gravity and absorption of the graded material are 2.5 and 1.4 percent respectively. An aggregate-cement ratio of 4.5 was selected because it was within practical limits.

A small quantity of sugar was added to some of the mixes to retard cement hydration. A sugar-cement ratio of 0.0025 by weight was adopted. This has been shown to sufficiently retard strength gain within 24 hours (12).

Test Procedure

A predetermined quantity of the mix was vibrated into the cell. Pilot tests had shown that vibration was the most effective practical technique for compacting the test specimen to minimize boundary flow. The specimen was then de-aired by applying a low back pressure that caused a gradual upward flow of de-aired water through the specimen. When no further air was observed from the top valve, the back pressure was cut off, and the specimen was ready for test.

The permeability test commenced exactly 1 hour after mixing; this time had earlier been found to be just sufficient for careful sample preparation. The test essentially consisted of recording the drops in the hydraulic head, the corresponding time intervals, and the quantities of flow from both the core and periphery zones.

Except for the investigation of time effects (or hydration), each sample was used for only one test. Six tests were made for each mix (i.e., water-cement ratio).

DISCUSSION OF RESULTS

Validity of Darcy's Law

It was postulated, as a premise for the laboratory study, that flow through plastic concrete obeys Darcy's law. The empirical data may be used to verify this postulation.

For each test, all terms in equation 5, except t and H_t, are constants. The equation may therefore be written in the following form:

$$t = B - C \log_{10} H_t \tag{6}$$

As equation 5 was developed from Darcy's law, the flow of water through plastic concrete actually obeys Darcy's law if a plot of t-values against $\log_{10} H_t$ is linear as implied by equation 6. Such plots were made from the test data, and Figure 6 is typical. The various curves are for different ages of the mix and increase upwards at 30, 60, 90, 120, 180, 240, and 300 min from the end of mixing.

Down to the 20.0-cm head, the flow generally obeys Darcy's law but deviates at lower gradients where nonlinearity occurs. This partial non-Darcy flow is attributed to particle migration that occurs with the progress of flow. Incomplete saturation as suggested by Matyas (13) and boundary flow as suggested by Mitchell and Younger (14) can be discounted as care was taken to eliminate these. Moreover, if incomplete saturation had been responsible, deviation would have occurred right at the outset rather than at lower heads since the degree of saturation would improve as the permeation front progresses. The establishment of particle migration in clays (14) and the observation that the head at which deviation occurred varied with the initial head lend support to the migration hypothesis.

Variation of k With Water-Cement Ratio

The permeability of plastic concrete obtained from this study is generally of the order of 10^{-5} cm/s. The results are shown in Figure 7, and the average values of the permeability are given in the following table:

Water-Cement Ratio	Equivalent Moisture Content (percent)	k-Values (10^{-5} cm/s)
0.50	9.10	7.76
0.47	8.50	7.52
0.43	7.72	6.32
0.40	7.27	2.71

Figure 7 suggests that k increases exponentially as the water-cement ratio increases. This result is considered logical because increasing water-cement ratio increases the porosity of the mix. The result is also consistent with the trends obtained for hardened concrete (15, 16). For moisture contents of 2 percent above optimum and more, the k-values for soils (soil being similar in structure to plastic concrete) also increase with moisture content (17).

I had previously determined indirect k-values of the order of 10^{-8} cm/s for plastic concrete from one-dimensional consolidation tests (18). The high consolidation pressures have the effect of considerably reducing the void ratio of the test specimen and consequently result in very low k-values. In this light, the two sets of results are considered to be compatible, and this order of difference is not uncommon in soil mechanics.

Effect of Sugar

The average of six values obtained for an unretarded mix (i.e., without sugar), having a water-cement ratio of 0.50, is 1.9×10^{-4} cm/s. When the unretarded mix was compared with the corresponding mix containing sugar, it was seen that the addition of sugar reduced the permeability of the mix.

The action of organic materials, such as sugar, in retarding the setting of cement is not yet fully understood. However, it is thought that some retard by adsorption through either their carboxyl or hydroxl groups, and such actions occur rapidly initially (19). The adsorption process would result in the fixation of part of the pore water and thereby reduce the effective pore channel (20) and give a less permeable structure.

Effect of Time

The well-known theories of Le Chatelier and Lea suggest that an intergrowth of crystals lock together during the hydration process and thus result in a simultaneous diminution in pore size and a change of pore geometry. This continuous change in pore structure would cause k-values to decrease with time, as shown in Figure 8.

The shape of the curve suggests that the k-value may approach a stable value. With further investigation into the effect of time, including hardened concrete, it may be possible to evolve a predictive correlation between the k-value and time. In this case, the k-value for hardened concrete can then be predicted from permeability tests on the fresh mix.

CONCLUSIONS

Experience gained from the present project confirms that permeability testing of plastic concrete is a feasible and viable proposition. However, a more comprehensive investigation into the permeability of plastic concrete is necessary before the program

Figure 7. Variation of coefficient of permeability with moisture content.

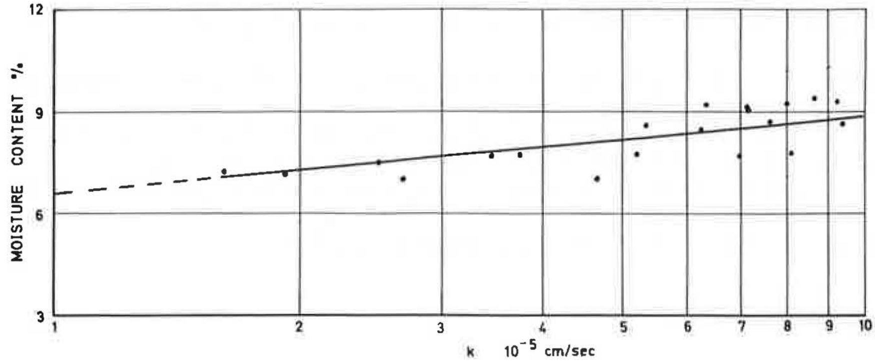
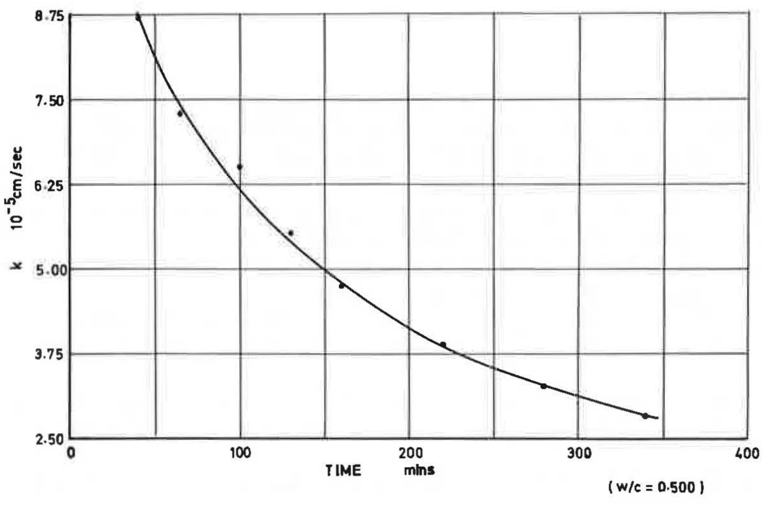


Figure 8. Variation of coefficient of permeability with time.



is extended to include hardened material. The rate at which the development proceeds will be expedited if several researchers cooperate.

The following conclusions have been made from the results of this study:

1. Flow of water through plastic concrete obeys Darcy's law down to a limited hydraulic gradient that varies with the initial value;
2. Non-Darcy flow at the lower gradients seems to be due to particle migration;
3. k-values increase exponentially with increasing water-cement ratio;
4. Retardation, by addition of sugar, reduces the permeability of plastic concrete; and
5. The effect of hydration causes the reduction of k with time.

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