A Review of the Pore Structure of Cement Paste and Concrete and its Influence on Permeability

by J.F. Young

Synopsis: The permeability of hardened cement paste is reviewed with particular reference to the influence of pore structure. Permeability is usually modelled by applying D'Arcy's Law, although permeability measurements and pore size distributions determine reveals the strong influence of large capillary pores (macropores) on flow through cement paste. The macropores form a continuous flow path within the paste. The effects of curing temperature, drying and admixtures on permeability can be understood in terms of their influence on macropores. Paste containing fly ash show anomalous behavior which apparently arises from internal damage occurring during pore structure measurements. It appears that the presence of fly ash promotes the formation of a discontinuous macropore system which inhibits flow.

Keywords: admixtures; calcium chlorides; cement pastes; concretes; fly ash; hardened paste structure; permeability; porosity; slags; water-reducing agents
INTRODUCTION

Permeability is an important property with regard to the durability of concrete. It represents the ease with which water (or other fluids) can move through concrete, thereby transporting aggressive agents. It is thus of critical importance for many types of distress experienced by concrete. For example:

- **sulfate attack** - movement of sulfate ions into concrete where adverse chemical reactions occur.
- **frost resistance** - flow of water to relieve stresses caused by ice formation.
- **alkali-aggregate attack** - movement of alkali ions to aggregates and water to swelling gels.
- **fire resistance** - escape of steam from heated layers causing spalling.
- **corrosion of steel** - movement of chloride ions to the surface of the steel.

PORE STRUCTURE

Since fluid flow takes place in the pore system it is first necessary to examine the pore structure in concrete. Pores in normal-weight concrete are considered part of the paste fraction and cover a very large size range (Figure 1). The traditional classification, suggested by Powers and Brownyard [1], considers two classes of pores: gel pores are associated with the formation of the hydration products ("cement gel"), which is the intrinsic porosity, while capillary pores are considered to be the remnants of water-filled space. However, it is customary with other porous systems to use a different classification which depends on how water behaves in the pores. Micropores are considered to form the intrinsic porosity although there are good reasons to include also the smaller mesopores. Both meso and macropores make up the capillary pore system.

In cement paste these pores form a continuum which can be measured using mercury intrusion porosity (MIP) down to the largest of gel pores (small mesopores). Sorption techniques are required to investigate the finest mesopores and micropores. Both capillary pore volume and pore size decrease significantly as hydration proceeds, or as w/c ratio is reduced. MIP is the most useful method of measuring pores for permeability predictions, but it must be remembered that there are several important assumptions inherent in the calculations and we are not
really measuring absolute values. This will become clearer in later discussion.

**CAPILLARY FLOW**

Flow in capillary pores can be described by D'Arcy's law for laminar flow through porous media:

\[ \frac{dq}{dt} = KA \frac{\Delta h}{L} \]  

(1)

where \( \frac{dq}{dt} \) is the rate of flow, \( A \) is the cross-sectional area of the specimen, and \( \frac{\Delta h}{L} \) is the hydraulic gradient across the section. \( K \) is the measured proportionality constant which represents the ease with which water flows through the specimen. The permeability coefficient is a material constant independent of the fluid used:

\[ K' = \frac{K\eta}{\rho g} \]  

(2)

where \( \eta \) is the viscosity of the fluid, \( \rho \) is its density, and \( g \) is the gravitational constant. In practice the measured value \( K \) is usually reported as the permeability coefficient, rather than \( K' \). The first comprehensive study of the factors affecting permeability of cement paste using this approach was made by Powers and his co-workers [2,3]. They quantitatively showed the effects of w/c ratio (Figure 2) and time of moist curing (Table 1). It was shown that well-cured pastes can attain very low permeabilities, characteristic of dense rocks, even though the total pore volumes of these pastes are high (Table 2). This was attributed to the fact that the continuous capillary pore system, through which water flows relatively easily, becomes cut off by the deposition of hydration products. The time at which this can occur is strongly dependant on the w/c ratio of the paste (Table 3).

In such discontinuous pore systems flow is limited by movement through the very fine gel pores (micropores), so that D'Arcy flow is greatly modified by the adsorption of water on the pore surfaces. Powers et al. [4] developed a theoretical approach to model this using Stokes Law applied to a concentrated suspension. Equation 3 was derived using a number of simplifying assumptions, which gave good agreement between observed and calculated values over the range 0-30°C.

\[ K_1 = \frac{1.36 \times 10^{-12}}{\eta(\Theta)} \frac{(1-c)^2}{c} \exp\left(\frac{-1242}{T}\right) + 0.7\left(\frac{c}{1-c}\right) \]  

(3)

where \( \eta(\Theta) \) is the viscosity of the fluid as a function of temperature \( T \), and \( c \) is the volume fraction of solid material. (The porosity of the paste is equal to \( (1-c) - 0.26 \). However, since in practice permeation in concrete mostly involves capillary flow, we will not concern ourselves with the details of this approach.
Hughes [5] used a different approach, considering Poiseuille flow in a 3-D random array of tortuous pores with circular cross-section. The flow equation thus obtained is:

\[
\frac{dq}{dt} = \left(\frac{P}{2}\right) r^2 A(\Delta h/L) \frac{32n}{\eta}
\]

where \( P \) is the porosity, \( n^2 \) is a tortuosity factor, and \( r \) is the pore radius.

**INFLUENCE OF PORE STRUCTURE**

Since the work of Powers, MIP has been developed commercially, so that pore size distributions can be measured routinely. Briefly, the method measures the volume of mercury forced into the pores under an applied pressure. Pore size is related to pressure by the Washburn equation, which assumes a circular cross section

\[
p = \frac{2\gamma \cos \theta}{r}
\]

where \( \gamma \) is the surface tension of mercury and \( \theta \) is the contact angle. In recent years there have been attempts to correlate pore structure with permeability. Parameters used and defined for this purpose are given in Figure 3. The pore diameters used to limit \( V_1 \) and \( V_2 \) are arbitrary and several values have been used: 135nm [6], 88nm [7], 75nm [8], and 50nm [5] for \( V_1 \); 30nm [6] and 15nm [5] for \( V_2 \).

Using paste of different w/c ratios Mehta and Manmohan [6] obtained extensive data, part of which is summarized in Table 4, from which the Equation 6 was obtained by regression analysis

\[
\ln K = 3.84V_1 + 0.20V_2 + 0.56 \times 10^{-6} d_t + 8.09V_t' - 2.53 \text{ m/s}
\]

where \( V_t' \) is the total capillary porosity divided by the degree of hydration [i.e., \( V_t' = (V_1 + V_2)/\alpha \)]. This accounts for different amounts of hydration. Inspection of Equation 6 shows that \( V_1 \) and \( V_t' \) are the most important parameters and the pore-structure-permeability relationship can be approximated by:

\[
\ln K = 4V_1 + 8V_t' - 2.5 \text{ m/s}
\]

or by [8]:

\[
\ln K = 10.9V_t' - 3.4
\]

Nyame and Illston [9], on the other hand, found a good correlation between \( \ln K \) and \( \ln r_0 \) (Figure 4). This latter parameter was taken to represent the smallest radius for which there is a continuous capillary pore system through which D'Arcy flow can
occur. A similar correlation with threshold diameter could be obtained [6] with a similar justification. In this way the complications of flow through micropores is eliminated from the analysis.

Hughes [5] used Equation 4, together with MIP data to obtain an experimental function for $r^2$. A value of 2.5 was used for $n^2$, which has been estimated for fluid flow through granular beds [10]. Hughes also recognized the restrictive nature of the gel pores, which were eliminated in the analysis by ignoring all pores with $r < 7.5$ nm. He also assumed that he was considering only the continuous pore system (as suggested by Nyame and Illston) by using the second intrusion curve (Figure 5). The first intrusion is considered to fill all capillary pores, but only those pores without restricted entryways will empty during extrusion. Thus the second intrusion is a measure of the continuous pore system through which mercury flows readily, and presumably also water.

**Effect of Curing Temperature**

The pore size distribution is strongly influenced by the curing temperature: high temperatures increase the volume of large mesopores [8,11] (see, for example Figure 6). One might expect this change to be reflected by higher permeabilities, and this has indeed been found [8,12] when curing temperatures are varied (see control curves in Figure 7).

**Effect of Drying**

The early work at PCA showed that drying a well-cured paste increased the $K$ value nearly 100-fold [2]. Recent studies have shown that drying changes the pore size distribution [13,14], being most graphically illustrated by observing freezing behavior [14] (see Figure 8).

**Effect of Mineral Admixtures**

Mineral admixtures, such as fly ashes and slags, are now accepted as valuable ingredients for durable concrete. Reductions in permeability are believed to be an important aspect of their beneficial effects. Several studies [7,15,16] have shown that for cement pastes containing reactive mineral admixtures, such as fly ash, silica fume, and rice husk ash, the total porosity is reduced compared to pastes of pure cement and a finer pore structure results (Figures 9 and 10). These changes correlate qualitatively with observed reductions in permeability. However, pastes containing fly ash show anomalous behavior. Such pastes have reduced permeabilities even though the much slower reactions of fly ash result in higher porosities and coarser pore structures even after 60 days curing (Figure 9).

It is clear that the pore structure-permeability relationships discussed above do not apply here. The pozzolanic
reaction seems to be able to develop a discontinuous pore system more readily [17]. Recently Feldman [18] has concluded that pastes containing fly ash are more prone to damage when MIP is used to measure pore sizes. This can be seen by comparing the first and second intrusion curves (Figure 4). It appears that mercury under pressure breaks through rather fragile barriers that isolate large pores, whereas this does not happen in pure cement pastes. These results suggest that lack of adequate curing of concretes with fly ash could seriously affect its potential permeability. However, increased curing temperature greatly increases the rate of pozzolanic reaction and reduces water flow [12] (see Figure 7). In contrast the curing temperature had a much less effect on slag hydration.

The pronounced reduction in pore size in pastes containing silica fume is attributed [16] both to its high pozzolanic reactivity, and also to its very small particle size which allows it to pack efficiently between the cement grains, thereby subdividing the space. The permeability coefficients are thus greatly reduced [18], particularly at high w/c ratios (Table 5).

**Effect of Chemical Admixtures**

Chemical admixtures should also affect permeability if they change pore size distributions in cement pastes. Additions of calcium chloride increase the volume of fine capillary pores at the expense of large ones [15,20] and provide a less permeable paste [15]. The addition of water-reducing agents should reduce permeability if they are used to lower w/c ratios. However, like calcium chloride, water reducing agents often increase drying shrinkage, which has been correlated with finer pores. Thus, they may well reduce permeability even when the w/c is not changed. A more uniform dispersion of cement grains within a paste, which is a consequence of using a water reducing agent, is more likely to provide a more uniform pore structure with less coarse pores.

**Mortars and Concretes**

It is now well known that the cement-aggregate interface is more porous than the bulk paste, in all but very well-cured systems [21]. This has been demonstrated by SEM observations, but it is not so easy to quantify. Only a few comparative MIP measurements on paste and mortars have been made [22,23] see Figure 11. It seems likely that the interfacial zone will be a favorable pathway for water flow. This is even more likely if bond cracking occurs under local stresses caused by thermal mismatch between paste and aggregate, or restraint of paste shrinkage by the aggregate.

The permeability coefficients for concrete are generally about 100 times higher than for comparable pastes (Figure 12) while for mortars they are 3-10 times higher.
CONCLUDING DISCUSSION

A link between pore structure and permeability has now been clearly established for cement pastes, although the exact quantitative relationships still need to be refined. It should be possible to meld the various approaches into a unified theory. Specific relationships need to be developed for pastes formed with blended cements, taking into account the anomalies inherent in the measurements. The role of the cement-aggregate interface needs to be further studied and quantified if the performance of field concrete is to be predicted with certainty.

Two cautionary notes should be mentioned which merit further consideration. Space does not permit detailed discussions; either topic could well be the subject of a separate paper. The first concern involves the assumptions inherent in the porosimetry measurements. Analysis involves idealized assumptions of geometry which are not realistic; the problem of restricted entryways to large pores is particularly troublesome. Furthermore, the paste or mortar must be strongly dried before mercury can be intruded. It is now recognized that drying significantly changes the pore structure (see Figure 8), particularly in pastes with a fine pore structure. Also, internal shrinkage stresses in mortars or concretes associated with differential shrinkage of paste and aggregate will undoubtedly lead to the formation of microcracks. It is uncertain the degree to which the apparent pore structure determined experimentally differs from the original material under study. Direct pore structure measurements on undried specimens would be most desirable.

The second concern is the degree to which the permeability coefficient for a given paste or mortar will differ for different chemical species, i.e., water, chloride ions, sulfate ions and mercury (in porosimetry). Until such relationships are known the prediction of field concrete durability from laboratory data cannot be successful. Accurate laboratory measurements of permeability coefficients require experiments of long duration with inherently large scatter. Current approaches to in situ permeability measurements need to be critically examined, and a continued search maintained for alternate methods.

ACKNOWLEDGMENTS

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REFERENCES


Concrete Permeability


TABLE 1

Effect of Curing Time of Cement Paste (w/c = 0.51) on Its Permeability Coefficient (Based on Data from Ref. 2)

<table>
<thead>
<tr>
<th>Time of Curing (Days)</th>
<th>Permeability Coefficient (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>3</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>7</td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td>14</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>28</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>90</td>
<td>$10^{-16}$</td>
</tr>
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</table>

TABLE 2

Comparisons of Permeability and Capillary Porosity between Well-Hydrated Cement Paste and Natural Rocks (Data from Ref. 2)

<table>
<thead>
<tr>
<th>Rock</th>
<th>Permeability Coefficient (m/s)</th>
<th>Cement Paste</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
<td>Porosity (%)</td>
</tr>
<tr>
<td>Sandstone</td>
<td>Fine-grained</td>
<td>4.3</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Marble</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Dense Trap</td>
<td>0.6</td>
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</table>
**TABLE 3**

Curing Time Required to Achieve a Discontinuous Capillary Pore System [3]

<table>
<thead>
<tr>
<th>w/c</th>
<th>Curing Time (days)</th>
</tr>
</thead>
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<td>0.40</td>
<td>3</td>
</tr>
<tr>
<td>0.45</td>
<td>7</td>
</tr>
<tr>
<td>0.50</td>
<td>28</td>
</tr>
<tr>
<td>0.60</td>
<td>180</td>
</tr>
<tr>
<td>0.70</td>
<td>365</td>
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</tbody>
</table>

**TABLE 4**

Volumetric Characteristics of Hydrated Cement Paste [6] (See text for definition of symbols)

<table>
<thead>
<tr>
<th>w/c</th>
<th>(V_L) (cm(^3)/g)</th>
<th>(V'_L) (cm(^3)/g)</th>
<th>(d_t) (nm)</th>
<th>(10^{12} k) (m/s)</th>
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</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0</td>
<td>0.26</td>
<td>&lt;100</td>
<td>0.1</td>
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<tr>
<td>0.5</td>
<td>0</td>
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<tr>
<td>0.6</td>
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<td>220</td>
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<td>0.7</td>
<td>0.28</td>
<td>0.54</td>
<td>460</td>
<td>22</td>
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<tr>
<td>0.8</td>
<td>0.38</td>
<td>0.63</td>
<td>780</td>
<td>96</td>
</tr>
<tr>
<td>0.9</td>
<td>0.44</td>
<td>0.77</td>
<td>1400</td>
<td>410</td>
</tr>
</tbody>
</table>
TABLE 5

Influence of Silica Fume Additions on the Permeability of Concrete [19]

<table>
<thead>
<tr>
<th>Cement Content (kg/m$^3$)</th>
<th>Silica Fume (% wt.)</th>
<th>W/S</th>
<th>Permeability Coefficient ($10^{12}$ m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-</td>
<td>2.4</td>
<td>12,000</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>2.3</td>
<td>1,000</td>
</tr>
<tr>
<td>250</td>
<td>-</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>250</td>
<td>10</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>400</td>
<td>-</td>
<td>0.5</td>
<td>0.007</td>
</tr>
<tr>
<td>400</td>
<td>10</td>
<td>0.5</td>
<td>0.04</td>
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</table>

PORE CLASSIFICATION

POWERS

<table>
<thead>
<tr>
<th>GEL</th>
<th>CAPILLARY</th>
<th>AIR VOIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>50</td>
<td>10,000</td>
</tr>
<tr>
<td>10</td>
<td>10,000</td>
<td></td>
</tr>
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</table>

IUPAC

<table>
<thead>
<tr>
<th>MICRO</th>
<th>MESO</th>
<th>MACRO</th>
<th>AIR VOIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10,000</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1--Pore size classifications for cement paste
Fig. 2--Effect of w/c ratio on permeability (Reference 2)

Fig. 3--Parameters defining MIP pore size distributions $V_1$ and $V_2$ are the pore volumes over the size ranges indicated, $d_t$ the threshold diameter, and $r_\infty$ the continuous pore diameter.
Fig. 4--Influence of continuous pore radius on permeability (Reference 9)

Fig. 5--Pore size distribution curves for cement pastes with and without fly ash (Reference 5)
Concrete Permeability

Fig. 6--Effect of curing temperature on pore size distribution (data for C3S pastes from Reference 11 at equal hydration [α = 0.87])

Fig. 7--Effect of curing temperature on water flow through pastes made with or without mineral admixtures (Reference 12)
Fig. 8--Heat evolved during freezing of a cement paste; a) dried to the relative humidities indicated and resaturated, b) full line: virgin paste, dashed line dried to r.h. = 0.58 and resaturated
Concrete Permeability

Fig. 9--Pore size distributions in cement pastes made with and without mineral admixtures — numbers beside legends represent relative permeability: control = 1.0 (Reference 15)

Fig. 10--Pore size distribution for paste made with and without silica fume (SF) (Reference 16)
Fig. 11--Pore size distribution for plain paste and paste in mortar (Reference 23)

Fig. 12--Comparison of permeability for paste and concrete
Influence of Superplasticizers, Polymer Admixtures, and Silica Fume in Concrete on Chloride Ion Permeability

by S.L. Marusin

Synopsis: This paper summarizes the results of permeability studies that have been undertaken at Wiss, Janney, Elstner Association, Inc. (WJE) since 1979. The research used a test procedure developed during the NCHRP Project 12-19A, "Concrete Sealers for Protection of Bridge Structures" which was reprinted in 1981 as NCHRP Report No. 244. This test method utilizes 10-cm-concrete cubes, and chloride ion penetration is determined at 4 depths after 21 days exposure to 15 percent NaCl solution. The test results show that lowering of w/c ratio in portland cement concrete or presence of superplasticizers, polymer admixtures, and silica fumes are able to significantly reduce concrete permeability.

Keywords: admixtures; chlorides; concretes; epoxy resins; latex; permeability; plasticizers; plastics, polymers, and resins; silica fume
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INTRODUCTION

Deterioration of concrete structures by the corrosion of reinforced steel due to the ingress of chloride ion is a serious and universal problem throughout the world. It is well known that the penetration of chloride ion into concrete depends on the quality of concrete and especially on its permeability. This paper summarizes the research that the author has undertaken since 1979 on the use of various chemical admixtures to minimize the chloride ion penetration from external sources into the concrete. The research used a test procedure developed by WJE during the National Cooperative Highway Research Program (NCHRP) Project 12-19A, "Concrete Sealers for Protection of Bridge Structures (1), conducted by the United States Transportation Research Board (TRB). The test results and recommendations for the methods are reported in NCHRP Report No. 244. This test method utilizes 10-cm-concrete cube specimens and the chloride ion content is measured on an entire half of each split cube after 21 days exposure to 15 percent NaCl solution. Subsequent studies determined the chloride ion content profile at four different depths. Following this research project, a research effort was undertaken to study chloride ion permeability of concretes made with various admixtures (2,3,4,5).

DESCRIPTION OF TEST PROGRAM

Materials

All tested concretes were made by using a Type I portland cement and a natural chloride-free river sand and gravel. Neutralized vinsol resin was used as an air-entraining agent.

Casting, Curing and Testing Procedure

All concretes were mixed and cast at room temperature at the WJE laboratories. The forms used for making the 10 cm cubes were constructed with a special resin-coated wood to preclude the need for any release agent which might chemically contaminate the concrete surfaces during casting. The forms were table-vibrated for each of two lifts of concrete. The top surfaces were then finished with a wooden float and covered with a polyethylene film for overnight curing at 23°C. The specimens were stripped at one day, lightly sandblasted and then placed within sealed heavy-duty plastic bags for 21 days of moist curing. They were then removed from the plastic bags and placed in the controlled
climate room on steel racks for air drying at 23 ± 3°C and 50 ± 4 percent R. H. for 14 days before immersing in a 15 percent NaCl solution. After 21 days of soaking, the cubes were exposed to air of a controlled climate room for an additional 21 days. Following this final air-drying period, 6 mm holes were drilled through the center of each cube face on all six sides of the cube to obtain powder samples for chloride ion determination at four different depth intervals. The intervals were 0 to 12 mm, 12 to 25 mm, 25 to 37 mm and 37 to 50 mm. Acid soluble chloride ion content was determined using an acid digestion, potentiometric titration procedure. All tests were performed on duplicate specimens and average values are listed in tables and graphs.

Of particular importance in reviewing the measured chloride ion profiles through the concrete, is the assumption that the corrosion threshold level for acid-soluble chloride ion content in normal weight reinforced concrete is about 0.03 percent by weight of concrete.

**TEST RESULTS AND DISCUSSION**

**Conventional Portland Cement Air-Entrained Concrete**

Mix proportions and properties of four portland cement concretes having cement contents from 325 to 365 kg/m³ and with w/c ratio ranges from 0.35 to 0.55 are given in Table 1. Chloride ion contents at 4 depths are listed in Table 2 and graphically depicted in Fig. 1. The data in Table 2 show that the concrete of the depth interval from 0 to 12 mm has extremely high levels of chloride ranging from 0.38 to 0.45 percent by weight of concrete. These values are thus about 13 to 15 times the corrosion threshold level. No significant influence of decrease of w/c on concrete permeability was found in this depth. In the next depth interval, 12 to 25 mm, the chloride contents range from 0.09 to 0.26 percent and the influence of w/c is well pronounced. For the concrete having a w/c of 0.35, the chloride content is about 5 times lower than was found at the depth interval of 0 to 12 mm and for the concrete having w/c of 0.55 about 2 times lower. However, the measured chloride ion content is still 3 to 9 times the corrosion threshold level. At a depth from 25 to 37 mm, the chloride value is less than the corrosion threshold level for concrete with w/c of 0.35. The concretes having w/c of 0.50 and 0.55 did not show any differences in permeability at this depth. In both concretes the chloride value is about 2 times the corrosion threshold level of 0.03 percent. At a depth of 37 to 50 mm the chloride level of the concrete having w/c of 0.40 fell to the corrosion threshold level. Both concretes with w/c of 0.50 and 0.55 were above this level, and again the chloride ion contents were similar and not influenced by increasing the w/c from 0.50 to 0.55. The influence of w/c on chloride ion content at different depths is graphically shown in Fig. 2.
Concretes Containing Superplasticizers and Polymer Admixtures

Mix proportions and properties of 5 concretes containing superplasticizers ("high-range water reducers", or HRWR) and polymer admixtures are given in Table 3. Chloride ion contents at 4 depths are listed in Table 4 and graphically depicted in Fig. 2.

The data in Table 3 show that the depth interval from 0 to 12 mm has high levels of chloride, ranging from 0.27 to 0.40 percent by weight of concrete. These values are lower than in conventional concrete, but still about 10 to 13 times the corrosion threshold level of 0.03 percent. Concretes A and B with HRWR contained 460 and 300 kg/m³ of cement and had w/c of 0.29 and 0.40, respectively. Concrete A was able to reduce the chloride ion content below the threshold level at the depth from 12 to 25 mm, and concrete B was able to do this at the next depth, 25 to 37 mm. Concretes C and D containing latexes reached the threshold level at the depth from 12 to 25 mm and reduced the chloride ion content below this level at the next depth of 25 to 37 mm. Concrete E with epoxy was able to reduce the chloride ion content below the threshold level at the depth of 25 to 37 mm. The influence of admixtures on chloride ion content is shown in Fig. 4.

Concrete containing Silica Fume (SF)

Mix proportions and properties of 9 concretes containing silica fume are given in Table 5. Chloride ion contents at 4 depths are listed in Table 6 and graphically depicted in Figs. 5 and 6.

Six concretes, identified as Mix No. SF1 through Mix No. SF6 and having cement contents from 340 to 370 kg/m³ and SF ranges from 2.5 to 15 percent by weight of cement were made. The other three concretes were made with about 300 kg/m³ of cement and their SF contents range from 6 to 30 percent.

As shown in Table 6, for all concretes, the depth interval from 0 to 12 mm has high levels of chloride, similar to concretes containing HRWR or polymer admixtures, ranging from 0.27 to 0.39 percent by weight of concrete. These values are about 10 to 13 times the corrosion threshold level of 0.03 percent.

In the next depth interval of 12 to 25 mm the chloride ion content is greatly reduced, to 0.03 and 0.06 percent by weight of concrete. Four concretes containing 6, 8 and 10 percent of SF were able to reach the corrosion threshold limit at this depth.

In the depth intervals of 25 to 37 mm and 37 to 50 mm all concretes exhibited chloride ion contents below the threshold level.

SUMMARY

A summary of test results is given in Table 7.
The vast majority of the absorbed chloride ion was found within the first 12 mm of depth in all tested concretes. The shape of chloride ion distribution is generally influenced by w/c for the portland cement concretes. However, this statement does not seem to be true in the first 12 mm depth interval and is also not well pronounced if w/c is increased from 0.50 to 0.55. Only the portland cement concrete with w/c of 0.35 exhibited a chloride ion content below the corrosion threshold limit at a depth of 25 to 37 mm. The concrete with w/c = 0.40 fell to the corrosion threshold limit at a depth of 37 to 50 mm and the concretes with w/c equal and above 0.50 were well contaminated with chloride.

The presence of HRWR, polymer admixtures and SF greatly influenced and decreased the concrete permeability. The permeability for portland cement concrete of w/c = 0.35 and concretes containing HRWR, polymer admixtures and SF was found to be similar. All these concretes were able to reach the corrosion threshold chloride ion level of about 0.03 percent, or exhibited a chloride ion content below this value at the depth interval of 25 to 37 mm. The presence of HRWR, latex type admixtures and SF from 6 to 10 percent by weight of cement reduced concrete permeability in such a way that the corrosion threshold level was reached at the depth of 12 to 25 mm.

No direct relationship was found between increased amounts of SF in concrete and a decrease of concrete permeability. However, the concrete permeability is more influenced by the amount of SF in concrete than the w/c value. It is believed that the best permeability reduction could be obtained with a concrete containing 10 percent of SF by weight of cement.

Decrease of concrete permeability could be achieved by lowering w/c at conventional portland cement concrete, using admixtures (i.e., HRWR and polymers), and, of course, using properly consolidated and cured concrete.

Results of this limited study also showed the importance of deep cover over the embedded reinforcement.
REFERENCES


5. Marusin, S. L., "Improvement of Concrete Durability Against Intrusion of Chloride-Laden Water by Using Sealers, Coatings and Various Admixtures," Concrete Durability, Katharine and Bryant Mather International Conference, ACI SP-100, Vol. 1, American Concrete Institute, Detroit, Michigan, 1987, pp. 599-619.
**TABLE 1 - MIX DESIGN AND PROPERTIES OF FRESH AND HARDENED PORTLAND CEMENT CONCRETE**

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Portland cement, kg/m³</th>
<th>Sand, kg/m³</th>
<th>Gravel, kg/m³</th>
<th>Properties of fresh concrete</th>
<th>28-day compressive strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>330</td>
<td>775</td>
<td>1175</td>
<td>Air content (%)</td>
<td>Water (cm)</td>
</tr>
<tr>
<td>2</td>
<td>365</td>
<td>639</td>
<td>1044</td>
<td>6.0</td>
<td>115</td>
</tr>
<tr>
<td>3</td>
<td>348</td>
<td>887</td>
<td>1012</td>
<td>6.5</td>
<td>145</td>
</tr>
<tr>
<td>4</td>
<td>325</td>
<td>721</td>
<td>1092</td>
<td>6.0</td>
<td>180</td>
</tr>
</tbody>
</table>

Conversion factors:

1 N/m² = 1 MPa = 145 psi
kg/m³ = 1.7 lb/yd³
1 cm = 0.39 in.

**TABLE 2 - ACID-SOLUBLE CHLORIDE ION CONTENT AT DIFFERENT DEPTHS OF PORTLAND CEMENT CONCRETE**

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>W/C</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0-12</td>
</tr>
<tr>
<td>1</td>
<td>0.35</td>
<td>0.427</td>
</tr>
<tr>
<td>2</td>
<td>0.40</td>
<td>0.384</td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>0.442</td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>0.451</td>
</tr>
</tbody>
</table>
### TABLE 3 - MIX DESIGN AND PROPERTIES OF FRESH AND HARDENED CONCRETES CONTAINING SUPERPLASTICIZERS (HRWR) OR POLYMER ADMIXTURES

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Concrete with admixtures</th>
<th>kg/m³</th>
<th>Air content (%)</th>
<th>Slump (cm)</th>
<th>W/C by wt</th>
<th>28 day compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>HRWR</td>
<td>462</td>
<td>168</td>
<td>5.8</td>
<td>13.5</td>
<td>0.29</td>
</tr>
<tr>
<td>B</td>
<td>HRWR</td>
<td>300</td>
<td>119</td>
<td>5.5</td>
<td>14</td>
<td>0.40</td>
</tr>
<tr>
<td>C</td>
<td>A latex</td>
<td>392</td>
<td>113</td>
<td>2.2</td>
<td>25</td>
<td>0.29</td>
</tr>
<tr>
<td>D</td>
<td>S-B latex</td>
<td>391</td>
<td>132</td>
<td>3.5</td>
<td>25</td>
<td>0.34</td>
</tr>
<tr>
<td>E</td>
<td>Epoxy</td>
<td>390</td>
<td>101</td>
<td>4.3</td>
<td>23.5</td>
<td>0.26</td>
</tr>
</tbody>
</table>

### TABLE 4 - ACID-SOLUBLE CHLORIDE ION CONTENT

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Type of concrete</th>
<th>W/C</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0-12</td>
</tr>
<tr>
<td>A</td>
<td>HRWR</td>
<td>0.29</td>
<td>0.334</td>
</tr>
<tr>
<td>B</td>
<td>HRWR</td>
<td>0.40</td>
<td>0.399</td>
</tr>
<tr>
<td>C</td>
<td>A latex</td>
<td>0.29</td>
<td>0.273</td>
</tr>
<tr>
<td>D</td>
<td>S-B latex</td>
<td>0.34</td>
<td>0.296</td>
</tr>
<tr>
<td>E</td>
<td>Epoxy</td>
<td>0.26</td>
<td>0.343</td>
</tr>
</tbody>
</table>
TABLE 5 - MIX DESIGN AND PROPERTIES OF FRESH AND HARDENED CONCRETE CONTAINING SILICA FUME (SF)

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Mix Properties (kg/m³)</th>
<th>Properties of Fresh concrete</th>
<th>28-day compressive strength (MPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Portland cement</td>
<td>Silica Fume</td>
<td>Air content (%)</td>
</tr>
<tr>
<td>SF1</td>
<td>368</td>
<td>2.5</td>
<td>7.0</td>
</tr>
<tr>
<td>SF2</td>
<td>363</td>
<td>5.0</td>
<td>7.0</td>
</tr>
<tr>
<td>SF3</td>
<td>382</td>
<td>5.0</td>
<td>5.6</td>
</tr>
<tr>
<td>SF4</td>
<td>367</td>
<td>10.0</td>
<td>6.5</td>
</tr>
<tr>
<td>SF5</td>
<td>354</td>
<td>10.0</td>
<td>7.4</td>
</tr>
<tr>
<td>SF6</td>
<td>337</td>
<td>15.0</td>
<td>7.0</td>
</tr>
<tr>
<td>SF7</td>
<td>304</td>
<td>6.0</td>
<td>6.3</td>
</tr>
<tr>
<td>SF8</td>
<td>300</td>
<td>8.0</td>
<td>6.3</td>
</tr>
<tr>
<td>SF9</td>
<td>283</td>
<td>30.0</td>
<td>5.4</td>
</tr>
</tbody>
</table>

* Percent by weight of cement
** Including water in SF admixture
<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Amount of SF* (kg/m)</th>
<th>Cement</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0-12</td>
</tr>
<tr>
<td>SF1</td>
<td>2.5</td>
<td>368</td>
<td>0.390</td>
</tr>
<tr>
<td>SF2</td>
<td>5</td>
<td>363</td>
<td>0.370</td>
</tr>
<tr>
<td>SF3</td>
<td>5</td>
<td>382</td>
<td>0.363</td>
</tr>
<tr>
<td>SF4</td>
<td>10</td>
<td>367</td>
<td>0.271</td>
</tr>
<tr>
<td>SF5</td>
<td>10</td>
<td>354</td>
<td>0.338</td>
</tr>
<tr>
<td>SF6</td>
<td>15</td>
<td>337</td>
<td>0.348</td>
</tr>
<tr>
<td>SF7</td>
<td>6</td>
<td>304</td>
<td>0.280</td>
</tr>
<tr>
<td>SF8</td>
<td>8</td>
<td>300</td>
<td>0.270</td>
</tr>
<tr>
<td>SF9</td>
<td>30</td>
<td>283</td>
<td>0.365</td>
</tr>
</tbody>
</table>

* % by weight of cement
<table>
<thead>
<tr>
<th>Type of concrete</th>
<th>Cement content W/C (kg/m³)</th>
<th>Admixtures type</th>
<th>kg/m³ or % by wt** of cement</th>
<th>Chloride ion content at depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement concrete</td>
<td>330 0.35</td>
<td>--</td>
<td>--</td>
<td>0.43 0.08 0.01 0.01</td>
</tr>
<tr>
<td>Concrete with HRWR and polymers</td>
<td>462 0.29</td>
<td>HRWR</td>
<td>2</td>
<td>0.33 0.02 0.01 0.01</td>
</tr>
<tr>
<td></td>
<td>300 0.40</td>
<td>HRWR</td>
<td>58</td>
<td>0.40 0.05 0.03 0.02</td>
</tr>
<tr>
<td></td>
<td>392 0.29</td>
<td>A latex</td>
<td>108</td>
<td>0.27 0.03 0.02 &lt;0.01</td>
</tr>
<tr>
<td></td>
<td>391 0.39</td>
<td>S-B latex</td>
<td>105</td>
<td>0.30 0.03 0.01 &lt;0.01</td>
</tr>
<tr>
<td></td>
<td>390 .26</td>
<td>Epoxy</td>
<td>78</td>
<td>0.34 0.12 0.03 0.02</td>
</tr>
<tr>
<td>Concrete with SF</td>
<td>368 0.37</td>
<td>SF</td>
<td>2.5</td>
<td>0.39 0.06 0.02 0.02</td>
</tr>
<tr>
<td></td>
<td>363 0.38</td>
<td>SF</td>
<td>5.0</td>
<td>0.37 0.04 0.02 0.02</td>
</tr>
<tr>
<td></td>
<td>382 0.41</td>
<td>SF</td>
<td>5.0</td>
<td>0.36 0.06 0.02 0.02</td>
</tr>
<tr>
<td></td>
<td>367 0.35</td>
<td>SF</td>
<td>10.0</td>
<td>0.27 0.03 0.02 &lt;0.02</td>
</tr>
<tr>
<td></td>
<td>354 0.41</td>
<td>SF</td>
<td>10.0</td>
<td>0.34 0.03 0.02 0.02</td>
</tr>
<tr>
<td></td>
<td>337 0.41</td>
<td>SF</td>
<td>15.0</td>
<td>0.35 0.04 0.03 0.02</td>
</tr>
<tr>
<td></td>
<td>304 0.42</td>
<td>SF</td>
<td>6.0</td>
<td>0.28 0.03 0.02 &lt;0.01</td>
</tr>
<tr>
<td></td>
<td>300 0.40</td>
<td>SF</td>
<td>8.0</td>
<td>0.27 0.03 0.02 0.01</td>
</tr>
<tr>
<td></td>
<td>283 0.43</td>
<td>SF</td>
<td>30.0</td>
<td>0.37 0.04 0.03 0.02</td>
</tr>
</tbody>
</table>

* kg/m³ for HRWR and polymers
** % by wt of cement for SF
Fig. 1--Portland cement concretes — chloride ion content at 4 depths

Fig. 2--Portland cement concretes — chloride ion content within 4 depths versus w/c ratio
Concrete Permeability

Fig. 3--Concretes containing HRWR and polymers — chloride ion content at 4 depths

Fig. 4--Concrete containing HRWR and polymers — chloride ion content within 4 depths versus type of concrete admixtures
Fig. 5--Concretes containing SF (cement content 340-370 kg/m³) — chloride ion content at 4 depths

Fig. 6--Concrete containing SF (cement content ~ 300 kg/m³) — chloride ion content at 4 depths
Concrete Permeability

Fig. 7—Concretes containing SF (cement content 340-370 kg/m³) — chloride ion content within 4 depths versus amount of SF in concrete

Fig. 8—Concrete containing SF (cement content ~ 300 kg/m³) — chloride ion content within 4 depths versus amount of SF in concrete
Resistance to Chloride Ion Penetration of Concretes Containing Fly Ash, Silica Fume, or Slag

by C. Ozyildirim and W. Halstead

Synopsis: The effects of two pozzolanic admixtures, fly ash and silica fume, and a ground-granulated blast furnace slag on the chloride ion intrusion of concretes prepared with low water-to-cementitious material ratios (w/c) (0.35 to 0.45) were investigated.

Results of the rapid permeability test (AASHTO T 277) showed that the resistance of concrete to the penetration of chloride ions increases significantly as the w/c is decreased for the same proportions of solid ingredients. Usually, concretes with pozzolans or slag exhibited higher resistance to chloride ion penetration than the control concretes containing Portland cement as the cementitious material. Results of the 90-day ponding test (similar to AASHTO T 259), which was conducted with 0.40 w/c concretes only, indicated minimal chloride content at depths below 3/4 in (19 mm) for all the test concretes. Strength values for all concretes made with the pozzolans and slag at 90 days were in excess of 5,000 psi (34.5 MPa), which is satisfactory.

Keywords: blast furnace slag; chlorides; compressive strength; concretes; fly ash; permeability; pozzolans; silica fume
ACI member Celik Ozyildirim is a research scientist with the Virginia Transportation Research Council in Charlottesville, Virginia. He received his PhD in civil engineering from the University of Virginia. Woodrow Halstead retired from his position as Chief of the Materials Division in the Office of Research of the Federal Highway Administration in 1975. Since 1976 he has served as a consultant with the Virginia Transportation Research Council.

INTRODUCTION

Significant damage to concrete results from the intrusion of corrosive solutions; for example, dissolved chlorides corrode reinforcing steel and cause spalling. Any treatment that effectively blocks the penetration of these solutions will eliminate or greatly reduce this damage and lead to increased durability with the consequent economic benefits.

Considerable research has been conducted on this problem, including the evaluation of special coatings, pore-blocking admixtures, and special concretes applied as overlays in the thickness range of 1-1/4 to 2 in (32 to 50 mm)\(^1_2\). The overlay concretes include water-reducing admixtures and usually have a w/c of 0.40 or lower. One successful system for overlays at a minimum thickness of 1-1/4 in (32 mm) has been latex-modified concrete (LMC). In addition to the added cost of materials for such overlays, special expertise and equipment are needed for field applications; consequently, such concretes are considerably more expensive than commercially prepared ready-mixed concretes.

The study summarized in this paper was conducted to assess the potential usefulness of several supplemental cementitious materials for increasing the resistance of hydraulic-cement concretes to penetration of chloride ions. The materials evaluated were a fly ash conforming to ASTM Specification C 618 (Class F), a silica fume and ground granulated iron blast furnace slag. A latex-modified concrete was included in the study for comparison.

The amounts of each supplemental cementitious material used were recommended by promoters of the various materials or by previous laboratory studies at the Council.

1. 15% of the cement by mass was replaced with 1.2 times that mass by a Class F fly ash.
2. 25% of the cement by mass was replaced with 1.2 times that mass by a Class F fly ash.
3. 50% of the cement by mass was replaced with slag
4. 7% of the cement by mass was replaced with silica fume.
Each combination of materials with C2, a Type II cement, was tested at w/c of 0.35, 0.40, and 0.45. Combinations with C1, a Type I cement, were tested at a w/c of 0.40. Also, specimens were prepared from control concretes and concretes with 15% fly ash, 50% slag, and 7% silica fume with Type II (C2) and Type III cements at 0.40 w/c to investigate the effect of curing temperatures of 40°(4°C), 73°F(23°C), and 100°F(38°C). The material combinations, mixture proportions, and characteristics of the materials are given in the Appendix.

TESTS CONDUCTED AND MIXTURE PROPORTIONS

The concretes were mixed and specimens prepared in accordance with ASTM C 192. They all contained an air-entraining and a water-reducing admixture. The air-entraining admixture was a neutralized vinsol resin added at amounts adequate to give the desired air content, and the water-reducing admixture was an aqueous solution of complex organic compounds added at the recommended dosage. A high-range water-reducing admixture (HRWR) was used to achieve workable concretes at w/c of 0.35 and 0.40; it was an aqueous solution of a modified naphthalene sulfonate. At a w/c of 0.35, it was necessary to add HRWR in amounts approximately double the dosage recommended by the manufacturer. At the 0.40 w/c, the amounts of HRWR added were within the manufacturer's recommended dosages. At a w/c of 0.45, HRWR was added only to the concretes containing silica fume. It was needed in this case to aid in the dispersion of the very fine silica fume particles and to increase the workability of the concretes. The air content of the freshly mixed concrete was measured by the pressure method, (ASTM C 231). Slump was measured by ASTM C 143, and unit weight determined by ASTM C 138.

The hardened concretes were tested for resistance to chloride ion penetration and compressive strength using 4 in by 8 in (100 by 200 mm) cylinders. The resistance to chloride ion penetration was determined using AASHTO T 277 ("Rapid Determination of the Chloride Permeability of Concrete"). This test is based on a relationship between the electrical conductance and the resistance to chloride ion penetration. The cylinders used for the test were moist cured for 2 weeks after which the top 2 in (50 mm) was cut off and used as the test specimen. The sides of the specimens were coated with an epoxy resin to prevent lateral moisture loss, and they were set on a plastic sheet and kept in the ambient laboratory conditions until the time of the test. This procedure is believed to partially simulate the continued curing of concrete in service where only the top surface is exposed to the atmosphere. Each reported test value is an average of the results from two cylinders.

The resistance of concretes to chloride penetration was also evaluated by tests on two cylinders from each batch at a w/c of 0.40 using a ponding test similar to AASHTO T 259 (Resistance of Concrete to Chloride Ion Penetration"). Cylinders measuring 4 in
by 8 in were moist cured for 2 weeks and air dried for an additional 2 weeks. Then they were ponded with 3% NaCl for 90 days. Afterward, they were drilled with a 2-in diameter bit to obtain samples for a determination of chloride content at two depths: 1/4 to 3/4 in (6 to 19 mm) and 3/4 to 1 1/4 in (19 to 32 mm). Samples were pulverized and the chloride ion contents determined using AASHTO T 260.

Compressive strength was determined at 1, 7, 28, 90, and 365 days. Specimens were prepared and tested in accordance with AASHTO T 22 using neoprene pads in steel-end caps for capping. Each reported test value is an average of the results from three cylinders.

Samples prepared using Type II and Type III cements to study the effect of curing temperature were tested for permeability (AASHTO T 277) and strength at 28 days.

TEST RESULTS

The slump, air content, and unit weight of the freshly mixed concretes are summarized in Table A-3 of the Appendix. Air-entrained concretes with satisfactory workability can be obtained with the use of air-entraining and either regular or regular and high-range water-reducing admixtures, depending on the w/c.

The results of the tests made on the hardened concretes were generally consistent with the results reported by others(3,4,5,6). However, the quantitative evaluation of the effect of different variables will be useful as a basis for the selection of combinations of available cementitious materials that will provide good resistance to chloride ion penetration of concrete at economical cost.

Chloride Ion Penetration

Electrical Conductance Test -- Table 1 shows the results of the tests for electrical conductance as determined by AASHTO Method T 277. This test measures the quantity of electricity, expressed as coulombs, that passes through the test specimens in six hours. This quantity is designated as Q for the purposes of this report. In accordance with AASHTO T 277, the test results are used to rate the concretes with respect to chloride permeability as follows:

<table>
<thead>
<tr>
<th>Coulombs</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4,000</td>
<td>high</td>
</tr>
<tr>
<td>2000 - 4000</td>
<td>moderate</td>
</tr>
<tr>
<td>1000 - 2000</td>
<td>low</td>
</tr>
<tr>
<td>100 - 1000</td>
<td>very low</td>
</tr>
<tr>
<td>&lt;100</td>
<td>negligible</td>
</tr>
</tbody>
</table>
Figures 1 and 2 show the values of Q at 28 and 90 days for concrete made with the Type II cement (C2). The w/c significantly affected the test results in all cases: the value of Q decreased as the w/c decreased. At 28 days, the Q values for the controls and the concretes containing fly ash were in the moderate or high permeability zone in all cases. The concretes containing slag had Q values in the moderate permeability zone with a w/c of 0.40 and 0.45, and in the low zone with a w/c of 0.35. At a 0.45 w/c, the Q values for slag concretes were slightly higher, and with 0.35 and 0.40 w/c they were lower than the LMC (with a w/c of 0.37). The most significant effect on the chloride permeability test results was shown by the concretes containing silica fume. With silica fume, the values of Q at 28 days were below 1,000 coulombs except for one at 1,020. At 28 days, the Q values for the LMC regularly used as overlay material over bridge decks were in the moderate permeability range.

At 90 days, controls and concretes with fly ash exhibited Q values that decreased significantly as the w/c decreased. The results for the LMC and the concretes containing slag were generally within the low range for all w/c. The results for the concretes containing silica fume were all substantially less than 1,000 coulombs, indicating a very low permeability to chloride ion.

The trends with respect to the effects of w/c at 28 and 90 days were also shown by the tests on the 365-day specimens.

A comparison of results on 28-day specimens and 90-day specimens indicate that for most concretes the resistance to chloride ion intrusion increases during that period. With the exception of concrete made with Type I cement with a 0.45 w/c, all the Q values for 90-day specimens were lower than the Q value for the corresponding 28-day specimens, and in most cases the difference was significant. Changes for those concretes containing pozzolans or slag were proportionately greater than the changes for the controls. Q values measured on 365-day specimens are inconclusive as to whether further changes occur after 90 days. In a majority of the cases, the Q value for the 365-day specimens, was greater than that recorded for the corresponding 90-day specimens. However, the chloride ion permeability classification in accordance with AASHTO T 277 remained unchanged in most cases. A notable exception is the LMC made with both cements. The Q values at 365 days for these concretes were in the very low range.

While there are some indications of differences between concretes made with Type I cement and Type II cement, such differences are not great. This indicates the relatively small effect of the cement type in these experiments. The effect, if any, is that at 28 days, concretes made with Type I cements have lower Q values than concretes made with Type II cements. At later ages,
differences caused by the cement type have diminished.

90-Day Ponding Tests

Table 2 summarizes the results of the tests for resistance of concrete with a w/c of 0.40 to chloride ion penetration using the 90-day ponding test. The results indicate that at a depth of 1/4 to 3/4 in (6 to 19 mm), all of the concretes except the one with silica fume and C1 had chloride content above 1.32 lb/yd³ (0.78 kg/m³), which is the threshold value for corrosion of the reinforcing steel reported by FHWA(7). The value for LMC with C1 was close to the threshold value. The concretes with Type I cement exhibited lower chloride content than those with Type II cement, except for the fly-ash concretes. The concretes with supplemental cementitious materials as well as LMC had a lower chloride content than the controls. Concretes with SF had the least amount of chloride penetration. At the lower depth of 3/4 to 1-1/4 in (10 to 32 mm) all the concretes had significantly lower values than the corrosion threshold value; the highest average value of any pair of two samples was 0.38 lb/yd³ (0.22 kg/m³). Thus, it appears that all the concretes with a low w/c in this study would have significant resistance to chloride ion penetration under actual service conditions. However, these results do not provide a measure of the length of service that may be expected from the concretes.

Relation of Rapid Permeability Test to 90-Day Ponding Test

The rapid chloride permeability test was developed by the Construction Technology Laboratories of the Portland Cement Association on a contract for the Federal Highway Administration(8). The development work showed a generally good correlation with the 90-day ponding test for chloride intrusion; but a large standard error for the test led the developer to conclude that the test was best utilized to rank concretes in order of expected permeability rather than to predict 90-day ponding results. It is also apparent that the condition of the test specimens and the characteristics of the materials being tested make it difficult to establish a relationship between the results of the 90-day ponding test and those from the rapid permeability test. Consequently, the extent to which differences in the Q values can be considered a measure of the differences in chloride permeability of the concrete under actual service conditions is uncertain.

Table 2 gives the Q value as an average of 2 specimens obtained for the same batch of concrete after the specimens had been aged for 28 and 90 days. The same table also gives the individual chloride content after the ponding test. There were large differences in the total salt found in the duplicate specimens. These differences make it impossible to establish a quantitative relationship between the Q values obtained in the rapid permeability test and the results of the ponding test.
When the sum of the average of chlorides absorbed at 1/4 to 3/4 in (6 to 19 mm) and 3/4 to 1-1/4 in (19 to 32 mm) are plotted against the Q values for the 28-day specimens on a logarithmic scale as shown in Figure 3, considerable scatter of the points is evident. Much of this may be caused by the poor precision of both the ponding test and the rapid permeability test. The line of best fit shows a correlation coefficient of 0.625 and indicates a general relationship of lower salt content with lower values of Q. A similar relationship was obtained at 90 days with a correlation coefficient of 0.577.

**Strength Development**

Table 3 provides the test results for compressive strengths at various ages for each combination of materials. The results are depicted in Figure 4 in which bar graphs of the strengths at 0.35, 0.40, and 0.45 w/c are shown for each combination of materials using Type II cement at 28 days. Figure 5 shows the pattern of strength development with age for the various materials. The plotted results are those for a w/c of 0.40, but the relationships are essentially the same at the other w/c tested. As noted in Figure 5, the patterns vary depending on the supplemental cementitious material used.

The results are summarized in the following sections.

**Effect of w/c**

In all cases an increase in strength is attained by reducing the w/c for a given proportion of solid ingredients. It should be noted that workable concretes with the lower w/c were obtained only through use of high-range water-reducing admixtures under laboratory conditions. Ratios as low as 0.35 may not be practicable for field concretes using locally available materials. However, these results indicate that the lowest practicable w/c ratio should be used in conjunction with all the supplemental cementitious material tested and that potentially lower strengths for concretes containing pozzolanic admixtures such as fly ash can be counteracted with relatively minor reductions of the w/c.

**Concretes Containing Fly Ash**

Results for concretes containing fly ash are as would be expected from previous research(9). In each case the strengths at early ages were lower than the controls. Generally, the strengths of the fly ash concretes increased at a slightly greater rate than the controls, and the rate of increase accelerated during the 28 to 90 day period. At 90 and 365 days, the fly ash concretes generally had strengths comparable to or significantly greater than the controls.

The same general trends were indicated by both the 15 and 25% replacement series. The lowest values were those for the 25% re-
placement specimens at the 0.45 w/c. They were 4,150 psi (28.6 MPa) at 28 days, 5,750 psi (39.6 MPa) at 90 days, and 6,620 psi (45.6 MPa) at 365 days, indicating satisfactory strength for bridge-deck concrete. This implies that the greater economy of replacing a larger proportion of the cement could be utilized with only minor adjustment in specifications and construction practices, and this would result in concretes with equal or higher strengths at later ages.

Concretes Containing Slag

The results show that an activation period is needed for strength development by the hydration of the slag components. One-day strengths are very low; they are approximately one half of the value of the control. But at seven days the slag concretes were stronger than the controls. There were further significant increases up to 28 days. After 28 days the slag concrete and control increased in strength at approximately the same rate.

Concretes Containing Silica Fume

The concretes containing silica fume developed strengths at approximately the same rate and amount as the control. Some differences are apparent for the different w/c, but this may be experimental error. The general indications are that the pozzolanic reactions with silica fume occur rapidly(10). Long-term increases such as those observed for fly ash concretes, should not be expected, especially for the small percentages of silica fume used in this study.

Latex-Modified Concretes

The strength development curves for the LMC are essentially parallel to those for the controls, but consistently lower. These concretes were prepared at a w/c of 0.37, the value normally used for bridge deck overlays using this material.

Type I vs Type II Cement

In general, control concretes with Type II cement had lower strengths than those with Type I cement at early ages and about equal strengths at 28 and 90 days. For each supplemental cementitious materials, similar trends were observed, indicating relatively minor effects of the cement characteristics at later ages.

Relation of Strength to Chloride Permeability

For the same type and amount of supplemental cementitious material, Q values decrease as strength increases, indicating an inverse relationship between chloride permeability (AASHTO T 277) and strength. However, there is no specific
Concrete Permeability

relation between the Q values and strength per se. For example, concretes containing silica fume had significantly lower Q values, indicating lower permeabilities than concretes containing slag; but their strengths were significantly lower.

Effects of Curing Temperature on Chloride Permeability and Strength

All of the specimens tested thus far in this study were cured under standard conditions in a moist room or air dried at 73°F (23°C). However, since it is known that moisture and temperature affect the rate of hydration or pozzolanic reactions, it was of interest to obtain some indication of the potential effects of curing temperatures on the results of the chloride permeability test and strength. It was also of interest to determine if Type II cements reacted significantly differently from Type III, especially with respect to the resistance to penetration of chloride ions as evaluated by the electrical conductance tests. Accordingly, additional specimens were made at a w/c of 0.40.

Control concretes and concretes containing 15% fly ash, 50% slag, and 7% silica fume with the same proportions given in the Appendix were prepared. For each variable, two batches of concrete, one with Type II and the other with Type III cement, were prepared. The concretes were tested at the fresh stage, and the characteristics are summarized in Table 4. Test specimens were prepared for chloride permeability and strength at room temperature, and within half an hour, they were placed in different curing environments at 40°F (4°C), 73°F (23°C), and 100°F (38°C) without removal of the molds. Molds were removed the following day and the specimens were returned to different temperature environments. Cylinders for the rapid chloride permeability test were kept moist for 2 weeks and air dried for 2 weeks. Those for the strength test were moist cured until the time of test.

Results at 28 days, summarized in Table 5, indicate that control concretes with either cement had comparable Q values when cured at 73°F (23°C) and 100°F (38°C); but concretes cured at 40°F (4°C) had significantly higher Q values except in one case. Strengths were comparable or significantly higher for the concretes containing Type III cement. With either cement the highest strengths were obtained when cured at 73°F (23°C) and the lowest when cured at 100°F (38°C). Of particular interest is the behavior of the concretes with fly ash with respect to the chloride permeability as indicated by the rapid permeability test. With either cement, the Q values of the specimens decreased significantly as the curing temperature increased. Specimens cured at 100°F (38°C) had Q values indicative of chloride permeabilities in or very close to the very low range. The results for specimens cured at 73°F (23°C) indicated high chloride permeabilities, and those for specimens cured at 40°F (4°C) indicated even higher permeabilities. Fly ash concretes with Type II cement had the lowest strength when cured at 40°F (4°C) and the
highest strength when cured at 100°F (38°C). With Type III cement, fly ash specimens cured at 73°F developed the highest strength.

The Q values for concretes containing slag cured at 73°F (23°C) and 100°F (38°C) indicated comparable chloride permeabilities. For specimens cured at 40°F, the Q values for concretes with Type II cement were the same as those for specimens cured at 73°F (23°C) and 100°F (38°C), but specimens containing Type III cement had significantly larger Q values when cured at 40°F (4°C). Strength values for concretes containing slag were higher for the concretes cured at 73°F (23°C) and 100°F (38°C) (those with Type III cement exhibited higher values) and lower for those cured at 40°F (4°C).

The results for concretes with silica fume indicated the lowest permeability of 580 coulombs when combined with Type III cement and cured at 100°F (38°C). The Q values for concretes made with either cement and cured at 73°F (23°C) were approximately 1,000 coulombs, indicating a low chloride permeability. This was also true for those containing Type II cement cured at 100°F (38°C). Significantly higher Q values were obtained for concretes containing either cement when cured at 40°F (4°C). The highest strengths for concretes containing SF were obtained when specimens were cured at 73°F (23°C) for either cement.

In general, the test results indicate that the chloride permeabilities were comparable in concretes with Type II and Type III cements, except that considerable differences were obtained for slag and silica fume concretes at 40°F (4°C) both of which had higher Q values with Type III cement (this needs further investigation). Strengths were comparable or significantly higher for the concretes containing Type III cement.

SUMMARY OF RESULTS AND CONCLUSIONS

1. Concretes with different w/c and prepared with different supplemental cementitious materials varied in their resistance to chloride permeability (using AASHO Test Method T 277). For each combination of materials, a reduction in the Q value in coulombs occurred as the w/c was decreased. Concretes with pozzolans, slag, or latex had lower Q values than the controls. Q values decreased as the age of the specimens increased from 28 to 90 days. The 365-day results were inconclusive as to whether changes in permeabilities occurred after 90 days.

2. Concretes with fly ash and slag had lower early strengths but generally higher ultimate strengths than the controls. For concretes containing silica fume, strengths were about the same or slightly higher at all ages. In all cases, a lower w/c resulted in higher strengths for concretes containing the same proportion of solid ingredients.
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3. Strengths of all the concretes at 90 days were in excess of 5,000 psi (34.5 MPa) and thus are satisfactory. In some concretes, early strengths were low. For the same type and amount of supplemental cementitious material, strength increased as Q values decreased. However, when concretes with different composition are considered, there is no specific relationship between strength and the results of the rapid test for chloride permeability (AASHTO T 277). Concretes with essentially equal strength but containing different supplemental cementitious material had significantly different Q values. For example, the test results indicated that concretes with pozzolans or slag having strengths similar to the controls generally had lower Q values.

4. Results of the 90-day ponding test on concretes with w/c of 0.40 and containing different supplemental cementitious material indicate differences in the chloride content at a depth of 1/4 to 3/4 in (6 to 19 mm). Concretes with pozzolans, slag, or latex had less chloride intrusion than the controls, but all the values were above the threshold value of 1.32 lb/yd³ (0.78 kg/m³) except for one batch of silica-fume concrete. At the deeper depth of 3/4 to 1 1/4 in (19 to 32 mm), the chloride intrusion for all the concretes was very low. The highest value was in a control concrete that had an average chloride content of 0.38 lb/yd³ (0.22 kg/m³). It appears likely that all the low w/c concretes in this study (0.40 or less) would have significant resistance to chloride ion penetration under actual service conditions. However, these values do not provide a measure of the length of service that may be expected from them.

5. When control, slag, and silica-fume concretes with Type II and Type III cements were cured at 73°F (23°C) and 100°F (38°C), there was little difference in the chloride permeabilities for the same concrete at each temperature. For concretes cured at 40°F (4°C), the chloride permeabilities were generally higher. However, fly ash concretes made with either cement showed a very significant reduction in Q values as the curing temperature increased. When the fly ash concrete was cured at 40°F (4°C) or 73°F (23°C), chloride permeabilities were in the high range, but when they were cured at 100°F (38°C), they were in or very close to the very low range. In general, the strengths of all concretes were highest when cured at 73°F (23°C). Concretes with Type III cement had strengths comparable to or significantly higher than those with Type II cement.

ACKNOWLEDGEMENT

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REFERENCES


APPENDIX A — TESTS CONDUCTED AND MIXTURE PROPORTIONS

TABLE A-1—MATERIAL COMBINATIONS AND BATCH PARAMETERS

<table>
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<tr>
<th>Identification</th>
<th>Cementitious Material&lt;sup&gt;a&lt;/sup&gt;</th>
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<th>Water-Cementitious Ratio&lt;sup&gt;b&lt;/sup&gt;</th>
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<th>0.40</th>
<th>0.35</th>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>C1 (Control)</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
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<td>F + C2</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
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<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
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<td>F + C1</td>
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<tr>
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<td>C2L</td>
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<td>C1L</td>
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<td>x</td>
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<sup>a</sup> C2 - Type II cement -- alkalies, 0.50%  
C1 - Type 1 cement -- alkalies, 0.78%  
F - Class F fly ash with good performance record  
S - Ground iron blast furnace slag with good performance record  
SF - Silica fume  
L - Latex

<sup>b</sup> Ratio of water to cement plus supplemental cementitious ingredient w/c.

<sup>c</sup> The mass of fly ash added was 1.2 times the mass of cement replaced.

<sup>d</sup> Water-cement ratio = 0.37.
<table>
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<th>W/C</th>
<th>Cement (lb)</th>
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<th>C.A. (lb)</th>
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1 lb = 454 g.

Latex modifier - 206 lb (98 lb solids, 108 lb water).
TABLE A-3--CHARACTERISTICS OF FRESHLY MIXED CONCRETE

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<td>C1F-15</td>
<td>0.40</td>
<td>3.2</td>
<td>7.5</td>
<td>140.4</td>
</tr>
<tr>
<td>C1F-25</td>
<td>0.40</td>
<td>2.7</td>
<td>5.4</td>
<td>143.6</td>
</tr>
<tr>
<td>C1S-50</td>
<td>0.40</td>
<td>2.3</td>
<td>5.3</td>
<td>144.4</td>
</tr>
<tr>
<td>C1SF-7</td>
<td>0.40</td>
<td>2.5</td>
<td>8.0</td>
<td>140.4</td>
</tr>
<tr>
<td>C1-L</td>
<td>0.37</td>
<td>4.6</td>
<td>3.6</td>
<td>144.0</td>
</tr>
</tbody>
</table>

1 in = 25.4 mm, 1 lb/ft³ = 16.02 kg/m³.
TABLE A-4--CHEMICAL AND PHYSICAL ANALYSES OF CEMENTS

<table>
<thead>
<tr>
<th>Chemical, %</th>
<th>Type II (C2)</th>
<th>Type I (C1)</th>
<th>Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>21.2</td>
<td>20.6</td>
<td>20.3</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.7</td>
<td>5.7</td>
<td>5.5</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.0</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>CaO</td>
<td>62.9</td>
<td>63.3</td>
<td>62.7</td>
</tr>
<tr>
<td>MgO</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>SO₃</td>
<td>3.0</td>
<td>2.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Total alkalies, as Na₂O</td>
<td>0.50</td>
<td>0.78</td>
<td>0.71</td>
</tr>
<tr>
<td>C₃S</td>
<td>58.6</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>C₃A</td>
<td>6.5</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

Physical

Fineness (Blaine) 3,677 3,725 5,285
TABLE A-5--CHEMICAL AND PHYSICAL ANALYSES OF FLY ASH, SLAG, AND SILICA FUME

<table>
<thead>
<tr>
<th>Chemical, %</th>
<th>Fly Ash (F)</th>
<th>Slag (S)</th>
<th>Silica Fume (SF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>54.5</td>
<td>36.0</td>
<td>87.2</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>30.4</td>
<td>10.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.2</td>
<td>0.7</td>
<td>2.3</td>
</tr>
<tr>
<td>CaO</td>
<td>0.7</td>
<td>42.7</td>
<td>1.2</td>
</tr>
<tr>
<td>MgO</td>
<td>N.D. (a)</td>
<td>8.9</td>
<td>0.8</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.2</td>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Total alkalies</td>
<td>0.82</td>
<td>0.32</td>
<td>0.56</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>2.16</td>
<td>1.89</td>
<td>3.80</td>
</tr>
</tbody>
</table>

**Physical**

**Fineness**

<table>
<thead>
<tr>
<th>% ret on No. 325 sieve</th>
<th>14.2</th>
<th>1.1</th>
<th>N.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area, air permeability, cm²/g</td>
<td>N.D.</td>
<td>5,250</td>
<td>N.D.</td>
</tr>
</tbody>
</table>

* N.D. = Not determined
**TABLE A-6--AGGREGATE CHARACTERISTICS**

Coarse Aggregate -- crushed granite gneiss

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum size</td>
<td>1/2 in</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.78</td>
</tr>
<tr>
<td>Unit weight</td>
<td>103.3 lb/ft³</td>
</tr>
</tbody>
</table>

Fine Aggregate -- siliceous sand

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness modulus</td>
<td>2.90</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.59</td>
</tr>
</tbody>
</table>

1 in = 25.4 mm, 1 lb/ft³ = 16.02 kg/m³.
<table>
<thead>
<tr>
<th>ID</th>
<th>w/c = 0.35</th>
<th></th>
<th>w/c = 0.40</th>
<th></th>
<th>w/c = 0.45</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28-days</td>
<td>90-days</td>
<td>365-days</td>
<td>28-days</td>
<td>90-days</td>
<td>365-days</td>
</tr>
<tr>
<td></td>
<td>Q&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>Q&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>Q&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>Q&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>Q&lt;sup&gt;(c)&lt;/sup&gt;</td>
<td>Q&lt;sup&gt;(c)&lt;/sup&gt;</td>
</tr>
<tr>
<td>C2</td>
<td>2,890</td>
<td>2,020</td>
<td>2,330</td>
<td>4,830</td>
<td>4,210</td>
<td>3,660</td>
</tr>
<tr>
<td>C1</td>
<td>2,850</td>
<td>1,940</td>
<td>2,260</td>
<td>3,860</td>
<td>3,590</td>
<td>4,800</td>
</tr>
<tr>
<td>C2F-15</td>
<td>3,190</td>
<td>1,540</td>
<td>1,900</td>
<td>5,110</td>
<td>2,960</td>
<td>3,730</td>
</tr>
<tr>
<td>C1F-15</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3,330</td>
<td>2,010</td>
<td>2,870</td>
</tr>
<tr>
<td>C2F-25</td>
<td>2,820</td>
<td>1,540</td>
<td>1,780</td>
<td>5,110</td>
<td>3,220</td>
<td>3,440</td>
</tr>
<tr>
<td>C1F-25</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3,430</td>
<td>1,890</td>
<td>1,920</td>
</tr>
<tr>
<td>C2S-5U</td>
<td>1,650</td>
<td>900</td>
<td>1,350</td>
<td>2,410</td>
<td>1,330</td>
<td>2,160</td>
</tr>
<tr>
<td>C1S-50</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2,050</td>
<td>1,600</td>
<td>2,350</td>
</tr>
<tr>
<td>C2SF-7</td>
<td>570</td>
<td>340</td>
<td>168</td>
<td>850</td>
<td>460</td>
<td>300</td>
</tr>
<tr>
<td>C1SF-7</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>760</td>
<td>490</td>
<td>390</td>
</tr>
<tr>
<td>C2L&lt;sup&gt;(e)&lt;/sup&gt;</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3,000</td>
<td>1,370&lt;sup&gt;(f)&lt;/sup&gt;</td>
<td>352</td>
</tr>
<tr>
<td>C1L</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2,290</td>
<td>1,410</td>
<td>439</td>
</tr>
</tbody>
</table>

(a) See Table A-1 for Code
(b) Water to cementitious material ratio 0.37 w/c
(c) Q = Coulombs, current passed through specimens in 6 h value at 104 days
(d) value at 76 days
(e) 0.37 w/c
(f) value at 104 days
<table>
<thead>
<tr>
<th>Identification</th>
<th>1/4&quot;-3/4&quot; Depth</th>
<th>3/4&quot;-1 1/4&quot; Depth</th>
<th>Avg. (b) Q, Coulombs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>Avg.</td>
</tr>
<tr>
<td>C2</td>
<td>6.15</td>
<td>3.89</td>
<td>5.02</td>
</tr>
<tr>
<td>C2FA-15</td>
<td>2.87</td>
<td>2.52</td>
<td>2.70</td>
</tr>
<tr>
<td>C2FA-25</td>
<td>3.37</td>
<td>2.75</td>
<td>3.07</td>
</tr>
<tr>
<td>C2S-50</td>
<td>2.36</td>
<td>4.28</td>
<td>3.33</td>
</tr>
<tr>
<td>C2SF-7</td>
<td>3.21</td>
<td>1.59</td>
<td>2.40</td>
</tr>
<tr>
<td>C2L</td>
<td>4.81</td>
<td>3.35</td>
<td>4.08</td>
</tr>
<tr>
<td>C1</td>
<td>3.95</td>
<td>2.09</td>
<td>3.02</td>
</tr>
<tr>
<td>C1FA-15</td>
<td>3.61</td>
<td>2.98</td>
<td>3.30</td>
</tr>
<tr>
<td>C1FA-25</td>
<td>4.96</td>
<td>3.39</td>
<td>4.18</td>
</tr>
<tr>
<td>C1S-50</td>
<td>1.27</td>
<td>3.84</td>
<td>2.56</td>
</tr>
<tr>
<td>C1SF-7</td>
<td>0.85</td>
<td>1.19</td>
<td>1.02</td>
</tr>
<tr>
<td>C1L</td>
<td>1.74</td>
<td>1.06</td>
<td>1.40</td>
</tr>
</tbody>
</table>

1 lb/yd³ = 0.59 kg/m³, 1 in = 25.4 mm

(a) Corrected for average base line chloride of 0.13 lb/yd³.
(b) Sum of average for both levels.
**Concrete Permeability**

<table>
<thead>
<tr>
<th>ID&lt;sup&gt;a&lt;/sup&gt;</th>
<th>w/c&lt;sup&gt;b&lt;/sup&gt;</th>
<th>1-Day</th>
<th>7-Days</th>
<th>28-Days</th>
<th>90-Days</th>
<th>365-Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>0.35</td>
<td>4,890</td>
<td>6,860</td>
<td>8,180</td>
<td>8,870</td>
<td>10,220</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>3,170</td>
<td>4,960</td>
<td>6,010</td>
<td>6,950</td>
<td>7,700</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>1,880</td>
<td>4,170</td>
<td>5,400</td>
<td>6,170</td>
<td>6,840</td>
</tr>
<tr>
<td>C2F-15</td>
<td>0.35</td>
<td>2,930</td>
<td>5,160</td>
<td>6,730</td>
<td>8,380</td>
<td>9,900</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>2,440</td>
<td>4,200</td>
<td>5,490</td>
<td>7,310</td>
<td>8,650</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>1,530</td>
<td>3,250</td>
<td>4,450</td>
<td>6,080</td>
<td>7,440</td>
</tr>
<tr>
<td>C2F-25</td>
<td>0.35</td>
<td>3,220</td>
<td>5,250</td>
<td>7,010</td>
<td>9,230</td>
<td>10,870</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>1,960</td>
<td>4,150</td>
<td>5,840</td>
<td>8,010</td>
<td>8,950</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>1,320</td>
<td>2,830</td>
<td>4,150</td>
<td>5,750</td>
<td>6,620</td>
</tr>
<tr>
<td>C2S-50</td>
<td>0.35</td>
<td>1,540</td>
<td>7,580</td>
<td>9,540</td>
<td>10,370</td>
<td>11,130</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>1,540</td>
<td>5,700</td>
<td>7,830</td>
<td>8,440</td>
<td>9,160</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>890</td>
<td>4,540</td>
<td>6,670</td>
<td>7,500</td>
<td>8,060</td>
</tr>
<tr>
<td>C2SF-7</td>
<td>0.35</td>
<td>3,900</td>
<td>6,650</td>
<td>8,600</td>
<td>9,200</td>
<td>9,780</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>3,030</td>
<td>5,200</td>
<td>6,850</td>
<td>7,410</td>
<td>7,690</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>2,350</td>
<td>3,930</td>
<td>5,260</td>
<td>5,860</td>
<td>6,120</td>
</tr>
<tr>
<td>C2-L</td>
<td>0.37</td>
<td>1,900</td>
<td>3,630</td>
<td>4,380</td>
<td>5,240</td>
<td>5,800</td>
</tr>
<tr>
<td>C1</td>
<td>0.35</td>
<td>4,600</td>
<td>6,470</td>
<td>7,810</td>
<td>8,920</td>
<td>9,550</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>3,800</td>
<td>5,590</td>
<td>6,490</td>
<td>7,610</td>
<td>8,250</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>2,830</td>
<td>4,480</td>
<td>5,340</td>
<td>6,140</td>
<td>6,600</td>
</tr>
<tr>
<td>C1F-15</td>
<td>0.40</td>
<td>2,850</td>
<td>4,440</td>
<td>5,520</td>
<td>7,030</td>
<td>7,790</td>
</tr>
<tr>
<td>C1F-25</td>
<td>0.40</td>
<td>2,820</td>
<td>4,390</td>
<td>5,890</td>
<td>7,560</td>
<td>8,290</td>
</tr>
<tr>
<td>C1S-50</td>
<td>0.40</td>
<td>1,750</td>
<td>5,980</td>
<td>7,580</td>
<td>8,200</td>
<td>8,440</td>
</tr>
<tr>
<td>C1SF-7</td>
<td>0.40</td>
<td>3,480</td>
<td>5,460</td>
<td>6,500</td>
<td>7,130</td>
<td>7,170</td>
</tr>
<tr>
<td>C1-L</td>
<td>0.37</td>
<td>2,560</td>
<td>3,510</td>
<td>4,390</td>
<td>5,150</td>
<td>5,660</td>
</tr>
</tbody>
</table>

1 psi = 6.895 kPa.

(a) See Table A-1 for Code

(b) Water to cement + admixture ratio by mass

(c) C<sub>2</sub> are type II cement concretes, C1 are type I.
### TABLE 4--CHARACTERISTICS OF FRESHLY MIXED CONCRETE (W/C = 0.40)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cement</th>
<th>Slump, in.</th>
<th>Air, %</th>
<th>Unit Weight, lb/ft³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>II</td>
<td>6.0</td>
<td>5.7</td>
<td>145.2</td>
</tr>
<tr>
<td>F-15</td>
<td>II</td>
<td>5.7</td>
<td>6.2</td>
<td>142.4</td>
</tr>
<tr>
<td>S-50</td>
<td>II</td>
<td>4.5</td>
<td>7.0</td>
<td>142.0</td>
</tr>
<tr>
<td>SF-7</td>
<td>II</td>
<td>3.5</td>
<td>7.5</td>
<td>139.2</td>
</tr>
<tr>
<td>Control</td>
<td>III</td>
<td>5.5</td>
<td>8.2</td>
<td>139.6</td>
</tr>
<tr>
<td>F-15</td>
<td>III</td>
<td>5.8</td>
<td>8.5</td>
<td>140.0</td>
</tr>
<tr>
<td>S-50</td>
<td>III</td>
<td>3.8</td>
<td>8.5</td>
<td>140.4</td>
</tr>
<tr>
<td>SF-7</td>
<td>III</td>
<td>5.0</td>
<td>8.9</td>
<td>138.8</td>
</tr>
</tbody>
</table>

1 in = 25.4 mm, 1 lb/ft³ = 16.02 kg/m³

### TABLE 5--EFFECT OF CURING TEMPERATURE ON CHLORIDE PERMEABILITY AND STRENGTH

<table>
<thead>
<tr>
<th>Curing Temp., °F</th>
<th>Permeability, coulomb</th>
<th>Strength, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type II</td>
<td>Type III</td>
</tr>
<tr>
<td>Controls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>8,240</td>
<td>8,580</td>
</tr>
<tr>
<td>73</td>
<td>4,260</td>
<td>4,200</td>
</tr>
<tr>
<td>100</td>
<td>4,300</td>
<td>3,640</td>
</tr>
<tr>
<td>15% Fly Ash</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>9,240</td>
<td>11,080</td>
</tr>
<tr>
<td>73</td>
<td>6,210</td>
<td>4,970</td>
</tr>
<tr>
<td>100</td>
<td>920</td>
<td>1,110</td>
</tr>
<tr>
<td>50% Slag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1,390</td>
<td>4,280</td>
</tr>
<tr>
<td>73</td>
<td>1,040</td>
<td>1,360</td>
</tr>
<tr>
<td>100</td>
<td>1,370</td>
<td>1,130</td>
</tr>
<tr>
<td>7% Silica Fume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>2,600</td>
<td>6,920</td>
</tr>
<tr>
<td>73</td>
<td>1,020</td>
<td>1,090</td>
</tr>
<tr>
<td>100</td>
<td>1,010</td>
<td>580</td>
</tr>
</tbody>
</table>

1 psi = 6.895 kPa, \( t^C = (t^F - 32)/1.8 \)
Fig. 1--Results of 28-day chloride permeability test
Fig. 2--Results of 90-day chloride permeability test
Fig. 3--Relation of Q at 28 days to total chloride absorbed (1/4 to 1 1/4 in.) after 90 days (1 lb/yd$^3$ = 0.59 kg/m$^3$, 1 in. = 25.4 mm)
Fig. 4--28-day strengths (1 psi = 6.895 kPa)
Fig. 5--Compressive strength versus age for concretes with Type II cement at 0.40 w/c (1 psi = 6.895 kPa)
Permeabilities of Silica Fume Concrete

by D. Perraton, P.C. Aitcin, and D. Vezina

Synopsis: Water, chloride-ion and air permeability of two series of silica fume and non-silica fume concretes having water/cementitious ratios of 0.4 and 0.5 were studied as well as that of a 0.24 water/cementitious ratio silica fume concrete. Silica fume dosage varied from 5 to 20% by weight of cement.

The water permeability of concrete samples having water/cementitious ratios lower than 0.5 is so low that they can be considered impervious whether they contain silica fume or not.

The chloride-ion impermeability provided by silica fume rivals that of latex for water/cementitious ratios of 0.4 to 0.5 and polymer-impregnated concrete with a 0.24 W/C ratio.

The two drying methods used in this research yielded a positive correlation between silica fume dosage and air permeability. Equal variations were observed for values of up to 10%, whereas at 20%, the increase was markedly sharper.

The characterization of concrete permeability is not as simple as it appears. Sample preparation and fluid type can significantly affect the interpretation of the effect of an admixture such as silica fume.

Keywords: air; chlorides; concretes; permeability; porosity; silica fume; water
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Daniel Vézina is head of concrete laboratory at the Laboratoire Central of the Ministry of Transportation of Quebec. His work involves research in concrete and evaluation of deterioration of concrete structure. He received B. Eng. Civil Engineering in 1974, from the Université Laval, Québec, Canada.

INTRODUCTION

Concrete durability is closely related, among other factors, to the type of environment in which the concrete has to perform and its permeability. In fact, permeability dictates, the rate at which aggressive agents will penetrate and attack the concrete. Since there is no single type of aggressive agent, there is no single type of permeability and no single way to measure permeability. If the aggressive agent is a gas (CO₂, SO₃ etc...), the measurement of gas permeability will be of prime importance. If the aggressive agent is a liquid (acid rain, acidic water, seawater, sulfate-rich water, extra pure water, etc...), liquid permeability will be the key factor for concrete durability. Finally, if chloride ions constitute the aggressive agent, then chloride-ion permeability will be of concern.

Are these different types of permeability related to each other? Are they only particular aspects of a more general concept related to the permeability of the matrix per se?

This paper does not intend to cover these aspects for every kind of concrete, but rather to study the incidence of the use of silica fume on concrete permeabilities, namely: water permeability, air permeability and chloride-ion permeability. Indeed, silica fume is increasingly used in the concrete industry, very often to make concrete more impervious.
It is often said, but not very well documented, that silica fume can be used to lower concrete permeability (1, 2, 3). Recently, Ozildirim (4) showed that silica fume drastically decreases chloride-ion permeability.

EXPERIMENTAL

In order to study the influence of silica fume on water, air and chloride-ion permeability, two series of air-entrained concrete having water/cementitious ratios of 0.4 and 0.5 were made with different silica fume dosages: 0 (reference), 5, 7.5, 10 and 20% by weight of cement. The composition of these different concretes was adjusted so they contained the same volume of paste (cement + water + silica fume), using a superplasticizer to maintain a constant slump. Moreover, the testing of 0.24 water/cementitious ratio silica fume concrete was also included in this program.

Materials

Both series used a Type I ASTM cement (Type 10 CSA), whose chemical composition is given in Table 1. An ASTM Type III (Type 30 CSA) was used for the W/C = 0.24 concrete; its chemical composition is also given in Table 1. The silica fume from a local plant producing silicon and 75% ferrosilicon alloy was used in powder form. Its SiO₂ content is quite high and its loss on ignition moderate as seen in Table 1. The fine aggregate was a natural siliceous sand having a fineness modulus of 2.50 and an absorption of 1.4%. The coarse aggregate was a metamorphic limestone (20-5mm) (3/4-No. 4) having an absorption of 0.6%.

The air-entraining agent was a synthetic detergent. The water reducer was a non-chloride polymer. The superplasticizer, when used, was naphtalene-based (42% solids) with a specific gravity of 1.21.

Concrete Composition and Characteristics

The composition of the different concretes is presented in Tables 2, 3 and 4. The 0.4 and 0.5 series were air-entrained and contained a water reducer. The slumps of these different concretes were adjusted to between 65 and 100 mm (2 1/2 to 4 in.). All the concretes specimens were vibrated. The 0.24 concrete was a flowing nonair-entrained concrete.

Nine 100 x 100mm (4 x 8 in.) specimens were cast for compressive strength measurements at 1, 7 and 28 days in accordance with the ASTM method C-192. Three specimens were tested at
each age. Two 150 x 300mm (6 x 12 in.) specimens were cast for water permeability measurement as well as a 180 x 500 x 100mm (7 x 20 x in.) slab for chloride-ion, air permeability measurements and mercury porosimetry. A concrete beam 100 x 100 x 400mm was cast for air-void characterization.

The air-void system of the hardened concrete was characterized in accordance with ASTM method C-457: Modified point count method on three 100 x 100 x 200mm samples.

Curing of samples before testing

The curing of the samples before testing is presented in Figure 4. The samples received the same type of curing before each different measurement of permeability, but these cureings were different from one type of measurement to another due to equipment failure.

Water Permeability Measurements

Water permeability was measured in special permeability cells illustrated in Figure 1. This design is derived from the one proposed by Bernaix (5) for rock samples and quite similar to the one proposed by Alegre et al. (6). Using this permeameter, it is not necessary to dry the 150 x 300mm (6 x 12 in.) specimens prior to measuring their water permeability. Water permeability was measured under convergent flow at 28 days with pressure gradients up to 7 MPa (1000 psi).

Air Permeability Measurements

Air permeability was measured with an air permeameter developed at the Institut National des Sciences appliquées de Toulouse by Thenoz (7). A schematic of this air permeameter is presented in Figure 2. The tests were made at various pressure gradients in the 93 to 33 kPa range (13.5 and 4.8 psi).

Two samples (38 x 50 mm - 1/2 x 2 in.) were cored at 28d from the 180 x 500 x 100 mm slab that was air-cured in the laboratory after 7 days. Then, the samples were cured according to Figure 4. At the end of the curing period, air permeability of the two samples was measured. Then, these two samples were oven-dried at 105°C for two additional days and the air permeability measured again on the same samples.

After the first drying, the samples will be referred to as air-dried; after the additional drying they will be referred to as oven-dried.
Concrete Permeability

Chloride-ion Permeability

Chloride-ion permeability was measured with a Rapid Chloride-Ion Permeameter, according to AASHTO T277-831 (Rapid Determination of the Chloride Permeability of Concrete) (8). A schematic of this apparatus is presented in Figure 3. Two specimens (95 x 50 mm - 3 3/4-2in.) were cored from each slab at 28 days. The curing of the specimens before testing is presented in Figure 4.

Mercury Porosimetry

Mercury porosity measurements were made on small concrete cores 20 x 100mm (3/4 - 4 in.) using a Carlo Erba mercury porosimeter where mercury can be intruded in the sample up to a pressure of 150 MPa (21 750 psi). This pressure corresponds to an equivalent pore radius entrance of 50Å. Two samples were tested each time, their curing is presented in Figure 4. Each sample was oven-dried for 24 hours at 105°C in a ventilated oven before testing.

PRESENTATION OF THE RESULTS

Compressive Strength Results

Compressive strength results are presented for both series in Table 5. In this table, it shown that the substitution of a certain volume of cement by silica fume always increase the 28d compressive strength, but that above a 7.5% substitution level the strength increase is less substantial than the one obtained in the 5 to 7.5% range.

Spacing Factor

Tables 2 and 3 show that entraining the right amount of air in silica fume concretes presented no problem, although the A.E.A. dosage had to be increased when the silica fume dosage increased. All the spacing factors fall below the ACI recommended 200 μm limit, which has also been found to be correct for silica fume concrete (9).
Mercury Porosimetry Measurements

The volume of intruded mercury (first intrusion) is presented in Figures 5 and 6, which illustrate that there is no major difference in the shape of the intrusion curves for the 0.4 and 0.5 series. The pore structure of silica fume concretes is however somewhat finer than that of non-silica fume concrete. The presence of pores with entrance radii greater than 0.1 μm has been observed in the two series. This result has been already reported for silica fume concrete containing water reducers and superplasticizer (2).

The total volume of intruded mercury is slightly lower for the 0.4 series than for the 0.5 series. It further seems to decrease slightly in both series as the silica fume content increases, but they remain at the same order of magnitude. This is not the case for the 0.24 concrete, which was intruded by a very low volume of mercury (23 mm³/g instead of 50 mm³/g on average for the 0.4 and 0.5 series).

Water Permeability Measurements

The specimens were kept for 7 days in the permeameter cells, while the water pressure was increased gradually to 7 MPa (1000 psi). The only concrete that exhibited a measurable water flow was the 0.5 reference concrete. Its permeability was $3 \times 10^{-14}$ m/s. No water flow was measured in the other concretes, they can be considered in that respect to be impervious to water.

Chloride-ion Permeability

The current intensity passing through the concrete samples of the 0.4 and 0.5 series is presented in Figures 7 and 8 as a function of time. It can be seen that this current is consistently much higher in the reference concrete than in the silica fume concretes.

These results have also been presented in Figure 9 as the total amount of electrical charges (Coulombs) passed through the concrete samples after 6 hours as a function of the silica fume percentage in the mix.

The values obtained for the 0.4 and 0.5 reference concretes are in good agreement with the ones given by Whiting (8). These figures clearly indicate the beneficial influence of silica fume on chloride-ion permeability as previously shown by Ozyildirim (4). These figures correlate also quite well with the compressive-strength results that have shown that when a 7.5% level of substitution is reached, the compressive strength increase is less
significant. According to the permeability scale provided by Whiting (8), it can be seen that the silica fume concretes of the 0.4 series exhibit a chloride-ion permeability equivalent to that of a latex-modified concrete.

In the case of the 0.24 silica fume concrete, the total amount of electrical charges passed in 6 hours was equal to 150 Coulombs. This level of chloride-ion permeability is only matched by polymer-impregnated concretes according to Whiting (8).

**Air Permeability**

Air permeability measurements are presented in Table 6 and Figure 10, where it can be seen that the type of drying greatly influences the measurement of the air permeability of the concrete samples. The oven-dried samples exhibit a much greater air permeability in comparison to those that were only air-dried. These results are in good agreement with those presented by Nagataki and Ujike (10).

In Figure 10, it is also seen that, in general, the higher the water/cementitious ratio, the higher the air permeability for the same type of drying. For the 0.24 W/C ratio concrete, the air-dried air permeability was equal to $2 \times 10^{-8}$ m/s and the oven-dried one $11 \times 10^{-8}$ m/s. Figure 10 clearly shows that the silica fume samples have higher air permeability than the reference samples and that air permeability increases with silica fume dosage which is opposite to the trend found by Nagataki and Ujike (10). Their concretes were cured longer and tested earlier than ours.

The lower-than-expected values obtained for the 10% dosage cannot be explained and should be treated as a lack of homogeneity of the concrete in the slab that yielded the cores.

**CONCLUSION**

The concept of the permeability of concrete is more complex than it appears on the surface. The permeability coefficient not only varies according to the type of fluid used to measure it, but also with sample preparation.

It has been found that concretes with water/cementitious ratios of 0.5 or less are practically impervious to any water flow ($k < 10^{-14}$ m/s) whether silica fume is admixed or not.

If chloride ions can pass through saturated non silica fume concrete, the higher the water/cement ratio, the higher the amount of chloride ions passing through the concrete. This pattern remains true when concrete contains silica fume. The
major effect of silica fume on chloride-ion permeability, however, is a drastic decrease, so that silica fume concretes provide chloride-ion impermeability in the same range as latex concretes with water/cementitious ratios of 0.4 to 0.5 or polymer-impregnated concretes with a 0.24 W/C ratio. Experimentation shows that dosages greater than 7.5% present practically no significant decrease of chloride-ion permeability. The same pattern has also been found in silica fume compressive strength results.

Gas permeability of concrete can likewise be related to its water/cementitious ratio: to a certain extent, the lower this ratio, the lower the air permeability. The type of drying, however, greatly influences the air-permeability measurement. When silica fume is introduced into the mix, the air permeability of silica fume concrete increases in direct proportion to the silica fume dosage and the effectiveness of the drying process.

Assessing the effect of a particular chemical or mineral admixture on concrete permeability requires a clear understanding of the type of fluid permeating the concrete and the type of drying to which it was subjected.

Field concretes are seldom exposed to conditions as well-defined as those used in our experimental procedures. Actual conditions fall between these extreme conditions so that the actual permeability of a given concrete can vary widely depending on its environment. There is, however, always a type of fluid to which a given field concrete will be more pervious. This fluid will control the type of attack, if any, to which the field concrete will be subjected.

REFERENCES


2. Wolsiefer, J., "Ultra High Strength Field Placeable Concrete in the Range 10,000 to 18,000 psi". ACI Annual Convention, Atlanta, Jan. 1982, pp. 1-23.


8. Whiting, D., "In Situ Measurements of the Permeability of Concrete to Chloride Ions". American Concrete Institute, special publication, SP-82, Detroit, 1982, pp. 501-524.


TABLE 1--CHEMICAL COMPOSITION OF THE CEMENTITIOUS MATERIALS

<table>
<thead>
<tr>
<th></th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO (total)</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>SO₃</th>
<th>LOI</th>
</tr>
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<tr>
<td>Type I</td>
<td>21.2</td>
<td>4.1</td>
<td>3.0</td>
<td>62.0</td>
<td>2.6</td>
<td>0.26</td>
<td>0.99</td>
<td>3.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Type III</td>
<td>21.0</td>
<td>4.6</td>
<td>1.8</td>
<td>64.0</td>
<td>2.8</td>
<td>0.75*</td>
<td>3.3</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Silica fume</td>
<td>91.8</td>
<td>0.4</td>
<td>1.7</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
<td>1.3</td>
<td>-- 3.5</td>
<td></td>
</tr>
</tbody>
</table>

* Na₂O equivalent

TABLE 2--COMPOSITION AND CHARACTERISTICS OF THE 0.40 W/C SERIES

<table>
<thead>
<tr>
<th>Silica fume (% by weight of cement)</th>
<th>0</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water [kg/m³]</td>
<td>152</td>
<td>152</td>
<td>150</td>
<td>149</td>
<td>146</td>
</tr>
<tr>
<td>Cement</td>
<td>380</td>
<td>360</td>
<td>347</td>
<td>336</td>
<td>292</td>
</tr>
<tr>
<td>Silica fume [kg/m³]</td>
<td>0</td>
<td>19</td>
<td>28</td>
<td>37.5</td>
<td>73</td>
</tr>
<tr>
<td>Coarse aggregate [kg/m³]</td>
<td>1060</td>
<td>1060</td>
<td>1050</td>
<td>1050</td>
<td>1045</td>
</tr>
<tr>
<td>Fine aggregate [kg/m³]</td>
<td>755</td>
<td>760</td>
<td>755</td>
<td>755</td>
<td>750</td>
</tr>
<tr>
<td>A.E.A. [mL/m³]</td>
<td>86</td>
<td>141</td>
<td>194</td>
<td>155</td>
<td>270</td>
</tr>
<tr>
<td>Water reducer [mL/m³]</td>
<td>950</td>
<td>950</td>
<td>950</td>
<td>930</td>
<td>925</td>
</tr>
<tr>
<td>Superplasticizer [mL/m³]</td>
<td>0</td>
<td>1670</td>
<td>2800</td>
<td>1240</td>
<td>3850</td>
</tr>
<tr>
<td>[mm] Slump</td>
<td>75</td>
<td>70</td>
<td>80</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>[%] Air content</td>
<td>fresh</td>
<td>5.1</td>
<td>4.6</td>
<td>5.3</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>hardened</td>
<td>4.3</td>
<td>3.8</td>
<td>4.3</td>
<td>4.8</td>
</tr>
<tr>
<td>[μm] Spacing factor L</td>
<td>150</td>
<td>150</td>
<td>125</td>
<td>125</td>
<td>110</td>
</tr>
</tbody>
</table>
Concrete Permeability  

### TABLE 3--COMPOSITION AND CHARACTERISTICS OF THE 0.50 W/C SERIES

<table>
<thead>
<tr>
<th>Silica fume (%) of cement weight</th>
<th>0</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water [kg/m³]</td>
<td>151</td>
<td>153</td>
<td>150</td>
<td>151</td>
<td>145</td>
</tr>
<tr>
<td>Cement [kg/m³]</td>
<td>302</td>
<td>290</td>
<td>277</td>
<td>273</td>
<td>231</td>
</tr>
<tr>
<td>Silica fume [kg/m³]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregate [kg/m³]</td>
<td>1060</td>
<td>1060</td>
<td>1050</td>
<td>1055</td>
<td>1050</td>
</tr>
<tr>
<td>Fine aggregate [kg/m³]</td>
<td>815</td>
<td>820</td>
<td>815</td>
<td>800</td>
<td>795</td>
</tr>
<tr>
<td>A.E.A. [mL/m³]</td>
<td>45</td>
<td>74</td>
<td>93</td>
<td>71</td>
<td>225</td>
</tr>
<tr>
<td>Water reducer [mL/m³]</td>
<td>760</td>
<td>760</td>
<td>755</td>
<td>755</td>
<td>725</td>
</tr>
<tr>
<td>Superplasticizer [mL/m³]</td>
<td>0</td>
<td>625</td>
<td>810</td>
<td>770</td>
<td>1880</td>
</tr>
<tr>
<td>Slump [mm]</td>
<td>100</td>
<td>80</td>
<td>80</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Air content [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fresh</td>
<td>5.3</td>
<td>4.5</td>
<td>5.7</td>
<td>5.5</td>
<td>6.7</td>
</tr>
<tr>
<td>hardened</td>
<td>3.6</td>
<td>5.1</td>
<td>4.8</td>
<td>4.6</td>
<td>6.5</td>
</tr>
<tr>
<td>Spacing factor L [μm]</td>
<td>175</td>
<td>200</td>
<td>150</td>
<td>150</td>
<td>110</td>
</tr>
</tbody>
</table>

### TABLE 4--COMPOSITION AND CHARACTERISTICS OF THE 0.24 W/C CONCRETE

| Water [kg/m³]                      | 141  |
| Cement [kg/m³]                     | 552  |
| Silica fume [kg/m³]                | 35   |
| Fine aggregate [kg/m³]             | 690  |
| Coarse aggregate [kg/m³]           | 1055 |
| Superplasticizer [L/m³]            | 9.9  |
| Slump [mm]                         |      |
| Air content [%]                    | 1.6  |
| Compressive strength [MPa]         |      |
| 1d                                | 71.5 |
| 7d                                | 80.4 |
| 28d                               | 84.6 |

* Non measurable.
### TABLE 5--COMRESSIVE STRENGTH RESULTS OF THE 0.4 AND 0.5 SERIES

<table>
<thead>
<tr>
<th>Water Cement Ratio</th>
<th>W/C = 0.4</th>
<th>W/C = 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica fume Dosage (%)</td>
<td>0 5 7.5 10</td>
<td>0 5 7.5 10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compressive Strength (MPa)</th>
<th>1d</th>
<th>7d</th>
<th>28d</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C = 0.4</td>
<td>19.8</td>
<td>22.8</td>
<td>41.6</td>
</tr>
<tr>
<td>W/C = 0.5</td>
<td>22.4</td>
<td>28.9</td>
<td>46.1</td>
</tr>
</tbody>
</table>

### TABLE 6--AIR PERMEABILITY

<table>
<thead>
<tr>
<th>W/C = 0.40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica fume dosage (%)</td>
</tr>
<tr>
<td>Absorption (%)</td>
</tr>
<tr>
<td>Permeability 10⁻⁸ m/s</td>
</tr>
<tr>
<td>Oven-dried 20 21 19 32 38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>W/C = 0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica fume dosage (%)</td>
</tr>
<tr>
<td>Absorption (%)</td>
</tr>
<tr>
<td>Permeability 10⁻⁸ m/s</td>
</tr>
<tr>
<td>Oven-dried 13 29 34 21 74</td>
</tr>
</tbody>
</table>
Fig. 1--Schematic of water permeability
Fig. 2--Schematic of air permeability cell
**Concrete Permeability**

**Fig. 3**--Rapid K chloride ion permeameter

- **NaCl 3%**
- **Concrete Core Ø 95 mm**
- **NaOH 0.3N**
- **Epoxy Coating**
- **Impervious Membrane**
- **Anode (+)**
- **Cathode (-)**
- **60 volts**
- **100 mm (dia.)**
- **50 mm**
Fig. 4--Different curing of the concrete samples before testing
Fig. 5--Mercury intrusion curves for the 0.4 series
Fig. 6--Mercury intrusion curves for the 0.5 series
Fig. 7--Current intensity as a function of time for the 0.4 series
Fig. 8--Current intensity as a function of time for the 0.5 series
Fig. 9--Chloride ion permeability (in coulombs) as a function of silica fume dosage
Fig. 10--Air permeability as a function of silica fume dosage and type of drying
The Relationship of Polypropylene Fiber Reinforced Concrete to Permeability

By G. Vondran and T. Webster

Synopsis: Concretes with and without polypropylene fibers were tested to determine their relationship to permeability. This paper focuses on one type of fiber, bundles of fibrillated polypropylene, at an addition rate of 1.5 lb/cubic yard (0.9 kg/m³). The bundles open during concrete mixing and separate into millions of multistrand filament fibers. Tests on permeability, cracking, and steel corrosion show reductions in all three when fibrous concretes are compared with conventional concrete at equal water-cement ratios. A new term, "Perm Point" explains the influence of the fibers on permeability. Subsidence cracking over steel reinforcement increases permeability and accelerates corrosion, whereas polypropylene fiber reinforced concrete (PPRC) reduces this phenomenon. Results suggest an inter-relationship exists among permeability, cracking, and steel corrosion.

Keywords: corrosion; cracking (fracturing); fiber reinforced concretes; permeability; polypropylene fibers; reinforcing steels
ACI member Gary Vondran is active on Subcommittees: 201 Durability; 544 Fiber Reinforced Concrete; and 524 Portland Cement Plastering. He holds a patent on a permeability testing device, commonly known as the VonTest Method. Mr. Vondran is Director of Research and Development for Fibermesh Company.

ACI member Ted Webster P.E. is on Subcommittee: 222 Corrosion of Metals in Concrete; and a former member of 224 Cracking and, 301 Specifications for Structural Concrete. Mr. Webster is principal engineer and president of Webster Engineering Associates Inc, in Cleveland, Ohio.

INTRODUCTION

Permeability, cracking, and corrosion are reduced with the addition of fibrillated polypropylene fiber to reinforce concrete. Permeability, cracking and corrosion inter-relate. One propagates the other. Environmental exposures determines the degree to which each has on the other. This paper briefly discusses how fibrillated polypropylene fibers at 0.1% volume influence these three inter-relationships in concrete.

PERMEABILITY TESTING

There are many different permeability tests. Testing for water and air flow through concrete is not common or wide spread, even though permeability greatly influences durability. The concrete industry assumes that: testing compressive strength; requiring proper consolidation and curing; specifying low water-cement ratios; will produce an impermeable or watertight concrete. These typical assumptions do not produce watertight concrete all the time. The lack of a standard permeability test is probably the reason for not having better control of permeability.

Research on permeability led to the development of the VonTest method (1) (2). This test measures the amount of water that permeates through a 2" thickness of concrete. Specimens are standard 6" x 12" cylinders with a preformed hollow core. Figure 1 shows a cross-section of a test specimen. Figure 2 illustrates the same specimen during testing. Water that flows into the center core is measured as the permeability rate of a specific concrete.
also be measured by applying water pressure into the center core. The concrete specimen is made of locally available concrete materials.

Similar permeability tests are performed by the plastics industry. The weight loss of a liquid in a standard container is monitored at 24 hours. A permeability rate or value is assigned to that specific type of plastic used in the container. As an example, this method leads to the conclusion that virgin polypropylene is highly resistant to permeation by liquids, vapors and air (gases).

Alegre, Lechega, and Pervas (3) developed the CALE method. This test employs hollow core cylinders, not only to measure the permeation of liquids, but to determine permeability of: carbon dioxide (gases), sulfates, chloride ions, and the absorptivity of concrete.

The above two approaches measure the rate of flow from the inside to the outside of the container specimen. The data in Figure 3 is based on measurement of the water flow from outside into the center core using the VonTest method. The water permeabilities of plain concrete and 2 quantities of fibrillated polypropylene fibers are presented. All three mixtures are at the same water-cement ratio. The top size aggregate is 3/4 inch (19mm) gravel with a cement factor of 517 lb/cu.yd (395 kg/m3).

PERMEABILITY POINT

Establishing a PERMEABILITY POINT may be the answer to control permeability of local concrete combinations. The "perm point" is that point where no water permeates the concrete using the VonTest method with a given set of materials at 28 days. It is at this "perm point" where concrete is watertight. At higher water-cement ratios beyond the perm point, the concrete is permeable. This is illustrated in Figure 4. The perm point is determined by plotting water-cement ratios versus amount of water ingress at 28 days and extrapolating to zero ingress.

Fibrillated polypropylene fibers may decrease the permeability by making concrete more dimensionally stable. Fibers help to reinforce what is referred to as the "transition zone"(4), the interface between cement paste and aggregate. By reducing permeability of this transition zone, the overall permeability is reduced.
CRACKING

There are many causes of concrete cracking. The Concrete Society of Great Britain in their Technical Report No. 22, classifies them as structural and intrinsic. The intrinsic or non-structured cracks occur because of internal stresses developed when free water evaporates from plastic or hardened concrete. The amount and rate of water gain at the surface and the ambient evaporation conditions determine the potential for cracking in fresh concrete. A typical plastic shrinkage crack is shown in Figure 5. Note that smooth separation of the largest portion of the crack forms at the weakest point between cement paste and aggregate.

PLASTIC SHRINKAGE CRACKING TESTS

A proposed crack potential test method has been developed by Kraai (6). The test employs a perimeter wire mesh restraint of concrete slabs where dry air at high velocity passes over the top surface to force cracking. Within 24 hours the top surface area of the cracks are measured. They are quantified in terms of length and width. Employing this test, the performance of polypropylene fibers shows typically 70 to 100% crack reductions compared with conventional concrete slabs without the fibers. The millions of multistrand filament fibers add an early tensile strain capacity, and reinforce the transition zone. Kraai evaluated over 66 panels. Figure 6 provides the cracking test comparisons and a summary of data. It shows Kraai's testing of concrete, mortar fractions of concrete, stucco, and mortar with 16 different polypropylene fibers. These tests indicate that the fibers reduce plastic shrinkage cracking an average of 86.4%.

By reducing plastic shrinkage cracking and settlement shrinkage cracking over steel reinforcement, polypropylene fiber reinforced concrete maintains a greater integrity, minimizing the area exposed to destructive ingress of water, air, and corrosive agents.

CORROSION MITIGATION

The vast majority of reinforcing steel corrosion in concrete occurs as a result of movement into the hardened concrete of alien chloride ions. Chloride ions concentrate in the pore water in the concrete and once the critical corrosion threshold concentration is reached within a given pore in contact with the rein-
forcing steel the gamma ferric oxide passive layer, which normally protects the reinforcing steel will break down, creating an anodic area on the surface of the steel. Once this has occurred galvanic corrosion can commence using this exposed spot as the anode, the adjacent reinforcing steel as the cathode, and the chloride bearing liquid in the pore water as the electrolyte.

The mechanisms that control the length of time required for the alien chlorides to move from the exterior surface into the pore water in contact with the steel are controlled by: the amount and degree of cracking; the water permeability of the concrete, and the chloride ion diffusion rate. Cady and Weyers related the chloride diffusion coefficient and the compounding effect of subsidence cracking to the time to corrosion initiation of reinforcing steel in bridge deck structures (7). Their paper reviewed earlier related work which indicated that as concrete cover was reduced from 2 inches (51 mm) to 0.75 inches (19 mm) the probability of subsidence cracking increases dramatically. They indicated that the presence of subsidence cracking provided a very rapid means of transferring chloride ions from the concrete surface to the reinforcement.

The term "chloride permeability" is a net quality of concrete that is affected by a number of different factors, including: water-cement ratio, the degree of consolidation, the presence of honeycomb, age of concrete, and the quality of the curing process (8). All these factors interact to create the resultant net permeability. Anything that can improve curing of the concrete, resist plastic shrinkage cracking and/or drying shrinkage cracks, without adversely affecting the placeability and other durability aspects of the concrete, will reduce the net permeability of the concrete system.

Tests comparing the performance of plain concrete specimens to identical specimens containing polypropylene fibers were carried out. The concrete mixture consisted of a 0.47 W/C ratio with 0.75 inch (19mm) limestone. Readings are shown on Figure 7. This data indicates that the inclusion of polypropylene fibers with the relatively thin 0.75 inch (19mm) concrete cover produced a significant reduction in the net chloride ion permeability.
Relative performance of plain and fiber reinforced concrete slabs in a configuration commonly utilized for evaluating the effectiveness of sealers against chloride ion intrusion was also determined (9). In this accelerated test program, one to two weeks delay of corrosion initiation of the reinforcing steel in three slabs with polypropylene fibers as opposed to plain concrete was again recorded. As testing continues, corrosion has initiated in all slabs and the rate of corrosion is being measured periodically utilizing a DC polarization technique (10). It was felt the DC polarization measurements may be used to estimate the relative corrosion rates since the slabs are simple corroding systems with a known amount of reinforcing steel surface.

Comparison between the plain concrete slabs and the slabs with 1.5 pounds per cubic yard (0.9Kg/m3) of .75 inch (19mm) polypropylene fibers is shown in Figure No. 8. The chart is presented as the reciprocal of the polarization resistance \( R(p) \). By using this format the value of \( 1/R(p) \) is proportionate to the rate of corrosion of the system.

CONCLUSIONS

The presence of polypropylene fibers reduces the net chloride permeability of concrete near the surface of the concrete. Fibers mitigate crack formation in the plastic state by arresting subsidence cracking. It is shown that the presence of polypropylene fibers reduces the water permeability. Time to initiate steel corrosion is increased when fibers are added to concrete, and once corrosion has been initiated, corrosion rates are lower in the concrete containing polypropylene fibers.

Thus the syndrome, the cycle of cracking, agents permeating, and steel corroding can be somewhat interrupted or reduced by using polypropylene fibers.
REFERENCES


2) Vondran, G., "Making More Durable Concrete with Polymeric Fibers", Mather International Conference SP-100-23 American Concrete Institute, Detroit, May 1987 pp. 382-383.


9) NCHRP Report 244, "Concrete Sealers for Protection of Bridge Structures".

Fig. 1--Cross section of hollow core cylinder

Fig. 2--Hollow core specimen is placed in 5 gallon pail -- water permeates into center core
WATER PERMEABILITY DATA
Permeated Water in Milliliters

<table>
<thead>
<tr>
<th>Age</th>
<th>Fibers-Lbs per Cubic Yard</th>
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<td></td>
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<td>2 Days</td>
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<tr>
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<td>Total</td>
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<tr>
<td>% Reduction</td>
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</table>

Fig. 3--Typical water permeability tests show reduction with polypropylene fibers

PERMEABILITY POINT

![Graph showing permeability point]

Fig. 4--To achieve watertight concrete with a given set of materials at a certain perm point, a lower w/c ratio is required with plain concrete than with polypropylene fibers
Fig. 5--Cross section of plastic shrinkage cracking magnified seven (7x) times
### Fig. 6--CRACKING TEST COMPARISONS

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Polyprop Fiber *</th>
<th>Fiber Quality</th>
<th>W-C Ratio</th>
<th>Weighted Avg. mm²</th>
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### SUMMARY OF POLYPROPYLENE FIBER CRACK REDUCTIONS

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<th>Description</th>
<th>Form</th>
<th>Depth</th>
<th>Number of Tests</th>
<th>Standard Deviation</th>
<th>Ave. % Crack Reduc.</th>
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Fig. 6--Forty-four (44) cracking test comparisons are summarized — polypropylene fibers reduce plastic shrinkage cracking an average of 86.4 percent.

---

**Fig. 6 (continued)--CRACKING TEST COMPARISONS**

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<tr>
<th>Mix Type</th>
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* Metric - Same 0.7%(C) = Percent of Cement Weight
  1.6 pounds per cubic yard = 0.95 Kg/m³
  1.5 pounds per cubic yard = 0.89 Kg/m³
  0.75 pounds per cubic yard = 0.45 Kg/m³
**Concrete Permeability**

**CORROSION INITIATION DELAY**

DAYS TO INITIATE CORROSION

Fig. 7--Evaluations using 2 different fiber volumes illustrate a delay in the initiation of corrosion.

**RATE OF STEEL CORROSION**

1/R(p) micro mho/(cm)$^2$

Fig. 8--Rate of steel corrosion is reduced about 25 percent with PFRC at relatively early ages.
Permeability as a Measure of Potential Durability of Concrete—Development of a Suitable Test Apparatus

by K. Schonlin and H. K. Hilsdorf

Synopsis: For the determination of the permeability on concrete discs a rapid test method has been developed. No special devices are required to fix the test apparatus to the specimen. Air permeability of the concrete can be measured within a period of about 15 minutes. Laboratory experiments show a close correlation between the measured permeability coefficient and the duration of curing, type of cement, w/c ratio and the content of fly ash.

Keywords: air; concrete durability; concretes; measuring instruments; permeability; test equipment; tests
Insufficient durability of concrete structures has become a serious problem in many parts of the world.

A number of deleterious processes in concrete are related to the pore structure and in particular to the diffusion characteristics and the permeability of the concrete. Therefore it is important to obtain information on such properties of a particular concrete within a short period of time.

Since the determination of diffusion coefficients of aggressive media in concrete is difficult and time consuming, it appeared to be advantageous to determine the air permeability of concrete as an auxiliary parameter.

A number of test apparatus are described in the literature, with which permeability of concrete under an external pressure can be determined [1, 2, 3, 4, 5]. None of them is suitable for short-term tests.

Description of the Test Apparatus

The Test apparatus described in the following allows the rapid determination of the air permeability of a concrete disc.

Figure 1 shows the permeability test apparatus. A bell-shaped vacuum chamber is placed on a rubber ring which encloses a concrete disc. The space inside the vacuum chamber is evacuated with a vacuum pump. After closing the stop cock between the vacuum chamber and the pump the gradual pressure increase inside the chamber is measured by means of a digital air pressure gage. A pressure increase is possible only if air penetrates through the specimen into the vacuum chamber. Therefore, the pressure will increase the faster the more permeable the concrete.

An airtight connection between the rubber ring and the concrete disc is reached by casting the fresh concrete directly into the rubber ring. After hardening and curing of the concrete the
Concrete Permeability

A disc is stored in a specified constant environment up to the time of testing.

Due to its elasticity the rubber ring adheres to the concrete despite of shrinkage of the concrete when drying. Figure 2 shows the individual elements of the test apparatus.

Test procedure

The following test procedure proved to be most suitable:

1. Evacuation of the vacuum chamber for 5 minutes. (The pressure will stabilize between 1 and 10 mbar)

2. Close the stop cock

3. Read initial time \( t_0 \) at a pressure \( p_0 = 20 \) mbar.

4. Read time \( t_1 \) at a pressure \( p_1 = 50 \) mbar.
   or
   Read pressure \( p_1 \) at time \( t_1 = t_0 + 120 \) sec.

5. Repeat the steps 1 through 4 until the rate of pressure increase is constant.

The time until a constant rate of flow has been reached depends on the permeability of the concrete. For the specimens tested so far, it takes between 3 and approx. 30 minutes.

Due to the vacuum and the air-tight connection between the rubber ring and the concrete disc no special devices are required to fix the test apparatus to the specimen.

Therefore, only a comparatively short period of time i.e. in most instances less than 15 minutes is required to perform a test.

An apparent limitation of this experimental approach is that the maximum pressure for which air permeability can be measured is 1 bar. Furthermore, the measured air permeability depends on the moisture state of the concrete. Therefore, to characterize a concrete on the basis of its air permeability, both specimen dimensions and environmental conditions to which the specimen has been exposed prior to testing have to be specified. A similar method has been developed to measure the permeability of a concrete surface layer [6].
Evaluation of test results

The volume of a constant gas flow through porous media can be calculated as follows [6]:

\[ \frac{p}{v} = K \frac{A}{p_a - p_e} \]

or

\[ K = \frac{p}{v} \frac{L}{A} \frac{1}{p_a - p_e} \]  

(1)

where

- \( K \) = permeability coefficient \([\text{m}^2/\text{sec}]\)
- \( V \) = volume of gas, which flows through the porous medium during time \( t \) and at a pressure \( p \)
- \( L \) = thickness of the specimen \([\text{m}]\)
- \( A \) = cross-section of the specimen \([\text{m}^2]\)

Knowing the air volume \( V_s \) inside the vacuum chamber, the permeability coefficient can be calculated on the basis of Boyle-Marriottte's law (see appendix):

\[ K = \frac{(p_1 - p_0) \frac{V_s}{L}}{(t_1 - t_0) \frac{p_a}{p_a + \frac{p_1 + p_0}{2}}} \]  

(II)

where:

- \( K \) = permeability coefficient \([\text{m}^2/\text{sec}]\)
- \( p_1, p_0 \) = pressure inside the vacuum chamber at the end and at the beginning, respectively, of the measurement \([\text{mbar}]\)
- \( p_a \) = atmospheric pressure \([\text{mbar}]\)
- \( t_1 - t_0 \) = duration of measurement \([\text{sec}]\)
- \( V_s \) = volume of vacuum chamber \([\text{m}^3]\)
- \( L \) = thickness of specimen \([\text{m}]\)
- \( A \) = cross-section of specimen \([\text{m}^2]\)

Note that the permeability coefficient \( K \) calculated according to equation (I) and (II) resp., does not follow the often applied Hagen-Poiseuille's law, which is valid only for laminar flow. For concrete with its small pores and especially at low pressures mixed modes of laminar and molecular flow (Knudsen-flow) occur [8] (see appendix).

Experimental Program

In an experimental program the permeability coefficient \( K \) was determined for different types of concrete which were exposed to different curing conditions.
The parameters studied were the duration of curing, type of cement, w/c ratio, amount of fly ash and air content.

Concrete Composition and Curing

The composition of the various types of concrete investigated are shown in Table 1.

Ordinary portland cement PZ 35 F (Type I) and a portland blast furnace slag cement (PBFS-cement) with a slag content of 65 percent were used. For the concretes containing fly ash, ratios w/c+FA were chosen such that the consistency of the fresh concrete was identical with the consistency of comparable mixes containing only portland cement.

Natural sand and gravel from the river Rhine, maximum size 32 mm, were used as aggregates.

After mixing the fresh concrete was cast into rubber rings having a diameter of 150 mm and a height of 40 mm. The rubber ring was fixed on a base plate and enclosed by a metal ring.

The concrete specimens were compacted on a vibrating table. Then the specimens were covered with wet burlap and plastic sheets and stored in a constant environment at a temperature of 20°C (+1°C). One, three, resp. seven days after casting of the concrete the cylindrical specimens were taken from the base plate, and then stored in a constant environment chamber at 20°C, 65% r.h. until the time of testing at a concrete age of 56 days. The rubber ring prevented moisture evaporation so that the specimens could dry in one direction only.

EXPERIMENTAL RESULTS AND DISCUSSION

The permeability coefficient K for various types of concrete is shown in Table 2 for different durations of curing. Each value represents an average of 4 individual measurements.

In Figures 4 through 8 the permeability coefficient K is shown on a logarithmic scale as a function of the duration of curing. For each data point also the range of standard deviation is given.

w/c Ratio

An increase of w/c ratio always results in an increase of the permeability coefficient for the same duration of curing (Fig. 3 and 4).
Type of Cement

From Table 2 and Fig. 5 it follows that for a given w/c ratio and short durations of curing, the concretes made of PBFS-cement always have a significantly higher permeability coefficient than those made of portland cement. However, if the duration of curing is sufficiently long, both concretes reach nearly the same permeability coefficients.

Addition of Fly Ash

Concretes containing fly ash need a longer curing period to reach the same permeability coefficient than those made without fly ash (Table 2 and Fig. 6). If curing is extended sufficiently long the effect of fly ash on the permeability coefficient is negligible.

Air-Entrainment

From Table 2 and Fig. 7 it follows that the use of air-entraining agents has no significant influence on the permeability coefficient compared to concrete without entrained air.

Duration of curing

It can be seen from Table 2 and Figs. 3 through 7 that the permeability coefficient always decreases with increasing duration of curing.

For most concretes the rate of decrease of the permeability coefficient decreases with increasing duration of curing. For some concretes especially for those with higher w/c ratios the duration of curing investigated appears to be too short to reach a limiting value of the permeability coefficient.

Further Observations

- Although the maximum aggregate size corresponds to the thickness of the specimens values of K determined on different specimens of identical composition and exposed to the same environmental conditions have only a mean coefficient of variation of 25 percent (see also Figs. 3 through 7). For permeability measurements these are small deviations considering the fact that the permeability coefficients of different concretes range over several orders of magnitude.

- Preliminary tests showed, that the moisture state of the specimens and thus the permeability coefficient is significantly influenced by the height of the specimen and the environmental conditions prior to testing. Therefore it is very important that all measurements are carried out on specimens
of the same height and that the environmental conditions are kept constant.

CONCLUSIONS

- A test apparatus was developed which allows the rapid determination of air permeability of concrete discs.

- No special devices are required to fix the test apparatus to the specimen and therefore one measurement takes only between 3 and a maximum of 30 minutes depending on the permeability of the specimen.

- Experiments carried out with different concretes showed, that the test method confirms the well known behaviour of concrete relative to duration of curing, type of cement, w/c ratio and content of fly ash.

- Tests are under way to correlate the measured permeabilities with corrosion resistances such as carbonation, freeze-thaw resistance and chloride penetration.

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TABLE 1--CONCRETE COMPOSITION
(1) SLAG CONTENT = 65 PERCENT
(2) AIR ENTRAINING AGENT, AIR CONTENT 5 PERCENT

<table>
<thead>
<tr>
<th>Series</th>
<th>type of cement</th>
<th>cement content [kg/m³]</th>
<th>fly ash content [kg/m³]</th>
<th>water content [kg/m³]</th>
<th>w/c+FA</th>
<th>aggregate content [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>PC(Type I)</td>
<td>360</td>
<td>-</td>
<td>162.0</td>
<td>0.45</td>
<td>1878</td>
</tr>
<tr>
<td>B</td>
<td>PC(Type I)</td>
<td>300</td>
<td>-</td>
<td>180.0</td>
<td>0.60</td>
<td>1878</td>
</tr>
<tr>
<td>C</td>
<td>PC(Type I)</td>
<td>270</td>
<td>-</td>
<td>189.0</td>
<td>0.70</td>
<td>1878</td>
</tr>
<tr>
<td>D</td>
<td>PBFSC (1)</td>
<td>360</td>
<td>-</td>
<td>162.0</td>
<td>0.45</td>
<td>1870</td>
</tr>
<tr>
<td>E</td>
<td>PBFSC (1)</td>
<td>300</td>
<td>-</td>
<td>180.0</td>
<td>0.60</td>
<td>1870</td>
</tr>
<tr>
<td>F</td>
<td>PC(Type I)</td>
<td>290 70</td>
<td>151.2</td>
<td></td>
<td>0.42</td>
<td>1889</td>
</tr>
<tr>
<td>G</td>
<td>PC(Type I)</td>
<td>240 60</td>
<td>165.0</td>
<td></td>
<td>0.55</td>
<td>1904</td>
</tr>
<tr>
<td>H</td>
<td>PC(Type I)</td>
<td>360</td>
<td>-</td>
<td>162.0</td>
<td>0.45(2)</td>
<td>1785</td>
</tr>
</tbody>
</table>

TABLE 2--PERMEABILITY COEFFICIENTS Kx10^10 [m²/sec] OF VARIOUS CONCRETES

<table>
<thead>
<tr>
<th>Series</th>
<th>Duration of curing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>A</td>
<td>556.0</td>
</tr>
<tr>
<td>B</td>
<td>3300.0</td>
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<tr>
<td>C</td>
<td>9606.2</td>
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<td>D</td>
<td>2676.1</td>
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<tr>
<td>E</td>
<td>63514.6</td>
</tr>
<tr>
<td>F</td>
<td>746.2</td>
</tr>
<tr>
<td>G</td>
<td>6439.9</td>
</tr>
<tr>
<td>H</td>
<td>537.0</td>
</tr>
</tbody>
</table>
Fig. 1--Test setup for the determination of the air permeability of concrete

Fig. 2--Individual elements of the permeability test apparatus
Fig. 3--Influence of w/c ratio on the permeability of concrete

Fig. 4--Influence of w/c ratio on the permeability of concrete
Fig. 5--Influence of type of cement on the permeability of concrete

Fig. 6--Influence of fly ash on the permeability of concrete
Fig. 7--Influence of air entrainment on the permeability of concrete
APPENDIX

The volume of gas passing through a porous medium at a constant rate can be calculated as follows [7]

\[
\frac{p \cdot V}{t} = K \cdot \frac{A}{L} \cdot \frac{p_c - p_e}{t}
\]  

(1)

or

\[
K = \frac{p \cdot V}{t} \cdot \frac{L}{A} \cdot \frac{1}{p_c - p_e}
\]  

(1a)

where 

- \( K \) = permeability coefficient \([m^2/sec]\)
- \( V \) = gas volume \([m^3]\), which flows through the porous medium during time \( t \) and at a pressure \( p \)
- \( L \) = thickness of the specimen \([m]\)
- \( A \) = cross-section of the specimen \([m^2]\)
- \( p_c - p_e \) = pressure difference between top and bottom of the specimen \([mbar]\)
- \( t \) = duration of test \([sec]\)

Eq. (1) is of general validity and does not depend on a special transport mechanism.

The transport mechanism of a gas through a porous media depends on the Knudsen number \( Kn \) [7, 8]:

\[
Kn = \frac{\lambda}{r}
\]

with

- \( \lambda \) = free path of the gas molecules
- \( r \) = capillary radius

For \( Kn \ll 1 \) stratified flow prevails which can be laminar or turbulent depending on the Reynolds-number. For laminar flow, the permeability coefficient \( K \) acc. to eq. (1a) can be calculated from the Hagen-Poiseuille-law:

\[
K = \frac{\mu \cdot V}{\eta \cdot \frac{L}{A} \cdot \frac{1}{p_c - p_e}} = \frac{r^2}{8 \eta} \bar{p}
\]  

(2)

with

- \( \eta \) = viscosity of the gas
- \( \bar{p} = \frac{p_c - p_e}{2} \) = mean pressure in the capillary

1) stratified flow means that the impulses between the gas molecules are more significant than their interactions with the surfaces.
Therefore if the transport mechanism is laminar, the permeability coefficient measured at different pressures has to be a linear function of the mean pressure in the capillary. Consequently many authors express the permeability coefficient as:

\[
K \ [\text{m/sec}] = \frac{p \cdot V}{t} \cdot \frac{L}{A} \cdot \frac{1}{p_c - p_e} \cdot \bar{p} \tag{2a}
\]

or

\[
K \ [\text{m}^2] = \frac{p \cdot V}{t} \cdot \frac{L}{A} \cdot \frac{n}{p_c - p_e} \cdot \bar{p} \tag{2b}
\]

For \( Kn \gg 1 \) molecular flow occurs (also Knudsen Flow) which can be calculated from eq. (1a) as follows:

\[
K = \frac{p \cdot V}{t} \cdot \frac{L}{A} \cdot \frac{1}{p_c - p_e} = 16 \cdot \frac{r}{3} \cdot \sqrt{\frac{2 \cdot R \cdot T}{\pi \cdot M}}
\tag{3}
\]

with \( R = \) gas constant

\( T = \) temperature

\( M = \) molecular weight of the gas

Here, the permeability coefficient is independent of the mean pressure in the capillary.

For concrete with its small pores and especially under low pressures (where the free path of the gas molecules is relatively high) a mixture of laminar and molecular flow occurs. Therefore, the test procedure described in this paper has to be evaluated in a general form according to eq. (1a). Since the relation between the permeability coefficient and the mean pressure in the capillary is not known, it is important to determine the pressure increase always in the same pressure range (see section "test procedure").

In equation (1a) the gas volume \( V \) which flows through the specimen is unknown. Since \( V \) or the rate of flow of the gas respectively, are not measured in the test, \( V \) has to be calculated from the pressure increase inside the vacuum chamber. From Boyle-Marriott's law it follows:

\[
p \cdot V = n \cdot R \cdot T \tag{4}
\]

with \( n = \) number of molecules
According to eq. (4) the gas molecules penetrating the concrete specimen occupy a volume $V_a$ at atmospheric pressure $p_a$:

$$V_a = \frac{n \cdot R \cdot T_a}{p_a}$$  \hspace{1cm} (5)

The number of air molecules $n$ can be evaluated from the difference in the number of air molecules in the vacuum chamber at the beginning and at the end of the experiment.

At the beginning of the experiment the following relation holds:

$$p_0 \cdot V_s = n_0 \cdot R \cdot T_0$$

and

$$n_0 = \frac{p_0 \cdot V_s}{R \cdot T_0}$$  \hspace{1cm} (6)

with $V_s =$ Volume of the vacuum chamber.

At the end of the experiment:

$$p_1 \cdot V_s = n_1 \cdot R \cdot T_1$$

and

$$n_1 = \frac{p_1 \cdot V_s}{R \cdot T_1}$$  \hspace{1cm} (7)

From equation (6) and (7) we obtain

$$n = n_1 - n_0 = \left(\frac{p_1}{T_1} - \frac{p_0}{T_0}\right) \cdot \frac{V_s}{R}$$  \hspace{1cm} (8)

Substituting eq. (8) in eq. (5) results in

$$V_a = \frac{(\frac{p_1}{T_1} - \frac{p_0}{T_0}) \cdot V_s \cdot T_a}{p_a}$$  \hspace{1cm} (9)

From eq. (9) in eq. (1a) we obtain:

$$K = \frac{p \cdot (\frac{p_1}{T_1} - \frac{p_0}{T_0}) \cdot V_s \cdot T_a}{(t_1-t_0) \cdot p_a \cdot (p_c-p_e) \cdot \frac{L}{A}}$$  \hspace{1cm} (10)
In eq. (10), p is the pressure at which V is determined. According to eq. (5), V is related to the atmospheric pressure $p_a$. Therefore:

$$p = p_a \quad (11a)$$

The pressure $p_c$ at one end of the specimen equals $p_a$:

$$p_c = p_a \quad (11b)$$

Since the temperature $T$ is constant during one measurement:

$$T_1 = T_0 = T_a \quad (11c)$$

The pressure $p_e$ is the pressure inside the vacuum chamber. This pressure is not constant during an experiment. However it is sufficiently accurate to estimate $p_c$ from the mean pressure:

$$p_c = \frac{p_1 + p_0}{2} \quad (11d)$$

Substituting eqs. (11a), (11b), (11c) and (11d) in eq. (10) results in

$$K = \frac{(p_1 - p_0) \cdot V_s}{(t_1 - t_0) \cdot (p_a - \frac{p_1 + p_0}{2})} \cdot \frac{L}{A} \quad (12)$$

where:
- $K$ = permeability coefficient [m$^2$/sec]
- $p_1, p_0$ = pressure inside the vacuum chamber at the end, resp. at the beginning of a measurement [mbar]
- $p_a$ = atmospheric pressure [mbar]
- $t_1 - t_0$ = duration of test [sec]
- $L$ = thickness of the specimen [m]
- $A$ = cross-section of the specimen [m$^2$]

The parameters which are necessary to evaluate the permeability coefficient $K$ from eq. (12) are either known or to be determined in the experiment.
Laboratory Experience with the Rapid Chloride Permeability Test
by B. Mobasher and T.M. Mitchell

Synopsis: The new rapid chloride permeability test, in which chloride ions are driven into concrete samples electrically over a 6-hour period, is becoming widely used and has been accepted as an American Association of State and Highway Transportation Officials (AASHTO) standard, T277. This paper summarizes the results of an extensive series of laboratory tests with the new method.

Results of an interlaboratory test program provide single operator and multilaboratory coefficients of variation suitable for use in a precision statement in the standard versions of the method. Several possible revisions to the AASHTO standard procedure are examined, but further study is necessary before any can be accepted. Test results on specimens with diameters other than the standard 3.75 in. (95 mm) called for in T277 are found to be easily adjustable to allow comparisons with standard size specimens. Several fundamental properties of concrete, namely water-cement ratio, coarse aggregate type and gradation, and air content, are shown to affect chloride permeability.

Keywords: aggregate gradation; air entrainment; chlorides; coarse aggregates; concretes; permeability; tests; water-cement ratio
ACI member Barzin Mobasher is a graduate student in the Department of Civil Engineering at Northwestern University, Evanston, Illinois. His current research is on the ductility of glass fiber reinforced concrete. He did the work presented here while a Graduate Research Fellow at the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center, McLean, Virginia.

ACI member Terry Mitchell is a research materials engineer in the Office of Engineering and Highway Operations Research and Development at the Turner-Fairbank Center. Dr. Mitchell has been with FHWA for 16 years and has been active in developing quality control tests for materials and construction and in improving quality assurance specifications.

INTRODUCTION

Concrete's ability to delay the initiation of corrosion of its reinforcing steel depends on the concrete's impermeability to chloride ions introduced in deicing salts. Until recently, highway departments and concrete producers have had to rely on ponding tests to assess chloride permeability. Typically in tests such as AASHTO standard test T259 (Ref. 1), small concrete slabs are ponded with 3 percent sodium chloride solution for 90 days; samples are then removed from the slabs and pulverized, and the chloride contents of various depth increments are established by laboratory titration procedures.

In 1983, a new AASHTO standard, T277, was adopted, in which chloride ions are driven into concrete samples electrically over a 6-hour period. The total electrical charge passed during that period has been shown (2) to correlate well with the chloride ion profiles found in various concretes after the 90 day ponding test. Because of its speed and good within-laboratory repeatability, the new test has become widely used by State highway agencies and by manufacturers of specialized concretes. Acceptance of the procedure as an American Society for Testing and Materials (ASTM) standard is also being sought currently.

The present paper summarizes the results of an extensive series of tests with the new method. The goals of the studies included development of: (1) a proposed precision statement for the method; (2) conclusions about the importance of several factors in the method such as variations in the sample conditioning procedure; and (3) conclusions about the effect of materials and construction variables such as coarse aggregate type and gradation and air content on the chloride permeability of concretes.
EXPERIMENTS

Test Procedures

Except where test parameters were intentionally varied, all chloride permeability tests were conducted according to AASHTO T277, "Rapid Determination of the Chloride Permeability of Concrete."(1) In this procedure 3.75 in. diameter by 2 in. long (95 mm diameter by 51 mm) slices of cores or cast cylinders are the test specimens. The curved side of a specimen is first coated with an epoxy sealant. The specimen is then brought to a standard moisture condition by the following vacuum saturation procedure: Vacuum is applied to the dry specimen for 3 hours and then continued for 1 more hour with the specimen immersed in deaerated water; after that, the specimen is soaked in the same water for an additional 18 ± 1 hours at atmospheric pressure. The ends of the specimen are then sealed into hollow, polymethylmethacrylate, e.g., Plexiglas, chambers (Figure 1). The chamber containing the top of the sample is filled with a 3 percent sodium chloride solution, the chamber containing the bottom with a 0.3N sodium hydroxide solution. Sixty volts DC is applied across the specimen between copper screen electrodes contained in each chamber. The total charge passed, i.e., the integral of the current with respect to time, during a 6 hour period is a measure of the chloride permeability of the concrete.

Materials and Concrete Mixture Designs

The mix proportions and the fresh concrete properties are shown in Table 1. A Type I cement was used in all mixes. Except for mixes L through P, the coarse aggregate was a 19.0 mm (3/4 in.) maximum crushed limestone from Riverton, Virginia. Mixes L and M, part of the study of the effects of different aggregates, employed a crushed granite from Occoquan, Virginia, and a river gravel from Brandywine, Maryland, respectively. Mixes N, O, and P used Riverton limestone as the coarse aggregate but the gradations met the requirements for ASTM sizes 5, 6, and 7, respectively. The fine aggregate was a natural sand from White Marsh, Maryland. Air-entraining agent, Darex AEA, was added to all mixes except the latex-modified concretes. Styrene butadiene latex modifiers were obtained from two different sources. Concretes were mixed in 1 1/2 ft³ (0.042 m³) batches in a pan-type mixer.

Three types of specimens were cast (and mechanically vibrated): slabs 14 x 14 x 4 in. (350 x 350 x 100 mm), cylinders 3.75 in. diameter x 13 in. high(95 mm dia. x 330 mm), and beams 3 x 4 x 16 in. (75 x 100 x 410 mm). Only the slabs and cylinders were used for the tests reported here. All of the portland cement concrete samples were cured under wet burlap for 24 hours, then demolded and stored in a fog room 73 ± 5 OF (23 ± 3 OC). Three cylinders 3.75 in. diameter x 4 in. high (95 mm dia. x 100 mm) were removed from each slab after 14 days in the fog room. All of the cylinders and slab were then returned to the fog room until test
time. The latex-modified concrete samples received the same initial 24-hour cure under wet burlap, but were then demolded and air-cured until test time.

RESULTS AND DISCUSSION

Development of Precision Statement

The approach for precision statement development was an interlaboratory test program following ASTM C802, "Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods for Construction Materials" (3). Full details of the sampling and testing program and the statistical analysis are given elsewhere (4) but are summarized briefly here.

The testing was performed by 11 State, Federal, and private laboratories on specimens from mixes A through D. After 28 days of curing, several of the 3.75 in. diameter x 13 in. long (95 mm diameter x 330 mm) cylinders of each mixture were sawed into 2 in. (51 mm) long specimens. The specimens were then distributed among the laboratories. Each laboratory received three randomly selected, replicate specimens of each of the four concrete mixes. They were instructed to follow the updated version of AASHTO T277 being proposed for ASTM adoption at the time; the updated version does not differ significantly from the AASHTO standard. Laboratories were also asked to conduct their tests within a specific 2-week time period so they would all be testing specimens of essentially the same age.

Table 2 and Figure 2 show the results of the interlaboratory tests. Twelve laboratories had originally agreed to participate in the study, but one, laboratory #7, was forced to withdraw just prior to starting the test program due to an equipment failure. The laboratory numbering system was not changed subsequently, so both Table 2 and Figure 2 lack results for laboratory #7. Table 2 shows the numerical results, the total charge passed in coulombs during the 6 hour test for each replicate specimen, along with the mean, variance, and standard deviation for each group of three replicates. Figure 2 is a plot of the individual laboratory averages. The plots of the averages are very similar for the 11 participating laboratories, thus leading to the conclusion there are no interactions between laboratories and materials.

Examination and rigorous statistical analysis of the data in Table 2 led to exclusion of two data sets from the precision statement development: (1) All of the mixture B results were excluded when the specimens were found statistically to be nonuniform, that is, the permeabilities of specimens from the tops of the cylinders were found to differ significantly from those from the bottoms (possible explanations include coarse aggregate settlement, bleeding, and preferential consolidation). And (2) the concrete C, laboratory 2 data was discarded on
statistical grounds as being too variable, i.e., much more variable than results from any of the other laboratories on the same concrete.

With the outlier data removed, the averages and the within- and between-laboratory standard deviations and coefficients of variation were calculated and are shown in Table 3. The concrete B data is shown for comparison purposes, but it was not used for the precision statement development.

Examining the within- and between-laboratory data for concretes A, C, and D suggested there may be a linear relationship between the standard deviations and the average coulomb values. However, the within- and between-laboratory coefficients of variation each varied only over a 6 percent range, so assuming a constant coefficient of variation and using it in the precision statement appeared to be more appropriate. A conservative approach was warranted, so the largest of three values for each of the two coefficients of variation was used in developing the precision statements.

The proposed precision statements themselves are based on guidelines presented in ASTM C670, "Preparing Precision Statements for Test Methods for Construction Materials" (3), and use the data summarized in Table 3. The recommended statements and associated footnotes, which have been incorporated into the version of the method being considered by ASTM, are:

Single-operator precision: The single operator coefficient of variation of a single test result has been found to be 12.3 percent. Therefore the results of two properly conducted tests by the same operator on the same material should not differ by more than 35 percent.

Multilaboratory precision: The multilaboratory coefficient of variation of a single test result has been found to be 18.0 percent. Therefore results of two properly conducted tests in different laboratories on the same material should not differ by more than 51 percent. The averages of three test results in two different laboratories should not differ by more than 29 percent.

(a) These numbers represent, respectively, the (1S%) and (D2S%) limits as described in ASTM Standard Practice C670.

(b) The test method does not require the reporting of more than one test result. The precision statement for the averages of three results is given since laboratories frequently will run multiple samples. The number represents the (D2S%) limit divided by the square root of 3.
The values stated for the precision are somewhat higher than were expected by the authors based on previous laboratory experience; the most likely causes are variability in the samples themselves and deviations from the test schedule and the test procedure by the participants. Specimens from individual mixes varied somewhat in weight and length and, as noted particularly with mix B, may not have been homogeneous across the cast cylinders. Test forms returned by the laboratories indicated some specimens were not tested during the time period designated and some were conditioned (vacuum saturated) differently than called for in the standard procedure. The test procedure is new and several of the participating laboratories had had very limited experience with it. The precision statements proposed here do represent the state-of-the-practice in laboratories currently.

Effect of Variations in the Test Method on Its Results

As is often the case after starting to use a new test method, laboratories have begun to seek more economical and more efficient ways of running the rapid chloride permeability test. Users have sought easy to both minimize the initial cost of the test equipment and reduce the time and labor involved in carrying out the test. These efforts result in suggested changes in the equipment and in the test procedure itself. In addition, during the initial use of a test, screening or "ruggedness" tests are desirable; these are procedures in which test parameters are intentionally varied to establish which are most critical and need to be controlled most closely during the day-to-day running of the test.

Four variables were examined during this part of the study: (1) length of the soaking period for specimens during the saturation process; (2) vacuum level during the same process; (3) screen material in the applied voltage cell; and (4) specimen diameter. The length of the soaking period is of interest because the current 18 ± 1 hour requirement in AASHTO T277 bars laboratories from conditioning samples on Friday for testing on Monday and, if the laboratory has only a single set of test apparatus, effectively bars the laboratory from conditioning more than one sample at a time. Relaxing the vacuum requirement, currently set at a maximum of 1 mm Hg, would allow a laboratory to use less expensive vacuum pumps for the vacuum saturation phase. The current copper screen electrodes accumulate corrosion products and, when very high permeability concretes are being studied, often disintegrate after a few tests; perforated stainless steel sheet is being used by at least one laboratory as a durable alternative. Finally, laboratories frequently receive concrete cores 2 or 3 in. (50 or 75 mm) in diameter for chloride permeability tests, while AASHTO T277 calls only for 3.75 in. (95 mm) diameter specimens. Establishing the relationship between chloride permeability tests on the small diameter cores and those on the standard size cores would give laboratories a means for interpreting small diameter specimen data.
The conditioning process in the standard procedure requires the sample to be maintained in an evacuated (< 1 mm Hg) chamber for 3 hours. Deaerated water is then introduced until the specimen is completely submerged, and the vacuum is maintained for an additional 1 hour. Finally the vacuum pump is turned off and the specimen is maintained under water at atmospheric pressure for an additional 18 ± 1 hours.

The goal in the first of the four experiments in this portion of the study was to examine the effect of an additional 48 hours of soaking. Specimens were selected from four mixes, three latex-modified concretes (mixtures C, D, and E) and one conventional concrete (F). One to three specimens of each mixture were tested after the standard soaking period and another two were tested after 48 to 56 hours of additional soaking. Table 4 shows the results of the rapid permeability test on each specimen along with the soaking period and the percent weight gain of the specimens during the saturation process. The table shows the preconditioning of two of the standard specimens deviated from the AASHTO T277 standard conditioning procedure, but these variations appear to have had little impact on the results when replicates are compared.

The results show that three of the four mixtures, C, D, and F, were not affected by the extended soaking period, but the, other, mixture E, showed significantly higher permeabilities after the extended soaking as compared to after the standard soaking. Concrete E differed from the two other latex-modified concretes in having a much higher air content. Later in this paper air content will be shown to significantly affect the chloride permeability of conventional concretes, but Kuhlman and Poon (5) have reported that air content does not significantly affect the chloride permeability of latex-modified concretes over the range of air contents from 3.0 to 16.0 percent. No reason is readily apparent for mixture E's increase in permeability unless the extended soaking produced some deterioration of the latex-cement component.

Previously unreported data accumulated by the second author were similar to those reported here. When high permeability conventional concretes were tested with the T277 standard soak times versus with an additional 72 hours of soaking, the former passed an average of 6817 coulombs (5 specimens) while the latter passed 6998 coulombs (3 specimens), not significantly different. A moderate permeability latex-modified concrete passed 3223 coulombs (5 specimens) with standard soaking versus 3579 coulombs (3 specimens) after the extra 72 hours. The data indicated some apparent increase in permeability with extended soaking of this concrete, although the 11 percent difference is not statistically significant with this number of specimens.

The conclusion from this series of tests was that soaking 48 or more hours beyond the current standard of 18 hours apparently
does affect the test results on some concretes. Therefore no revision of the soaking period is warranted at present. A possible alternative, still needing investigation, would be to remove the sample from the water after 18 hours and maintain it in a sealed container or humidifier for (up to) 48 or 72 hours before testing.

The other variable examined in the preconditioning procedure was the vacuum level. If the vacuum requirement, currently a maximum of 1 mm Hg, can be relaxed, testing laboratories might be able to use less-expensive vacuum pumps. Unfortunately the vacuum experiment in this series included only a single higher vacuum level, between 1 and 2 mm Hg, and a single, high permeability concrete. Specimens from mixture F were used and the results are shown in Table 5. Under the standard procedure, the vacuum pump produced about a 0.2 mm vacuum before the water was introduced, about 0.8 mm after, on three replicates. When a stopcock was maintained slightly open to allow some air to enter, the pump produced 1.1 mm Hg before the water was introduced, 1.7 mm after. Not surprisingly, the table shows the chloride permeability test results do not differ significantly at the two vacuum levels. Additional testing is needed, at other vacuum levels and on low to moderate permeability concretes as well as the high one tested here, before the vacuum requirement in the test procedure is relaxed.

Another possible way to reduce test costs is to use more durable electrodes in the test cells. The No. 20 copper mesh called for in the standard procedure accumulates corrosion products and often disintegrates after a few tests on very high permeability concretes. Researchers elsewhere have substituted 1/16 in. (1.6 mm) thick, i.e., 16 gauge, stainless steel sheet perforated with a staggered pattern of 1/8 in. (3.2 mm) holes on 3/16 in. (4.8 mm) centers, as shown in Figure 3. The perforated sheet has about 40 percent open area. With conductive liquids surrounding each electrode, the electric fields around the copper screen and the stainless steel sheet should look very similar and the test results were not expected to differ significantly.

Two replicate samples of each of five different mixtures, latex-modified concretes C, D, and E, and conventional concretes G and H, were tested in this portion of the study. One of the two replicates was tested with the copper screens, the other with the stainless steel electrodes. The results are shown in Table 6. Data available from copper screen tests developed during the study of other variables is included in this table (mixes C and E).

Using the proposed within-laboratory precision statements from earlier in this paper as the criterion (two tests in one laboratory should not differ by more than 35 percent), the results on mixtures C and H differ significantly. However, with mixture C the copper screen gives the higher value; with mixture H, it gives the lower value. The results on the other three
mixtures are no more conclusive. Additional work is needed before a definite conclusion can be reached about the electrode material. Multiple replicates of at least two concretes need to be tested with each electrode type. The changeover to a more durable electrode is highly desirable.

The last variation in the test procedure that was examined was specimen diameter. Specimens were removed from slabs of mixtures I and J by 1.75, 3, and 3.75 in. (45, 75, and 95 mm) inside diameter core drills and then tested by the AASHTO procedure. Table 7 lists the specimens tested, the average permeability values, and other data. The surface area in contact with the electrolyte solutions decreases as the sample diameter decreases and, as the table shows, the total charge passed decreases also.

Figure 4 is a plot of the total charge passed versus the cross-sectional area of the specimens. The figure shows it is reasonable to assume a linear relationship exists between the two quantities and shows the lines resulting when a linear regression program was applied to the data for each of the two concretes. Since the electrical resistance between two ends of a cylinder varies inversely as its cross-sectional area and the current flowing through the cylinder varies directly as the area, the linear relationship in the figure is not surprising. Further, the linear relationship and the fact that the x- and y-intercepts of the lines are near the origin suggests the best relationship to use to convert the coulomb reading on a nonstandard specimen to that on a standard 3.75 in. (95 mm) diameter specimen is just to multiply by the ratio of the areas. That is,

\[ Q_s = Q_x \cdot \left( \frac{3.75}{x} \right)^2 \]

where \( Q_s \) = charge passed (coulombs) through 3.75 in. (95 mm) diameter specimen;

\( Q_x \) = charge passed (coulombs) through \( x \) in. diameter specimen;

\( x \) = diameter (in.) of the nonstandard specimen.

Because the proportion factor gets larger as the specimen diameter gets smaller, the user must be particularly careful to conduct the chloride permeability test properly on small diameter specimens: errors and deviations will be magnified by the proportion constant.

Effect of Materials and Construction Variables on Test Results

The third part of this study was a series of tests aimed at examining how several materials and construction (M&C) variables affected chloride permeability. The study in which the rapid permeability test was originally developed (2) showed the effects of water-cement ratio on permeability. Other results since have shown the effect of M&C variables such as degree of consolidation.
aggregate type (6), granulated slag and silica fume admixtures (7, 8), and air content (9). The literature also contains references to how a number of M&C parameters have affected chloride permeability measured by other means such as long term ponding tests (10).

The present study examined the effects of the following on chloride permeability: water-cement ratio, coarse aggregate type and gradation, and air content. Such information will be useful to engineers in designing low permeability, conventional concrete mixes.

Water-cement ratio -- The original research on the rapid chloride permeability test (2) and other studies have demonstrated that chloride permeability increases as water-cement ratio increases. Three concretes, mixes A, B, and K, were prepared in the present study to reexamine the water-cement ratio effect. The cement content of these mixes was maintained at 705 lbs/yd$^3$ (418 kg/m$^3$), but water-cement ratios ranged from 0.42 to 0.5. Mix design information is given in Table 1.

Specimens were removed from slabs of each concrete after 28 days of moist curing and tested shortly thereafter. The rapid permeability test results, as well as the percent weight gains during vacuum saturation, are shown in Table 8. The results clearly show the increase in chloride permeability as water-cement ratio increases, as expected.

Coarse aggregate type -- Coarse aggregates used in concretes are chosen based on their availability and cost and their ability to meet various specifications on their properties. The water permeability of aggregates has been studied as far back as 1959; in one of the earliest studies, Powers (11) determined the coefficients of permeability for different rocks ranged from $3.45 \times 10^{-13}$ to $2.18 \times 10^{-9}$ cm/sec. He pointed out that these corresponded to the permeabilities of mature cement pastes with water-cement ratios ranging from 0.38 to 0.71. With coarse aggregate typically occupying 30 to 45 percent by weight of a concrete mix, and having permeabilities of the same order as the other components of the mix, it is expected to play an important role in the concrete's overall permeability.

The interface between the coarse aggregate and the mortar can also be a significant contributor to the chloride permeability of a concrete. Cracks in the bond interface can arise in concrete before it is externally loaded, even in concrete kept wet continuously from the time it is cast. These cracks arise from segregation and from tensile and shear stresses caused by volume changes during setting and hardening (12). The surface texture of the coarse aggregate affects the bond quality: angular, rough-textured aggregate will develop a much stronger bond than a smooth, round aggregate.
Concrete Permeability

The objective of this portion of the study was to determine empirically the effects of aggregate type on the chloride permeability of concrete. As noted in the mixture design discussion earlier, three aggregates were examined, Riverton (Va.) limestone, Occoquan (Va.) granite, and Brandywine (Md.) river gravel. The particle size distributions and specific gravities of the aggregates are given in Table 9, and the mix designs and fresh concrete properties are given in Table 1 (mixes H, L, and M). As Table 1 shows, the three mixes were virtually identical except for the coarse aggregate material.

Three specimens from each mixture were tested by the rapid chloride permeability procedure. Figure 5 shows the permeability values for the three samples of each concrete. The crushed limestone shows the lowest permeability (average of 4493 coulombs), while the concretes prepared with granite and river gravel show progressively higher values (5652 and 6251 coulombs, respectively). Limestone and river gravel differed, but in the opposite direction, in a recent study by Whiting, et al. (6), although in their case water-cement ratio was allowed to vary between the mixes. These two opposing sets of results suggest that aggregate contribution to permeability must be established source-by-source rather than by rock type.

Coarse aggregate gradation -- Coarse aggregate gradation is also expected to affect the chloride permeability of concrete. To examine this, concrete mixes N, O, and P (in Table 1) were prepared. Initially a stockpile of Riverton limestone was separated through 25.0, 19.0, 12.5, 9.5, and 4.75 mm (1, 3/4, 1/2, and 3/8 in., and #4) sieves. The aggregate retained on each sieve was then collected and recombined in accordance with the percentages shown in Table 10. The resulting coarse aggregates met the specifications for grading size numbers 5, 6, and 7 in ASTM C33, "Standard Specifications for Coarse Aggregates" (3), and consisted of size intervals 25.0 to 12.5, 19.0 to 9.5, and 12.5 to 4.25 mm, respectively. Concretes N, O, and P were mixed with size 5, 6, and 7 aggregates, respectively, as shown in Table 1. Table 10 also shows the size 67 gradation which was used for all of the other mixes in this paper. Size 67 consists of material in the 19.0 to 4.75 mm (3/4 in. - No. 4) range. Concrete B, prepared for other purposes in this study, was virtually identical to concretes N, O, and P in terms of mix design, air content, and water-cement ratio, but used the size 67 coarse aggregate.

Three specimens each of mixtures N, O, and P were obtained by coring slabs and then were tested by the rapid chloride permeability procedure. The results are shown in Table 11, along with the results for concrete B.

The size 5 material (mixture N) shows the highest permeability among the size 5, 6, and 7 mixes. This is undoubtedly because it is gap-graded, i.e., it lacks the material in the 12.5 to 4.75 mm (1/2 in. to No. 4) range that would make the mixture a
dense-graded concrete. The lowest permeabilities are attained in the size 7 and 67 mixtures, those with the more uniform and continuous gradations.

Between the two dense-graded mixtures, the 12.5 mm (1/2 in.) maximum size mixture (size 7) provides a lower chloride permeability than the 19.0 mm (3/4 in.) maximum size mixture (size 67). Although the difference in permeabilities is small, the reason may be that the mixture with smaller particles may provide a more tortuous path for the chloride ions to follow in migrating through the paste. That is, a chloride ion will have to travel a longer path to reach any specified depth as the maximum particle size decreases. More knowledge of the relative permeabilities of aggregate, paste, and aggregate-paste interface will lead to a further understanding of the relationship of chloride permeability to aggregate size and other variables.

Air content -- Increasing entrained air content is generally accepted as increasing the water permeability of concrete. For example, Powers (11) indicated permeability is a function of capillary porosity and the porosity is, in turn, a function of both air content and water-cement ratio. Sprinkle has recently reported (9) that chloride permeability acts the same as water permeability, that is, also increases as air content increases. This portion of the study was aimed at verifying the chloride permeability versus air content relationship.

Mixtures Q, R, and S were designed for evaluating the air content effect. These concretes had identical mix designs, as shown in Table 1, except for a variation in the dosage of air-entraining admixture. The varying dosages produced air contents of 1.5, 2.5, and 5.4 percent, respectively, in mixtures Q, R, and S. The chloride permeability test results and the percent weight increases during vacuum saturation are shown in Table 11. Although there was no significant difference in permeability or absorption between the two low air content mixes, both permeability and absorption were substantially higher in the 5.4 percent air content mixes than they were in the 1.5 and 2.5 percent mixes.

Applying a least squares fit to the permeability versus air content data in Table 11 and to the permeability versus water-cement ratio data in Table 8 allows an equivalence statement to be developed for the two concrete properties. That is, comparison of the slopes of the two least squares lines indicates that a 1 percent increase in air content has the same effect on chloride permeability as an increase of 0.03 in water-cement ratio.

CONCLUSIONS

The newly developed rapid chloride permeability test, AASHTO T277, has been applied to a number of different concrete specimens under a variety of conditions. The results obtained
continue to indicate the test is valid and can be used with confidence. Specific conclusions about the test itself and about the chloride permeability of various concretes include the following:

1. A proposed precision statement has been developed for the test. The statement is based on an interlaboratory test program carried out by 11 laboratories on specimens from 4 concretes. The results indicate the single operator coefficient of variation of a single test result to be 12.3 percent and the multi-laboratory coefficient of variation to be 18.0 percent. This statement has been submitted to the appropriate ASTM committee for inclusion in a proposed ASTM standard and will be submitted to AASHTO for inclusion in T277.

2. Several possible revisions to the AASHTO standard procedure were investigated, but none are acceptable based on the data developed here. Allowing an additional 48 hours of soaking of the specimen during the vacuum saturation process was found to affect test results on some concretes. A slight relaxation of the vacuum level required during the vacuum saturation process did not affect the test results, but further investigation is needed on other concretes and at other vacuum levels before the standard procedure is altered. Changing the electrodes from copper screen to a more durable perforated stainless steel sheet is desirable but the results were not conclusive.

3. Test results on specimens with diameters other than the standard 3.75 in. (95 mm) called for in AASHTO T277 can be adjusted to allow comparisons with standard size specimens. The adjustment factor is simply the ratio of the cross-sectional area of a 3.75 in. diameter specimen to that of the nonstandard specimen. Multiplying the charge passed through the nonstandard specimen by this adjustment factor will give a reasonable estimate of the charge that would be passed through a standard specimen.

4. Several fundamental properties of concrete were shown (or confirmed) to affect its chloride permeability, as follows: (a) chloride permeability increases as water-cement ratio increases; (b) permeability varies somewhat with coarse aggregate selection, but the effect of particular aggregate sources must be established individually; (c) for a given aggregate source, permeability is lower for a dense-graded than for a gap-graded concrete and, among dense-graded concretes, it decreases somewhat as the maximum size of the aggregate decreases; and (d) permeability increases as entrained air content increases. A 1 percent increase in air content has the same impact on chloride permeability as a 0.03 increase in water-cement ratio. Combined with results from other recent studies with the new test as well as from previous studies with ponding tests, this data will be useful in optimizing concrete mix designs for minimal chloride permeability.
REFERENCES


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1 C=Conventional; L=Latex-Modified  
2 Including water contained in latex emulsion  
kg/m^3 = lbs/yd^3 x 0.593; mm = in. x 25.4; kg/m^3 = pcf x 16.02
TABLE 2--INDIVIDUAL CHLORIDE PERMEABILITY DETERMINATIONS FROM INTERLABORATORY TESTS

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### TABLE 3--OVERALL AVERAGE, STANDARD DEVIATIONS, AND COEFFICIENTS OF VARIATION OF PERMEABILITY VALUES FOR EACH CONCRETE TYPE FROM INTERLABORATORY TESTS

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### TABLE 4--EFFECT OF EXTENDED SOAKING PERIODS ON CHLORIDE PERMEABILITY TEST RESULTS

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### TABLE 9--PARTICLE SIZE DISTRIBUTION OF COARSE AGGREGATES

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<thead>
<tr>
<th>Aggregate Type</th>
<th>Limestone</th>
<th>Granite</th>
<th>River Gravel</th>
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<tbody>
<tr>
<td>Source</td>
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<td>Occoquan, Virginia</td>
<td>Brandywine, Maryland</td>
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<table>
<thead>
<tr>
<th>Percent Passing</th>
<th>Sieve Size (by Weight):</th>
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<tr>
<td></td>
<td>25.0 mm (1 in.)</td>
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<tr>
<td></td>
<td>19.0 mm (3/4 in.)</td>
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<tr>
<td></td>
<td>12.5 mm (1/2 in.)</td>
</tr>
<tr>
<td></td>
<td>9.5 mm (3/8 in.)</td>
</tr>
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<td></td>
<td>6.3 mm (1/4 in.)</td>
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<td></td>
<td>4.75 mm (# 4)</td>
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<tr>
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<td>Bulk Specific Gravity</td>
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### Table 10--Coarse Aggregate Gradations for Size 5, 6, 7, and 67 Mixes

<table>
<thead>
<tr>
<th>Coarse Aggregate Size</th>
<th>Percent by Weight in Each Coarse Aggregate Size Range</th>
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<tr>
<td></td>
<td>Size 5</td>
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<tr>
<td>25.0 - 19.0 mm (1 - 3/4 in.)</td>
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<td>19.0 - 12.5 mm (3/4 - 1/2 in.)</td>
<td>40</td>
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<td>12.5 - 9.5 mm (1/2 - 3/8 in.)</td>
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</tr>
<tr>
<td>9.5 - 6.3 mm (3/8 - 1/4 in.)</td>
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<td>6.3 - 4.75 mm (1/4 in. - No. 4)</td>
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### Table 11--Effect of Aggregate Size and Gradation

<table>
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<tr>
<th>Concrete Mix</th>
<th>Coarse Aggregate Size</th>
<th>Specimen Number</th>
<th>Total Charge Passed, coulombs</th>
<th>Average Charge Passed, coulombs</th>
<th>Age, days</th>
<th>Weight Increase, percent</th>
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<tr>
<td>N</td>
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<td>O</td>
<td>6</td>
<td>P601A</td>
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### TABLE 12--EFFECT OF AIR ENTRAINMENT

<table>
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<th>Concrete Mix</th>
<th>Air Content, percent</th>
<th>Specimen Number</th>
<th>Total Charge Passed, coulombs</th>
<th>Average Charge Passed, coulombs</th>
<th>Age, days</th>
<th>Weight Increase, percent</th>
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</thead>
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<tr>
<td>Q 1.5</td>
<td></td>
<td>P591A</td>
<td>3702</td>
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<td></td>
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<td>R 2.5</td>
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<td>P592A</td>
<td>3421</td>
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Fig. 1--Schematic of rapid permeability test apparatus (Reference 5)
Fig. 2a--Average permeability versus concrete type for laboratories 1, 2, 3, and 4

Fig. 2b--Average permeability versus concrete type for laboratories 5, 6, 8, and 9
Concrete Permeability

Fig. 2c--Average permeability versus concrete type for laboratories 10, 11, and 12

Fig. 3--Perforated stainless steel sheet used as alternate electrode material
Fig. 4--Permeability test results as a function of specimen size

Fig. 5--Effect of coarse aggregate type
Synopsis: Equipment and procedures for measuring actual permeability of portland cement concrete are presented. The equipment is built from readily available parts and materials and requires only standard laboratory air pressure and vacuum sources. The sample size used is 3 in. (7.5 cm) diameter by 3-1/8 in. (8 cm) long, however other sample sizes could be used. Typical measurements are presented to show repeatability and time required for permeability testing. The equipment has been used for permeabilities as low as $1 \times 10^{-11}$ cm/sec. Concrete with lower permeability would require equipment modifications and/or longer measurement times.

Keywords: concretes; measuring instruments; permeability; samples; test equipment; tests
Dr. Janssen has studied moisture movement in saturated and unsaturated soils, soil-geotextile systems, and PCC for the past ten years. While involved in a study of D-cracking, he developed a procedure for permeability testing of PCC pavement cores.

INTRODUCTION

Civil engineers have long been interested in the rate of water flow through portland cement concrete (PCC). In 1931, Norton and Pletta (1) presented a paper at the 27th Annual ACI Meeting that described a permeability testing device. Concretes tested had water-cement ratios (w/c) of from 0.62 to 1.20 pounds of water per pound of cement. By 1937, Wiley and Coulson (2) were stating that most permeability investigations were using equipment that was "...so costly and time consuming as to make it prohibitive...". They described a "flower pot" method of permeability measurement in which a container was cast from the concrete in question. The rate at which the water in the container had to be replenished was used to calculate permeability. Water-cement ratios of from 0.35 to 0.75 were used in their study. In 1951 the U.S. Army Corps of Engineers (3) was measuring the permeability of lean concretes used in dams. Their method used positive pressures of 100 or 200 psi to force water through the specimens, and is described in their specification CRD-C 48.

More recently, electric resistance tests have been used to measure concrete permeability. The lower the concrete permeability, the higher the electrical resistance. One such test, the Rapid Chloride Permeability test, has been especially useful in evaluating the relative permeability of various bridge deck overlay materials (4). Unfortunately, actual permeability is not directly measured by the electric resistance methods. The purpose of this paper is to present a simple and inexpensive method of
Concrete Permeability

measuring actual permeability from field or laboratory samples.

BACKGROUND

The flow of water through a porous material is described by the well-accepted equation:

\[ k = \frac{Q}{LHA} t \]  

(1)

where

- \( k \) = permeability, cm/sec,
- \( Q \) = the quantity of water that flows through the sample, cm³,
- \( L \) = the length of the sample in the direction of flow, cm,
- \( H \) = the hydraulic head loss in the distance \( L \), cm,
- \( A \) = the cross-sectional area of the sample, cm²,

and

\( t \) = the time required for flow \( Q \) to occur.

Though an assumption in using Equation 1 is that the flow through the pores is laminar, this equation is often used for permeability calculations whether the flow is laminar or turbulent (5). Errors in measurement caused by turbulent instead of laminar flow are very difficult to measure, but can be considered to be worse at higher hydraulic gradients (\( H/L \) in Equation 1). Because PCC permeability values are often not needed to a high degree of precision, the laminar/turbulent error is often ignored.

In addition, to the above theoretical problem with PCC permeability measurement, a number of practical problems exist.

Problems with PCC Permeability Measurement

The fact that numerous PCC permeability measurement methods exist indicates that there are many problems encountered when measuring concrete permeability. A number of these problems are described below:

Specialized Sample Requirements--Tests that require specially made samples are not applicable to cores obtained from
field concrete, and may not be realistic for special finishing and sealing applications.

Small quantity of flow—Typical permeabilities for medium and high strength PCC can be expected to be around $10^{-10}$ cm/sec or less (6). Equation 1 indicates that for low hydraulic gradients and reasonable sample sizes, the quantity of flow through a sample, Q, can be expected to be quite small. This was recognized by McMillan and Lyse (7), who resorted to reducing the moist curing period of their PCC samples to increase the permeability. This would not be applicable for field samples. Other solutions to the small flow problem include long time periods, t, for measuring flow, high hydraulic gradients, H/L, as used by the U.S. Army Corps of Engineers (3), or a combination of these.

Leakage around the sample—When high pressures are used to overcome the low flow problem, sealing around the sample becomes quite difficult. Some researchers have resorted to specially tapered samples (8) which are very difficult to produce from field samples, and still may leak if not properly made.

Effect of air in PCC voids—Air in a small pore effectively blocks water flow through that pore (5). Not only must a sample be saturated for reliable permeability measurements to be made; it must also remain saturated during the test. When high hydraulic gradients are used to increase the quantity of flow, the drop in pressure across the sample can cause air dissolved in the water to come out of solution. This leads to decreasing permeability over time.

Expense of equipment and difficulty of test—Whenever equipment is expensive or the testing method is difficult, the test is often omitted unless it is absolutely necessary. This causes information that is useful but not required to be lost, which slows down the advance of technology.
EQUIPMENT AND MATERIALS

A schematic of the permeability measuring equipment (permeameter) is shown in Figure 1. The system consists of a water reservoir, sample cell, mercury manometer, and assorted valves and fittings. A regulated air pressure source is used to pressurize the system to approximately 40 psi (3 kg/cm²). The individual system components are described below.

Water Reservoir

The water reservoir is made of acrylic tube, 4-in. (10 cm) diameter and 1/4-in. (0.6 cm) wall thickness. End caps are sealed to the tube with rubber O-rings and held in place by eight threaded-rod ties. The reservoir is filled with de-aired water, and a layer of mineral oil on top of the water is used to keep the water de-aired when the system is pressurized.

The water tank is refilled by means of a siphon tube connected to the bottom of the tank. This is not shown in the schematic in Figure 1.

Sample Cell

The sample cell is commercially available as a "Tempe Pressure Cell" produced by Soilmoisture Equipment Corporation, though a variety of sample cell types and sizes could be used. Figure 2 shows a cross-section of the sample cell. The PCC sample is sealed into a brass sample ring 3-1/2 in. (9 cm) diameter by 3-1/8 in. (8 cm) long. Leakage between the cell top or base and the brass sample ring is prevented by the use of rubber O-rings and a thin film of silicone vacuum grease. The cell is held together with threaded rods and wing nuts. Water flow into and out of the cell is provided for by 1/4 in. (0.6 cm) diameter tube nipples. On some of the commercially available cells these tubes are acrylic; they should be replaced with brass or stainless steel tube nipples as the acrylic nipples break off easily. A
small space is provided between the PCC sample and the cell base or top so that water access is provided to the entire sample end.

**Mercury Manometer**

The mercury manometer is a 30-in. (76 cm) U-tube manometer with a pressure rating of at least 50 psi (3.5 kg/cm²). Other manometer lengths could also be used. The tube inside diameter should be 1/4 in. (0.6 cm) or less. The manometer should be fitted with a mercury trap on each leg, as a broken connector in the permeameter could otherwise cause loss of mercury into the laboratory.

**Valves and Fittings**

Fittings are provided to connect to the sample cell tube nipples so that samples can be easily moved into and out of the permeameter. Isolation valves are provided for both sides of the sample. Water is bled from the system with the bleeder valve, and the rate of water flow is controlled by a micro-adjust valve. Bleeding water from the system causes a pressure decrease on the bottom side of the sample.

**Equipment Assembly**

The various parts of the permeameter are mounted to a piece of plywood with the water tank attached to slots so that it can be adjusted up or down. The tank is adjusted so that the top of the mineral oil is even with "0" on the mercury manometer.

The tubing used to connect the pieces together is flexible clear plastic, 1/4-in. (0.6 cm) inside diameter by 1/16-in. (0.016 cm) wall thickness. The tubing from the air pressure source to the manometer and the top of the water tank contain air; the rest of the tubes contain water. The left leg of the manometer, Figure 1, contains mercury with water on top.
TESTING METHOD

Sample Preparation

The PCC samples used in the development of this equipment were obtained by taking 3-in. (7.5 cm) diameter cores from existing highway pavements (9). Other size samples could be used with appropriate sample cells. The samples must be trimmed so that they are no longer than the brass sample rings.

The samples must be sealed into the brass sample rings. Numerous sealers were tried, including asphalt, butyl rubber, and silicone rubber. The only material tried that did not leak was Dow-Corning Concrete Sealer. This is a silicone-based sealer, but it does not give off acetic acid as it cures. The circumference of each concrete sample and the inside of each brass sample ring are coated with concrete sealer and allowed to cure overnight. Additional sealer is then spread around the sample and the sample is inserted into the sample ring. After curing the sealer for 24 hours, the sample cell is assembled. A piece of filter paper should be placed between the top of the PCC sample and the cell top during assembly.

Sample Saturation

The PCC sample is prepared for saturation by connecting the nipple on the top of the sample cell to a vacuum source and the nipple on the bottom of the cell to a de-aired water supply. The water supply should be connected to the cell bottom with a short length of 1/4-in. (0.6 cm) inside diameter by 1/16-in. (0.016 cm) wall thickness rubber tubing so that a tubing pinch clamp can be used as a shut-off. When connecting the water supply, all air space between the PCC surface and the inside of the sample cell base should be filled with water. A hypodermic syringe with a large diameter blunt needle is quite useful for squirting water into this space.
With the de-aired water supply shut off, a vacuum of at least 17-in. (45 cm) mercury is maintained on the top of PCC sample for 24 hours. The pinch clamp on the water supply tube is then released, and the sample is allowed to saturate. For low permeability PCC, this may take from a few days to a week. The PCC sample is considered saturated when the filter paper on the top of the sample is wet. Leaking samples that are not properly sealed into the brass sample ring can be easily identified when the filter paper gets wet quickly from the edge of the sample. Leaking samples should be re-sealed or replaced.

**Connection of Sample Cell**

When the sample cell is connected to the permeameter, air should be removed from the tubing connectors and the spaces at the ends of the sample cell. Again, a syringe is quite useful. After the tubing connectors have been attached to the cell nipples and tightened, the sample isolation valves are opened and the permeameter is ready for pressurization.

The air pressure in the permeameter should be gradually increased to about 40 psi (3 kg/cm²). During pressurization, the mercury manometer should be observed so that the pressure differential across the sample does not exceed the capacity of the manometer. Expansion of the tubing connecting the left leg of the manometer to the base of the sample cell will cause the mercury level to rise in the left leg of the manometer. At the same time, the mercury level in the right leg will decrease. If the mercury level in the right leg drops to the bottom of the manometer, air will bubble past the mercury and invalidate the test.
Readings

A hydraulic gradient is imposed across the sample by removing water from the tubing connected to the bottom of the sample cell, Figure 1. This is often accomplished when the system is pressurized to 40 psi (3 kg/cm²) and the plastic tubing expands. If a higher hydraulic is desired, the bleeder valve can be opened to drain water from the system. The pressure difference across the sample is read on the mercury manometer.

For samples with permeabilities less than about $10^{-7}$ cm/sec, the bleeder valve is closed after the hydraulic gradient is established, and flow through the sample causes the manometer pressure difference to decrease. The quantity of flow through the sample is equal to the cross-section area of the manometer tube times the distance that the mercury level in the left leg of the manometer decreases. This is actually a falling head permeability test (5), and the equation describing this is:

$$k = 3.33 \times 10^{-2} \frac{\alpha L}{A(t_2-t_1)} \log_{10}(H_1/H_2)$$

(2)

where

- $k =$ permeability, cm/sec,
- $a =$ cross-section area of the manometer tube, cm²,
- $L =$ length of the sample, cm,
- $A =$ area of the sample, cm²,
- $t_1 =$ time of first reading, sec.,
- $t_2 =$ time of second reading, sec.,
- $H_1 =$ manometer reading at time $t_1$, in. mercury, and
- $H_2 =$ manometer reading at time $t_2$, in. mercury.

For permeabilities greater than $10^{-7}$ cm/sec, the bleeder valve is left open, and the rate of flow is adjusted with the micro-adjust valve. This is a constant-head permeability test, and Equation 1 is used to calculate the permeability. The quantity, $W$, of flow through the sample is measured by collecting the water that is bled from the system, and the pressure difference across the sample, $H$, must be converted to cm water by the following equation:
\[ H = 13.6 \times 2.54 \times \text{manometer reading, in. mercury} \quad (3) \]

At least three consecutive readings should be taken for each sample. The head difference for each successive reading should be at least 0.2 in. (0.5 cm) mercury for the falling head test so that sufficient water has passed through the sample to provide an accurate measurement.

RESULTS

Table 1 shows typical permeability data for a core taken from an Interstate highway near Champaign, Illinois. The total time from initial reading to final reading was 33 days, however readings could have been taken at closer intervals. Table 1 also shows the permeability value for each reading, and the permeability calculated over the entire duration of the test. The repeatability appears quite good, even though the permeabilities are very low. The slight increase in permeability during the first three weeks of the test is probably due to incomplete saturation at the beginning of the test. As the pressurized, de-aired water flows through the sample, air in the pores is probably dissolving in the water. This would tend to increase the permeability. A major increase in permeability value would probably indicate a leak in the seal around the sample.

CONCLUSIONS AND RECOMMENDATIONS

For many applications, relative permeability measurements are good enough, and actual permeability values are not needed. But when actual permeability values are needed, as for moisture movement or concrete durability predictions (9), a permeability test that is easy, accurate, and reliable for a wide range of permeabilities is needed. The equipment and procedure described in this paper has the following advantages:

1. The method can be used with laboratory or field samples.
2. The system is a closed system; evaporation does not affect the measurement of low quantities of flow.

3. The use of a moderate hydraulic gradient along with a modern sealer prevents sample leakage.

4. The use of de-aired water in a pressurized system reduces problems with air in PCC voids. With this system, the degree of saturation of the PCC can actually improve throughout the test.

5. Though the testing time is long, the minimal operator time required for the test along with the use of inexpensive equipment makes this test feasible for most labs.

No matter what test method is used, actual permeability of PCC should be measured on a more frequent basis. A single set of data is often used by many researchers in many locations. Improving the completeness of that data by including permeability measurements can only improve the level of PCC technology.

ACKNOWLEDGEMENTS

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DISCLAIMER

The contents of this report reflect the views of the author, who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Illinois Department of Transportation. This report does not constitute a standard, specification, or regulation.
REFERENCES


### TABLE 1--PERMEABILITY DATA, PAVEMENT CORE

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<thead>
<tr>
<th>DAY</th>
<th>TIME</th>
<th>MINUTE</th>
<th>HEAD in, Hg</th>
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<td>00</td>
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**Fig. 1--Schematic of permeameter**
Fig. 2--Cross section of sample cell
Permeability Testing System
for Grout, Concrete, and Rock

by B.R. Sullivan

Synopsis: A testing system which can accommodate up to seven samples simultaneously with computer-controlled data acquisition, analysis, and reporting is described. The system consists of seven core holders of the Hassler type which can handle cylindrical samples ranging from 1-1/2 in. to 4 in. in diameter, and from 4 in. to 11 in. in length. Confining and driving pressures can be independently varied up to 4,000 psi. The test medium can be either liquid or gas including brine since all tubing and containers are stainless steel.

Flow is determined by pressure increase in a collector tank for gas and change in liquid level in a pipette column for liquid. Four pressure transducers per core holder are used to monitor all pressure levels during a test.

A computer-based data acquisition system is used to scan up to seven tests simultaneously and record all data on a disc. Upon termination of a test, flow and permeability are computed and plotted against time and a report printed for the test. The data are saved permanently on the disc and a backup copy is transferred to a floppy disc for safe storage.

Sample preparation, sealing, and testing procedures are explained.

Data analysis and typical results are presented on salt cores, and concrete samples.

Keywords: computers; concretes; grout; measuring instruments; permeability; rocks; test equipment; tests
INTRODUCTION

Permeability is a measure of the capacity of a porous medium to transmit fluids. It is a measure of the liquid or gas conductivity of a material, and consequently, represents the reciprocal of the resistance which the material offers to the flow of fluids. Permeability is regarded as a material property affecting the durability of concrete (1). It is considered one of the most important properties of concrete and grout used to seal storage systems for waste liquids and gases in various environments. Recent work at the Waterways Experiment Station (WES) concerning nuclear waste isolation required that data be obtained using brine and nitrogen gas while simulating overburden pressures on grout and concrete seal systems. The system herein described was developed expressly for that purpose and is capable of measuring low flow rates corresponding to the sub-microdarcy permeability range. The system now being used at WES can accommodate cores, and the core holder and piping is stainless steel to accommodate salt water as a permeant.

Testing Apparatus

Hassler core holders form the basis for the permeability test system. A drawing for 4-in. core is shown in Figure 1. These stainless-steel cells can accommodate specimen sizes from 1-1/2 in. to 4-1/2 in. in diameter and up to 11 in. in length. Confining pressures up to 4,000 psi can be used to simulate overburden pressures with driving pressures being any value up to 20 percent less than the confining pressure. A 3/8-in. thick rubber sleeve is placed around the specimen with stainless steel perforated end plates against the specimen. A porous 1/16 in. thick layer of stainless steel mesh is used on both ends of the specimen. The rubber sleeve is clamped to the end plates, and the assembly is then placed inside the holder. Water is used for confinement around the rubber sleeve and end plates so that any leaks can be easily detected following a test. Pressures are maintained with bottled nitrogen gas applied to the water confinement and one end of the sample as the source pressure behind the permeant.

Seven stainless-steel chambers are available for simultaneous use in this system. These are connected to a common evacuating manifold containing de-aired water, brine, or any other test fluid at each cell. Following evacuation of the
source or input side of chamber, the appropriate test fluid is allowed to fill the lines and source side. A driving pressure using bottled gas is then applied to the fluid separated by a diaphragm to prevent solution of the gas in the liquid. The collection end of the chamber has a selection valve for gas or liquid measurement. In the case of liquid, a graduated pipette or column is used for collection and measurement. These are read periodically, and the values are entered via the keyboard to the data-acquisition system. For special long term runs, a micro pressure cell is used to monitor the increase in water column height automatically. For low flow, a small opening pipette is used; therefore, the force from the column is small and requires a very sensitive load cell.

**Measurement System**

The seven chambers are connected so as to have independent confining and driving pressures up to 4,000 psi. Three chambers are equipped with high-pressure sight glasses to measure the input liquid to the sample as shown in Figure 2. Independent liquid reservoirs are provided with each test cell and coupled to a common vacuum manifold. When each cell is filled with the test liquid it is vacuum de-aired and, if allowed to remain motionless, will not take on additional gases.

The exit end of the test chamber is equipped to measure liquid or gas. Gas is collected in a closed chamber, and the volume is computed from the pressure buildup. When the test fluid is a liquid, a micro pipette is used and read manually, or a pressure transducer can be used to monitor the column height automatically when sufficient flow is obtained.

The automated-control system is a Hewlett Packard 200 series Computer and a model 3497 Data Acquisition/Control Unit. It is programmed to allow independent start and stop for each chamber. The scanning sequence and timing is selectable at the start of or during a test. Special function keys allow a permeability calculation to be made and plots and a test report to be prepared. When adequate test data are obtained, the test is terminated, and all data are transferred to a backup disc for permanent record.

**Liquid Flow Calculations**

The apparatus has a liquid reservoir at the source end of the core holder with provisions for measuring the amount of liquid absorbed by the test sample. After passage, the volume of liquid is collected and measured for a period of time when the flow is steady state, and then the permeability is calculated.

Assuming Darcy's law to hold for the conditions of this experimental measurement, we only have to measure a steady-state flow rate to compute permeability. The standard
form of Darcy's equation for a liquid gives permeability coefficient \((K)\) in darcies for a cylindrical sample of length \(L\) as follows:

\[
K = \frac{Q \mu L}{A \Delta P}
\]

where
- \(Q\) = flow rate, mL/sec
- \(\mu\) = viscosity of liquid, centipoises
- \(L\) = length of specimen, cm
- \(A\) = end area of specimen, cm\(^2\)
- \(\Delta P\) = pressure difference across specimen, atmospheres

**Gas Flow Calculations**

The use of a gas as the test medium may be advantageous for materials having very low intrinsic permeability or materials which are likely to be reactive with the fluid normally used for the test. The apparatus used for measurement is the same as for liquid flow with the substitution of a collector tank in lieu of the pipette tube to measure the pressure increase as the gas flows through the sample. Also, the equations describing the flow must be altered due to the compressibility of the gas being used.

The test gas is chosen to be nonreactive with the sample. Nitrogen gas was chosen for tests on salt cores or grout-rock simulated borehole (SBH) samples. The flow of gas through porous materials has been described by Pitts and Brandt (2) along with some experimental verification of the basic assumptions involved in the development of the flow equations. These experiments show that flow occurs according to the following equations:

The continuity equation

\[
\nabla (\rho u) + \epsilon \frac{\partial P}{\partial t} = 0
\]

where
- \(\nabla\) = del operator
- \(\rho\) = specific gravity of gas
- \(u\) = apparent velocity = volume flow rate/unit area
- \(\epsilon\) = porosity
- \(P\) = pressure
- \(t\) = time

Darcy's law (3) for the momentum equation is

\[
u = \frac{k}{\mu} \Delta P
\]
where $k$ is permeability, and 
$\mu$ is gas viscosity

An equation of state for an ideal gas is

$$\rho = \frac{p}{RT}$$

where $P$ is pressure
$R$ is the gas constant
$T$ is absolute temperature

If the experiments are conducted such that conditions are isothermal, steady state, and one-dimensional flow, it follows that the permeability $K$ in darcies is given by

$$K = \frac{2\mu L}{A} \cdot \frac{P_a}{(P^2 - P_a^2)}$$

where $\mu$ is the viscosity of the gas in centipoises
$P_a$ is atmospheric pressure
$P$ is the source pressure in atmospheres, and all other terms are the same as previously noted for liquid flow.

It is then only necessary to determine permeabilities at pressures sufficiently high that the phenomenon called Klinkenberg slip does not affect the results appreciably.

From Klinkenberg (3), an approximate equation is developed for gases which includes a mean pressure correction on Darcy's law for fluids as follows:

$$P_a Q = \frac{K a A}{\mu L} \cdot (P - P_a) \left(\frac{P + P_a}{2}\right)$$

where $K_a$ is the apparent gas permeability
$P$ is the applied pressure of the gas at one end of a cylindrical sample with area (A) and length (L)
$P_a$ is atmospheric pressure on opposite end of sample and the term $\frac{P + P_a}{2}$ is the mean pressure, $\bar{P}$, on the sample.

Rearranging then,

$$K_a = \frac{2\mu L}{A} \cdot \frac{P_a}{(P^2 - P_a^2)}$$

$K_a$ (apparent permeability) is related to $K$ (true permeability) for an idealized porous system to gas as follows
where the term $b = \frac{4C\lambda}{r}$ relates the fact that the mean free path is inversely proportional to the pressure, $r$ is the radius of the gas capillary, and $b$ is constant.

Klinkenberg's experiments up to mean pressures of 20 atmospheres on glass filters and cores having permeabilities in the millidarcy range show $b$ to approach a maximum value of 1. It follows that for mean pressures of 50 atmospheres, then $K\alpha = K$ to within 2 percent.

This term takes into account the phenomenon of slip which is related to the mean free paths of the gas molecules. The phenomenon of slip becomes significant for low permeabilities measured at low pressures. His experiments show the relationship to be a linear function, and for a mean pressure greater than 20 atmospheres, the gas permeability approaches the liquid values in the millidarcy range. It follows that in the microdarcy-permeability range, higher pressures are required to reduce the mean free paths since the pore dimensions are smaller and may be comparable to the mean free path of the gas (4). The results then are the so-called "liquid" permeability.

The flow rate $Q$ is computed from the measured pressure buildup in the collector tank of known volume $V_c$.

Initially, the volume $V_c$ is at atmospheric pressure and filled with the test gas.

So, the initial conditions are:

$$V_c = 500 \text{ mL}$$
$$P_c = 14.697 \text{ psi}$$

After some time $t$ and some pressure $P_2 = 14.697 + \text{gage}$ pressure is recorded. To reduce the measured pressure ($P_2$) to atmospheric pressure ($P_1$), we use Boyle's law for perfect gases

$$P_1V_1 = P_2V_2$$

at constant temperature and compute a volume $\Delta V$ required to reduce $P_2$ to $P_1$ with

$$V_1 = \Delta V + V_c$$
Substituting $P_2V_2 - P_1(\Delta V + V_c)$ where $V_c = V_2$

or $P_2V_c = P_1(\Delta V + V_c)$

then $P_1\Delta V = P_2V_c = P_1V_c$

$$\Delta V = \left(\frac{P_2}{P_1}\right) - 1 V_c$$

Therefore, the volume collected per unit time is the term $Q$ in the equation for $K$ (the permeability coefficient in darcies) which for gas flow is as follows:

$$K = \frac{2Q\mu L}{A \Delta P^2}$$

where $Q =$ flow rate, mL/sec
$\mu =$ viscosity of test gas, centipoises
$L =$ length of specimen, cm
$A =$ end area of specimen, sq cm
$\Delta P =$ pressure difference across specimen in atmospheres

**Approximate Error Analysis**

Both confining pressure and source pressure are measured using electrical bridge transducers which have an accuracy of ± 0.25 percent. Check calibrations are done periodically using known masses and consistently showed the system to be within this accuracy limit.

The collector tank has a volume of 500 mL ± 10 mL or ± 2.0 percent.

The volume calculation then yields

$$\Delta V = \frac{P_2}{P_1} V_1 - V_1 = V_1 \left(\frac{P_2}{P_1} - 1\right)$$

or $\sim \pm 2 + 1/4 + 1/4 = \pm 2-1/2$ percent

Assuming 1/4 percent error in time determination, then yields

$$Q = \frac{\Delta V}{\text{time}} = \pm 2-1/2 + 1/4 = \pm 2-3/4 \text{ percent.}$$

Then computation of permeability

$$K = \frac{2Q\mu L}{A \Delta P^2} \text{ or } = \frac{2-3/4 + 1/4}{1/4 + 1/4} = 3-1/2 \text{ percent}$$
assuming 1/4 percent errors in L, μ, and ΔP. Therefore, a value of ± 4 percent seems reasonable for the total error for permeability K for both gases and liquids.

All tests were run at laboratory ambient temperature constant to within ± 1° F. This could result in ± 0.01 psi in the collector tank. This together with all the limits on measurement accuracy limit the resolution of the tests to 0.01 microdarcies.

Typical Results

Upon completion of a permeability test at a constant pressure level, a soft key on the series 200 computer is programmed to plot.

a) Driving pressure vs time,
b) Confining pressure vs time, and
c) Collector pressure vs time.

Typical plots are shown in Figure 3. A second key causes a calculation to be made, and a brief report is printed on a series of runs made on the same specimen at different pressure levels. Also a linearity check is made on the collector data, and a warning is printed if it does not meet the required criteria. More time is then allowed for steady-state conditions to develop, and calculations are only made when the flow meets the requirements for steady state. Other soft keys are programmed to dump data to disc, start and stop a run, allow keyboard entry of data corrections, etc.

Samples of the types of data that result from tests are shown in Tables 1 and 2. Table 1 shows some results on 4-in. diameter rock salt cores from the Water Isolation Pilot Plant (WIPP) side at Carlsbad, New Mexico. This was a study to look at times required for the disturbed cores to flow or heal (5) to close micro-fractures under confining pressures up to expected in-situ levels. These are low permeabilities of the order of 0.01 microdarcies and is about the limit of resolution of the system. Table 2 shows some results on two samples (3 in. diameter by 6 in. length) of concrete used for repair on a Corps of Engineers study. These tests required approximately 2 hours per run and showed the permeability of the concrete to be from 2 to 20 microdarcies.

Discussion

The permeability testing system as presently developed works satisfactorily and has the following desirable features.
a) It can accommodate up to seven samples simultaneously with independent start and stop times and pressures.

b) It can provide for de-airing of liquid by evacuation.

c) High pressure sight glass is used on input to monitor and measure inflow to sample on three cells.

d) Water is used as a confining medium for safety and leak detection out following test.

e) It can be programmed to compute permeability and plot to show linearity of flow and print test report.

f) Data are permanently stored on discs and retained for later more complete analysis and comparison.

g) The system is stainless steel and can handle brine as well as other corrosive fluids.

h) Hydrostatic pressures up to 4,000 psi can be used for simulating overburden pressure or other confinement.

i) Large samples can be used up to 4-1/2 in. in diameter and 11 in. in length.

Recommendations

Improvements to the system which are being completed are as follows.

a) A more refined statistical linear fit to the flow data to ascertain steady-state flow with confidence limits is being added to the computer program.

b) An O-ring piston is to be incorporated in the system to separate the nitrogen driving gas from the liquid used in the flow for permeability test. The present system minimized the surface contact so that gas-liquid mixing was minimized. To eliminate any possibility will be an improvement.

c) Fluid measurements could be further automated depending on the volume flow rate. For low flow, the level in a micro-pipette must be detected and converted to an electrical signal.

Acknowledgement

The development of the automated system and the data presented were accomplished for Sandia National Laboratory (SNL) under the WIPP study investigations. The Project Monitor for this work was Mr. Chuck Gulick of SNL. All work was by the U.S. Army Engineer Waterways Experiment Station, under the
general supervision of Mr. Bryant Mather, Chief, Structures Laboratory.

COL Dwayne G. Lee was Commander and Director of WES during the preparation and publication of this paper. Dr. Robert W. Whalin was Technical Director.

Permission was granted by the Chief of Engineers to publish this information.

REFERENCES


TABLE 1--PERMEABILITY OF NITROGEN GAS OF SALT CORES FROM THE WIPP SITE

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Sample No.</th>
<th>Source</th>
<th>Confining Pressure (psi)</th>
<th>Time Interval (hrs)</th>
<th>Permeability (larcies)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>V3-SF</td>
<td>0</td>
<td>2,300</td>
<td>0 - 21</td>
<td>--</td>
<td>Healing</td>
</tr>
<tr>
<td></td>
<td>(11-16.5 in.)</td>
<td>500</td>
<td>2,300</td>
<td>21 - 67</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,000</td>
<td>2,300</td>
<td>67 - 91</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,500</td>
<td>2,300</td>
<td>91 - 115</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,000</td>
<td>2,300</td>
<td>115 - 139</td>
<td>&lt;0.01</td>
<td>Detected leak (slight) water to spec.</td>
</tr>
<tr>
<td>2</td>
<td>H1-SE</td>
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<td>2,300</td>
<td>0 - 21</td>
<td>--</td>
<td>Healing</td>
</tr>
<tr>
<td></td>
<td>(23-33 in.)</td>
<td>500</td>
<td>2,300</td>
<td>21 - 45</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,000</td>
<td>2,300</td>
<td>45 - 69</td>
<td>&lt;0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,000</td>
<td>2,300</td>
<td>69 - 72</td>
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<td>3</td>
<td>V2-SE</td>
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<td>(0-10.5 in.)</td>
<td>0</td>
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<td>1 - 19</td>
<td>&lt;0.01</td>
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</tr>
<tr>
<td>4</td>
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<td>(10.5-20.5 in.)</td>
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<td></td>
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<tr>
<td>Test No.</td>
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<td>Confining Pressure (psi)</td>
<td>Time Interval (hrs)</td>
<td>Permeability (μdarcies)</td>
<td>Comments</td>
<td></td>
</tr>
<tr>
<td>----------</td>
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<td></td>
<td></td>
<td>500</td>
<td>18 -25</td>
<td>&lt;0.01</td>
<td></td>
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</tr>
<tr>
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<td>1,000</td>
<td>25 -42</td>
<td>&lt;0.01</td>
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<tr>
<td></td>
<td></td>
<td>1,500</td>
<td>42 -46</td>
<td>&lt;0.01</td>
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</tr>
<tr>
<td></td>
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<td>2,000</td>
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<td>2,000</td>
<td>50 -57</td>
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<td></td>
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<td>2,000</td>
<td>57 -64</td>
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</tr>
<tr>
<td>5</td>
<td>H3-SF</td>
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<td>0 -0.75</td>
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<tr>
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<td></td>
<td>(23.5-31.5 in.)</td>
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<tr>
<td></td>
<td></td>
<td>0</td>
<td>1 -18</td>
<td>--</td>
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<tr>
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<td>2,000</td>
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<td>6</td>
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<td>0 -0.5</td>
<td>110</td>
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<tr>
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<td></td>
<td>(38-47 in.)</td>
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<tr>
<td></td>
<td></td>
<td>0</td>
<td>1,200</td>
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<tr>
<td></td>
<td></td>
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<td>2.5-10.5</td>
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<td>10.5-26.5</td>
<td>0.019</td>
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<td>1,500</td>
<td>26.5-44.5</td>
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<td>1,500</td>
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<td></td>
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<td>--</td>
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<tr>
<td></td>
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<td>2,000</td>
<td>72 -74</td>
<td>--</td>
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<td></td>
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<td></td>
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<td>2,000</td>
<td>74 -188</td>
<td>&lt;0.001</td>
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### TABLE 2--WATER PERMEABILITY OF CONCRETE — REMR STUDY

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Sample No.</th>
<th>Source Pressure (psi)</th>
<th>Confining Pressure (psi)</th>
<th>Permeability (darcies)</th>
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<tr>
<td>1</td>
<td>FS-1 (2)</td>
<td>103</td>
<td>160</td>
<td>11.9</td>
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<tr>
<td></td>
<td>3.0 in. diameter x 5.9 in. length</td>
<td>150</td>
<td>205</td>
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<td>2</td>
<td>FS-2 (1)</td>
<td>51</td>
<td>101</td>
<td>15.0</td>
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<td>3.0 in. diameter x 5.95 in. length</td>
<td>92</td>
<td>160</td>
<td>11.0</td>
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<tr>
<td></td>
<td></td>
<td>195</td>
<td>266</td>
<td>1.6</td>
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Fig. 1--Cross section view of Hassler Whole Core Holder
Fig. 2--Photograph of testing system showing three of seven permeability test cells.
Fig. 3--Typical plots of confining pressure, driving pressure, and outlet pressure versus time
Permeability of Concrete
Using a Uniaxial Water-Flow Method

by A. Bisaillon and V. M. Malhotra

Synopsis: This paper describes the modifications made to a previously developed CANMET test method to measure the permeability of concrete, and discusses test results to determine the reproducibility of the test method. Briefly, the test method consists of measuring the uniaxial water flow through cylinders (125-mm high with a diameter of 150 mm) under a pressure of 3.5 MPa. A large number of concrete specimens with water/cement of 0.65 and 0.80 were tested. A limited number of test specimens having W/C of 0.22 and 0.27 were also tested.

The test results show that the within-batch variation for the test method is high, and this is probably due to the heterogeneous nature of the concrete. For concrete with W/C of 0.22 and 0.27, there was no outflow of water, and this technique in the present form may not be suitable for measuring the permeability of very high-strength concrete.

Keywords: coefficient of variation; concretes; measuring instruments; permeability; test equipment; tests; water-cement ratio
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V. Mohan Malhotra is Head, Construction Materials Section, CANMET, Dept. of Energy, Mines and Resources, Ottawa, Canada. He is Hon. member of ACI, Hon. member of Concrete Society (London), Hon. fellow, Inst. of Concrete Technology (London), and fellow Engineering Institute of Canada.

INTRODUCTION

During 1979-83, investigations sponsored by CANMET led to the development of an apparatus for measuring the water permeability of concrete (1). This apparatus was based on the modifications of test methods proposed by International Standards Organization Technical Subcommittee (ISO/TC-71 SC-1), and that developed by Gjørv and Løland (2,3). Following the development of this equipment, limited data were obtained on the permeability of concrete with a wide range of water/cement and air content. It was concluded that in spite of the large coefficients-of-variation obtained for the permeability values, the test was a valid means of determining the permeability of concrete.

This paper describes some modifications made to the test equipment, and presents additional permeability data for both low- and high-strength concretes.

ORIGINAL TEST APPARATUS

The original test apparatus is described in detail elsewhere (1). It consisted of a series of pressure cells connected to a hydraulic system capable of subjecting the cells to 3.5 MPa pressure (Fig. 1). Each cell contained a cylindrical concrete sample 150 mm in diameter with a height of 150 mm (height from a maximum of 150 mm to a minimum of 50 mm can be used) through which water passed in the longitudinal direction. The equipment was designed to ensure a uniaxial flow. The volume of water passing through the concrete sample, for a given time period, was measured and recorded.

MODIFICATIONS TO THE TEST APPARATUS

Modifications to the Sample Preparation

In the original test procedure, the sides of the concrete sample were sealed with a fiberglass-resin compound to ensure a uniaxial water flow. However, this procedure was cumbersome, and the resin developed cracks on occasion. Therefore, the resin was replaced by an epoxy mortar, which has given
satisfactory performance. The finished sample height is 125 mm.

**Modifications to the Hydraulic System**

In the original apparatus, the cells were connected in parallel by a high pressure line to a pressure vessel (Fig. 2).

The vessel consisted of two cylinders closed at one end and the other end fitted with a welded collar, that can be bolted together. A rubber diaphragm, clamped between the collars divides the interior of the vessel into upper and lower halves. The top section was connected directly to a nitrogen tank, with the bottom section connected, via water filled lines, to the pressure cells. When the gas pressure in the top of the vessel is increased by means of a valve on the nitrogen tank, the diaphragm is pushed downward pressurizing the water in the lower half of the vessel. This increased the water pressure in the lines and, in turn, the pressure in each cell.

The intent of the rubber diaphragm was to prevent the dissolution of nitrogen by the water under high pressure. In the present series of experiments, it was found that the diaphragm did not always fulfill its function, and nitrogen did leak through the diaphragm, forming bubbles in the water, and thus affecting the measurement of the volume of water in the capillary tube measuring device. Therefore, the nitrogen pressure system was replaced by a constant oil pressure equipment (Fig. 3).

The new apparatus provides a pressure of up to 3.5 MPa in increments of 20 kPa, by means of a set of calibrated weights. The accuracy is within 0.5% of set pressure. For initial rapid pressurizing, a handwheel is fitted to the front of the unit to increase the pressure at a higher rate.

**SCOPE**

The objective of the present investigation was to develop within-batch data for non air-entrained and air entrained concrete with water-to-cement ratios of 0.65 and 0.80. Three batches were made for each water-to-cement ratio, and from each batch five test specimens were cast for the permeability test. In addition, tests were performed to determine the feasibility of this method to measure the permeability of very high-strength concrete with a water-to-cementing materials ratio of less than 0.30.

**CONCRETE MIXTURES**

The concrete mixtures were prepared in the Laboratoire de Béton Ltée., Montréal in 1985. A tilting drum mixer was used for the machine mixing procedure of ASTM C-192. The properties of the fresh and hardened concrete were then determined.
Materials

Cement--Portland cement (ASTM Type I) was used.

Aggregate--The coarse fraction consisted of graded crushed limestone with a maximum size of 19 mm, and the fine fraction was natural sand.

The grading and physical properties of the fine and coarse aggregates are given in Tables 1 and 2.

Air-entraining admixture--A sulphonated hydro-carbon type air entraining admixture was used in the air entrained concrete mixtures.

Mixture Proportions

The detailed mixture proportions are given in Table 3.

Properties of Fresh Concrete

The properties of freshly mixed concrete i.e. temperature, slump, density, and air content are given in Table 4.

PREPARATION AND CASTING OF TEST SPECIMENS

Three 150 x 300-mm cylinders for compressive strength tests and five 150 x 125-mm cylinders for permeability tests were cast from each batch. All cylinders were compacted by an internal vibrator. After casting, the moulded specimens were covered with water-saturated burlap and left in the casting room at 23 ± 1.7°C for 24 hours. The cylinders were then demoulded and the densities were determined. Following this, the 150 x 300-mm cylinders were stored in the moist-curing room until required for compression testing; the cylinders for permeability tests were placed in a water bath for 12 days. The test cylinders for high-strength concrete were part of another investigation, and the preparation and casting of the test specimens is described in reference 4.

PERMEABILITY CELLS: DESIGN DETAILS, ASSEMBLY AND OPERATION

Design Details

The detailed design of the stainless steel permeability cells has been described elsewhere (1). Briefly, a cell consisted of:

(1) A cell base fabricated by welding a 200-mm diameter base plate for holding the concrete sample to a 300-mm diameter circular collar.
A groove is cut in the collar adjacent to the sample cell, in which an O ring is fitted to provide water tightness.

(ii) A second hollow collar grooved on its upper inside surface and fitted with an O ring to provide a second seal for water tightness placed over the first collar.

(iii) A cylinder closed at one end and welded to a third collar at the other end designed to fit over the second collar and enclose the concrete sample.

(iv) A series of bolts to hold the total assembly tightly together.

A cross section of a pressure cell is shown in Fig. 4.

Assembly of Permeability Cells

The concrete sample is placed on the cell base fitted with an O ring. The second collar is placed above the cell base and fitted with an O ring. The main cylinder closed at one end is placed on top, and the three steel flanges are bolted together.

The cell is filled with deaerated (boiled) water by means of the top outlet. It is then connected, by means of the same fitting, to the water lines which had been previously water-filled. The valves on the individual water lines to the pressure cells are then opened, and the pressure in the system is gradually increased to 3.5 MPa.

Operation of Permeability Cells

There is variable time delay between the application of the pressure and the appearance of the water in the measuring system. This delay varies with the porosity and hence with the permeability of the concrete. For 14-day old concretes with water-to-cement ratios of 0.80 and 0.65, the delays are from one to 30 hours. For concretes which have been cured for more than 14 days or for concretes with water-to-cement ratios < 0.65, the appearance of outflow water may take several days or months, or the outflow of water may not take place at all. Generally, the rate of outflow increases for several hours before reaching a maximum followed by a gradual decrease. The measurements are only commenced when a steady state of flow is reached. During the first few days, the system is monitored hourly, and when the operation is under control it is monitored twice a day.
DARCY'S LAW FOR UNIAXIAL WATER FLOW

Darcy's law for uniaxial water flow through a saturated medium states that:

\[ q = AKi \]

where

- \( q \) = Volume of water flowing per unit time (m\(^3\)/s)
- \( A \) = Cross sectional area of sample (m\(^2\))
- \( K \) = Coefficient of permeability (m/s)

and

\( i = \frac{\text{Hydraulic gradient across sample}}{(\text{m head/m})} = \frac{\text{(pressure at the top of concrete minus - Pressure at the bottom of concrete)}}{\text{divided by height of the sample}} \)

The pressure at the base of the concrete sample is equivalent to the atmospheric pressure, taken as 101.3 kPa which can be expressed as an equivalent water column of 10.34 m.

The pressure at the top of the concrete was 3.5 MPa, which can be expressed as:

\[ \frac{3.5 \times 1000 \text{ kPa} \times 10.34 \text{ m}}{101.3 \text{ kPa}} = 357.2 \text{ m of water} \]

For a sample with a diameter of 150 mm and a height of 125 mm, the values of \( A \), \( i \), and \( K \) in the above equation are as follows:

\[ A = \frac{\pi D^2}{4} = \frac{\pi (0.150)^2 \text{m}^2}{4} = 0.01767 \text{ m}^2 \]

\[ i = \frac{357.2 \text{ m} - 10.3 \text{ m}}{0.125} = 2775.2 \text{ m head/m} \]

\[ K = \frac{q (\text{m}^3/\text{s})}{0.01767 \text{ m}^2 \times 2775.2 \text{ (m/m)}} = \frac{q}{49.04} \text{ m/s} \]

Solving the above question for a \( q \) value of 1 g/hour (0.000001 m\(^3\)/h or 2.778 x 10\(^{-10}\) m\(^3\)/sec) gives a permeability coefficient of 5.665 x 10\(^{-12}\) m/sec.
TESTING OF SPECIMENS

The test cylinders were capped and tested, in compression, one at 7 days and two at 28 days. Unused cylinders from permeability testing were broken in compression at 91-days.

The cylinders for the permeability testing were removed from the water bath after 12 days, and allowed to dry for one day at room temperature. A dry concrete surface is necessary to achieve a good bond between the concrete surfaces and the epoxy mortar.

Following this, the cylinders were jacketed with an epoxy resin incorporating mineral fillers and fine sand; this was necessary to reduce shrinkage and to prevent bond failure due to cracking. The jacketed cylinders were then placed in the permeability cells for testing.

TEST RESULTS AND THEIR ANALYSIS

A summary of the test results i.e. the rate of flow and the coefficient of permeability is shown in Table 5, and the data are plotted in Fig. 5 to 10. Also shown in the Table are the within-batch coefficients-of-variation and the standard deviation values.

DISCUSSION OF TEST RESULTS

Concrete With W/C of 0.65 and 0.80

The rate of flow of water percolating through concrete is generally very small. For the concrete tested, it is of the order of 1 litre per year. The outflow varies with the duration of the test which also corresponds to the increased hydration of the cement paste with the ageing of the specimen under test. At the beginning of the test, there is a rapid rate of outflow which gradually decreases and starts to stabilize at around 800 hours of testing. After 1200 hours of testing, the rate of decrease tends to be minimal. The coefficient of permeability K, in m/sec, is proportional to the outflow, and follows the same pattern.

The within-batch standard deviation decreases as the test time increases, and follows more or less the same trend as the permeability coefficient.

The coefficient-of-variation is relatively constant within a test series but the variation is somewhat large from one series to another. An average coefficient-of-variation is of the order of 40 per cent.
After 2000 hours of testing, the average values of coefficient of permeability for non air-entrained concrete with water-to-cement ratios of 0.65 and 0.80 are $0.53 \times 10^{-12}$ m/sec and $1.00 \times 10^{-12}$ m/sec, respectively. For air-entrained concrete with water-to-cement ratios of 0.65 and 0.80, the permeability was found to be 0.43 and $1.87 \times 10^{-12}$ m/sec. The initial results indicate lower values for the permeability of air-entrained concrete when compared to non-air entrained concrete at a W/C of 0.65, and a higher value at a W/C of 0.80. However, this is based on only one series of tests for air-entrained concrete.

Initially, two series of tests with W/C of 0.65 and 0.80 were conducted on concrete specimens consolidated by hand rodding. The coefficient of permeability measured on those specimens is considerably higher than that for the vibrated concrete indicating the importance of proper consolidation (Fig. 11 and 12).

**Concrete With W/C of 0.22 and 0.27**

The permeability tests were commenced at an age of 270 days. At this age, the concretes with W/C of 0.27 and 0.22 had attained compressive strength exceeding 80 MPa. After 5000 hours under a pressure of 3.5 MPa in the permeability cells, no outflow of water had occurred. In order to determine the depth of penetration of water in the concrete test specimens, one cylinder with a W/C of 0.27 was broken in splitting tension, and the depth of water penetration was measured. The average penetration depth was 16 mm. Though the tests are being continued on 50-mm specimens to determine if an outflow of water can be obtained, it is considered that the test under study is not a suitable technique to measure the permeability of very high-strength concrete. An alternative approach such as measuring the depth of water penetration in a given time may yield more useful information.

**CONCLUSIONS**

The modifications made to the pressurizing system resulted in making the test relatively simple, and the use of epoxy mortar instead of fiber-resin contributed to the elimination of cracking in the concrete jackets. However, the above modifications did not contribute to any significant decrease in the variability of the permeability test results. It is believed that the high coefficient-of-variation values obtained in the present investigation and the one reported earlier (1) are due to the inherent heterogeneous nature of the concrete itself.
REFERENCES


TABLE 1--GRADING OF AGGREGATES

<table>
<thead>
<tr>
<th>Fine Aggregate</th>
<th>Coarse Aggregate</th>
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<tr>
<td>Sieve Size</td>
<td>Cumulative</td>
</tr>
<tr>
<td></td>
<td>Percentage Retained</td>
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<tr>
<td>4.75 mm (no. 4)</td>
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<tr>
<td>2.36 mm (no. 8)</td>
<td>9.7</td>
</tr>
<tr>
<td>1.18 mm (no. 16)</td>
<td>21.3</td>
</tr>
<tr>
<td>600 µm (no. 30)</td>
<td>45.1</td>
</tr>
<tr>
<td>300 µm (no. 50)</td>
<td>68.5</td>
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<tr>
<td>150 µm (no. 100)</td>
<td>93.6</td>
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<td>74 µm (no. 200)</td>
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<td>Pan</td>
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<td>Fineness Modulus</td>
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### TABLE 2--PHYSICAL PROPERTIES OF AGGREGATES

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<tr>
<th></th>
<th>Fine Aggregate*</th>
<th>Coarse Aggregate**</th>
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<tr>
<td>Specific Gravity</td>
<td>2.64</td>
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<tr>
<td>Absorption</td>
<td>0.60%</td>
<td>0.8%</td>
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<tr>
<td>Unit weight (kg/m³)</td>
<td>----</td>
<td>1648</td>
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*Natural sand  
**Crushed limestone

### TABLE 3--CONCRETE MIXTURE PROPORTIONS

<table>
<thead>
<tr>
<th>W/C (by weight)</th>
<th>Cement, kg/m³</th>
<th>Aggregate</th>
<th>Fine, kg/m³</th>
<th>Coarse, kg/m³</th>
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<td>231</td>
<td>832</td>
<td>1118</td>
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<td>284</td>
<td>814</td>
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<td>829</td>
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<td>0.65</td>
<td>253</td>
<td>789</td>
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<td>HIGH-STRENGTH CONCRETE</td>
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<td>0.27*</td>
<td>508**</td>
<td>710</td>
<td>1060</td>
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</tr>
<tr>
<td>0.22*</td>
<td>605**</td>
<td>570</td>
<td>1050</td>
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*Water-to-cementitious materials ratio.  
**Includes 15% fly ash and 6% silica fume.
<table>
<thead>
<tr>
<th>W/C</th>
<th>Mixture No.</th>
<th>Concrete Temperature °C</th>
<th>Slump, mm</th>
<th>Air Content, %</th>
<th>Unit Weight, kg/m³</th>
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<td>0.80</td>
<td>3</td>
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<td>20</td>
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<td></td>
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<td>80</td>
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<td>100</td>
<td>5.8</td>
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NOTE: Test specimens from mixture nos. 2 and 3 were compacted by hand rodding whereas test specimens from mixture nos. 5, 6, 4, 7, 9 and 10 were compacted by vibration.
TABLE 5—SUMMARY OF PERMEABILITY TEST RESULTS ON CONCRETE CYLINDERS: DIAMETER 150 mm, HEIGHT 125 mm, PRESSURE 3.5 MPa

<table>
<thead>
<tr>
<th>Series No.</th>
<th>Hours Under Test</th>
<th>Average Rate of Flow g/h</th>
<th>Permeability Coefficient &quot;K&quot; m/s x 10^-12</th>
<th>Number of Specimens</th>
<th>Within-Batch</th>
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<tr>
<td></td>
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<td></td>
<td>Standard Deviation m/s x 10^-12</td>
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<td>65-2*</td>
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<td>1.32</td>
<td>4</td>
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*Hand rodded specimens
Fig. 1--Assembled test apparatus

Fig. 2--View of the pressure vessel
Fig. 3--New constant pressure equipment which operates by means of a set of calibrated weights.

Fig. 4--Cross section of a pressure cell.
Fig. 5--Permeability versus time for non air-entrained concrete with a w/c of 0.65 — Mixture no. 4

Fig. 6--Permeability versus time for non air-entrained concrete with a w/c of 0.65 — Mixture no. 7
Fig. 7--Permeability versus time for non air-entrained concrete with a w/c of 0.80 — Mixture no. 5

Fig. 8--Permeability versus time for non air-entrained concrete with a w/c of 0.80 — Mixture no. 6
Fig. 9--Permeability versus time for air-entrained concrete with a w/c of 0.65 — Mixture no. 10

Fig. 10--Permeability versus time for air-entrained concrete with a w/c of 0.80 — Mixture no. 9
Fig. 11--Permeability versus time for non air-entrained concrete with a w/c of 0.65 -- Mixture no. 2

Fig. 12--Permeability versus time for non air-entrained concrete with a w/c of 0.80 -- Mixture no. 3
Permeability of Selected Concretes

by D. Whiting

Synopsis: A study of permeability was made using six concrete mixtures ranging in water-to-cementitious material (w/c) ratio from 0.26 to 0.75. Concrete specimens were tested for permeability to water and air, permeability to chloride ions (rapid and long-term), volume of permeable voids, and porosity. Results confirm that permeability is a direct function of w/c ratio. The addition of silica fume results in even greater decreases in permeability than would be anticipated based solely on w/c ratio. A period of initial moist curing of at least seven days is essential for achieving low permeability. Results also indicate that rapid test procedures offer a reasonable alternative to more lengthy and complex conventional permeability tests.

Keywords: absorption; chlorides; concretes; moist curing; permeability; porosity; silica fume; tests; voids; water-cement ratio
ACI member David Whiting is a Principal Research Engineer at Construction Technology Laboratories, Inc. Skokie, Ill. Dr. Whiting has been at CTL for thirteen years, working in the area of concrete materials research. His field of activity includes concrete admixtures, corrosion of reinforcing steel, concrete permeability, durability studies, coatings for concrete, and thermal properties. He is a member of ACI Committees 201, Durability of Concrete; 212, Chemical Admixtures; and 222, Corrosion of Metals in Concrete.

HIGHLIGHTS

There is a growing awareness of the important role of permeability with regard to the long-term durability of concrete structures. A renewed interest in this subject has led to a need for test procedures that can be used to rapidly assess the permeability of concretes. The use of admixtures such as high-range water reducers (HRWR), silica fume, and latex emulsions allows placement of highly impermeable concretes for a variety of applications. More information on effects of concrete mix design, use of admixtures, and curing requirements is needed so that low permeability concretes can be uniformly specified and manufactured. As a variety of test procedures have been used to characterize permeability of concretes, a knowledge of the interrelationships between these various procedures is needed so that test results may be compared on a rational basis.

Objectives and Scope

The objectives of the study were twofold; first, to establish the effects of mix design variables, materials, and curing on permeability of selected concrete mixtures, and second, to compare results on this set of concretes using a variety of test procedures. These procedures included conventional steady-state flow tests for air and water permeability, as well as novel, more rapid, test methods.

The program included concretes prepared with w/c ratios ranging from 0.26 to 0.75. Silica fume and HRWR were used to produce the low w/c ratio mixtures. Curing included a "standard" 7-day moist cure as well as simulation of cases where only a minimal cure is used. After a 90-day conditioning period, concretes were subjected to a variety of tests. These included permeability to air and water, ponding with chloride solution, "rapid chloride permeability," helium porosity, and volume of permeable voids.
FINDINGS AND CONCLUSIONS

1. Results of this study confirm the strong influence that w/c ratio has on permeability of concrete. Permeability of water under hydrostatic head increased up to four orders of magnitude when the w/c ratio was increased from 0.26 to 0.75. Amounts of chloride ion detected within the first 1-1/2 inch (40mm) of concrete cover, after 90-day ponding with sodium chloride solution, increased by a factor of ten over the same range of w/c ratios.

2. Maintenance of moist curing for the minimum of 7-days recommended in ACI 308 results in a more impermeable concrete. This is especially important at higher w/c ratios. At a w/c ratio of 0.75, permeability to liquid water was almost five times greater for concretes given a minimal moist curing period of 24 hours as opposed to those moist cured for a full 7 days.

3. Concretes produced at w/c ratios less than 0.3, especially when silica fume was utilized, were virtually impermeable to water and chloride ions. These concretes should be considered for severe exposure conditions where concrete is subjected to high hydraulic heads, where it is necessary to prevent chloride ions from penetrating the concrete, when unique freeze-thaw conditions exist, or where deleterious chemicals must be resisted.

4. Several rapid test procedures are available that can be used to estimate permeability in lieu of more complex flow testing. These include the rapid chloride permeability test (AASHTO T 277) and a test for the volume of permeable voids (ASTM C 642). Correlation between results of rapid chloride permeability tests and long-term ponding and hydraulic permeability tests for the same set of concretes is excellent.

BACKGROUND

In recent years there has been a renewed interest in the permeability of concrete. Much of this interest relates to the realization that durability is often a determining factor in the life of a concrete structure, and that durability may be directly related to permeability of the concrete in question. If an aggressive substance, be it water, sulfate or chloride ions, or other materials, can be kept out of concrete by virtue of low permeability, then associated problems, such as freeze-thaw deterioration, corrosion of reinforcement, and formation of expansive components, may be mitigated. Therefore, there has been an interest both in determining permeabilities of conventional concretes, and in development of improved concretes having very low permeabilities.
Those concerned with this problem have generally adopted a broader definition of "permeability" than that associated with saturated flow under a hydraulic gradient. Permeability is viewed as the ability of a given concrete to resist penetration of a particular substance (be it liquid, gas, ions, etc.). This ability may be expressed in absolute units of flow (e.g. cm/sec), by the amount of substance deposited in a given time, or as a relative ranking derived from a test. For the present study, all of these categories are considered measures of "permeability".

The need for data on concrete permeability dates from the early 1930's, when designers of large hydraulic structures required information on rates of passage of water through concrete under the influence of relatively high hydraulic heads. These "lean mass concretes" generally had w/c ratios greater than 0.5 and cement contents less than 500 lb/yd³ (840 kg/m³). In such instances, flow of water through concrete can be adequately described by Darcy's Law (1) as:

\[ Q = \frac{k \cdot A \cdot dp}{\mu \cdot ds} \]

Where
- \( Q \) = volume outflow (cm³/sec)
- \( A \) = area (cm²)
- \( \mu \) = viscosity (centipoise)
- \( \frac{dp}{ds} \) = pressure gradient (atmos/cm)
- \( k \) = permeability constant ("darcy's")

If SI units are used throughout, then the permeability constant is expressed in terms of m². Conversion factors are given in Table 1.

Primary factors influencing hydraulic permeability were found to be w/c ratio and age of concrete. Ruettgers, et al. (2) found permeabilities to increase from about 5x10^-11 cm/sec (5x10^-20 m²) at w/c ratios less than 0.5 to 5x10^-8 cm/sec (5x10^-17 m²) at w/c above 0.8. Effects of age of concrete were more difficult to determine experimentally, as flow rates generally decreased over time during the test. However, Glanville (3) noted a twentyfold decrease in permeability between 7 days and 12 months of age for a concrete with w/c ratio of 0.60. Recent studies by Gaerty and Freeman(4) have confirmed the importance of age of concrete on permeability, especially as regards the benefits of early moist curing on subsequent reductions in permeability.

Flow of substances other than water through concrete have also received some attention. Mantialay(5), using applied pressures of approximately 2 atmospheres (0.2MPa), found air permeabilities of concretes stored for 20 months in laboratory air to range from 1.4x10^-7 cm/sec (1.4x10^-16 m²) at w/c = 0.37 to 3.3x10^-7 cm/sec (3.4x10^-16 m²) at w/c = 0.52. Permeabilities to such fluids as liquid nitrogen (6), methane
Concrete Permeability

(7) and oil (8) have also been measured. In general, permeabilities to gases are from 1 to 2 orders of magnitude greater than those for water, which is to be expected from comparative viscosities of the respective fluids.

Under conditions other than those of saturated fluid flow, transport of substances through concrete can occur by a variety of different mechanisms. These may include: 1) capillary attraction, 2) vapor transmission, or 3) ionic diffusion. Data developed by Wing(9) and Dunagan(10) indicate that movement of water into dry concrete via capillary attraction can be quite rapid and approach fluid flow rates in saturated concrete brought about by application of 400 psi (2.8MPa) hydraulic pressure to the specimen. An initial surface absorption test--ISAT has been developed using these principles.

There is currently much concern with corrosion of reinforcing steel promoted by chloride ions that penetrate through the concrete cover and eventually reach the reinforcement. While in dry to semi-dry concretes these ions can migrate along with water under the influence of capillary attraction, in near-saturated concrete, migration of chloride ions occurs primarily through diffusion processes. Various studies (11-13) indicate the coefficient of diffusion to be of the order of $10^{-7}$ to $10^{-8}$ cm$^2$/sec. Diffusion will generally follow Fick's Second Law as:

$$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2}$$

(2)

Where:

- $C$ = concentration at distance $x$(cm) from a boundary
- $t$ = time (sec)
- $D$ = effective diffusion coefficient (cm$^2$/sec)

Concentration as a function of time may be determined using classical diffusion cell techniques (14), an approach limited to the laboratory environment. Alternatively, field samples of concrete can be obtained, analyzed for chloride ion using wet chemical analysis(15), and concentration gradients can be constructed from which $D$ may be calculated. Simple measurement of the amount of chloride ion deposited at a given level in the concrete(16) may also serve as a relative indication of permeability to chloride ions. A rapid test procedure(17) based on ion migration under an imposed electric field is being increasingly used to obtain relative indications of chloride permeabilities of various concretes.

While a need for inclusion of permeability limits in specifications for certain concrete applications is gradually being recognized, the existence of a plethora of laboratory
and field test procedures creates confusion on the part of the user as to just what should be specified. The designers of a dam may accept a "permeability" value which would be far too high for the designer of a parking deck who wished to keep chloride ions from entering the concrete. Some specifications may call for such low values of hydraulic permeability that they cannot be measured by current techniques, the aim being to obtain permeabilities low enough to prevent ionic migration into concrete. In such cases more appropriate test methods may be needed. Comparisons of a variety of test methods using the same set of well-characterized concretes was needed to develop relationships between the various techniques available. In addition, comparisons of permeability data with other measures of concrete "quality," such as absorption or void volume, affords a greater confidence in use of these techniques as rapid, indirect measures of permeability. Therefore, the study described in this paper was undertaken.

MATERIALS

Cement and Silica Fume

The cement used in this study was a blend of three Type I cements. Calculated potential compound compositions and other pertinent data are presented in Table 2.

Silica fume was obtained from a ferro-silicon alloy producer located in the northwestern United States. Pertinent properties are included in Table 3.

Fine Aggregate

Natural siliceous sand from Eau Claire, Wisconsin was used in all concrete mixtures. The total chloride content of this sand was very low (<0.01%), making it ideal for use in a study where analyses for chloride ion were to be performed. Sand was conditioned to a moisture content less than 3 percent prior to batching of concrete. Pertinent data are given in Table 4. This particular lot of sand was somewhat coarser than would normally be desirable; however, workability of concretes was acceptable.

Coarse Aggregate

Crushed limestone from Milan, Illinois was used as the coarse aggregate. As with the sand, this stone was chosen based on its low chloride content. Pertinent data are also included in Table 4.
Admixtures

Two chemical admixtures were used in this study. The first was a hydroxycarboxylic acid-based water reducer (ASTM C 494 Type A) supplied in liquid formulation at 42 percent solids. The second was a sulfonated naphthalene-formaldehyde condensate (ASTM C 494 Type F) supplied at 42 percent solids.

CONCRETE MIXTURES AND MIX PROCEDURES

Mix Designs

Six different mixtures were used in this study. They were designed to cover a wide range of w/c ratios and cement contents. Mix quantities, slumps, and air contents are given in Table 5. W/c ratios ranged from 0.26 for mixture number 1 to 0.75 for mixture number 6. Slump was controlled at 4±1-inch (100±25mm). All concretes were non-air entrained so as to eliminate effects that variation in air contents might have on measured permeabilities. Compressive strength data are given in Table 6.

Mixing Procedures

Coarse aggregate was weighed and then inundated with water in a closed container 18 to 24 hours prior to mixing. Immediately before mixing, a measured amount of water was drained from the container such that the water remaining (which was subsequently placed into a second container) would satisfy the absorption of the aggregate plus the net amount of water required for the batch. Fine aggregate was weighed and batched in a moist condition. All mixing was carried out in a 1.75 cu. ft. (0.044 m³) counter-current open pan mixer. Charging sequence was coarse aggregate, cement (and silica fume, if used), sand, and the remainder of the mixing water. Concrete was mixed until the batch had obtained a homogeneous appearance, then mixing was continued for an additional 3 minutes. In cases where chemical admixtures were used (mixtures 1, 2, and 3) the admixture was added just after homogeniety was achieved, and the concrete then mixed an additional 3 minutes.

SPECIMEN PREPARATION AND CURING

A variety of specimens were prepared from each batch for each particular test procedure used in the study. Specimen type, dimensions, and associated test procedures were:
Compressive Strength - 4x8-in. (100x200-mm) cylinders cast in plastic molds.

Rapid Chloride Permeability - 2-in. (50mm) thick x 4-in. (100 mm) diameter disks cast in plastic molds.

Water and Air Permeability, Porosity, Volume of Permeable Voids - 4x8-in. (100x200-mm) cylinders cast in plastic molds—Tests carried out consecutively on the same set of specimens.

Chloride Ion Penetration ("90-day ponding"-12x12x3-in.) (300x300x75-mm) slabs cast in sheet metal forms.

All specimens were consolidated using hand-rodding and finished using a wooden float. Specimens were covered with moist burlap and plastic sheeting for 18 to 24 hours after casting. At the end of this time period one set of specimens from each batch was placed in a room maintained at 73±3°F (23±1.5°C) and 50±5% R.H. All cylindrical specimens were left in their molds in order to simulate conditions seen in an actual concrete member, where air drying would mostly occur from a single exposed surface. The slab specimens were coated with an epoxy resin to restrict loss of moisture from all but the top (finished) surface. A second set of specimens was placed into a fog room at 73±3°F (23±1.5°C) immediately after removal of the moist burlap. The cylindrical and disk specimens in this case were also left in their molds. After 7 days of moist curing the second set of specimens from each batch was placed in the air-dry environment along with the first set. After 1-day of air drying the slab specimens from the second set also were coated with epoxy.

All specimens were maintained in their molds in the air-dry environment for a period of 90-days. This was done so that the concretes would reach a relatively high degree of maturity prior to testing. In addition, casting of the concrete mixtures was staggered so as to minimize differences in age between mixtures at the time of testing.

TEST PROCEDURES

In all, six different test procedures (for permeabilities, porosity, and void content) were used in this research program. As some of these procedures are adequately described in published standards, only brief descriptions of the procedures will be reported. Where techniques not commonly used for testing of concrete materials were employed, more detailed information is supplied.

Hydraulic Permeability

Permeability to liquid water under saturated conditions was determined using American Petroleum Institute (API)
concrete permeability procedures (18). The test apparatus, along with a typical 4x8-inch (100x200-mm) test specimen is shown in Fig. 1. Prior to test, the specimen was conditioned by evacuation at 1 mm of mercury (133 Pa) for 24 hours and then pressurized under air-free distilled water at 2,000 psi (13.8 MPa) until a stable pressure was reached. The specimen was then removed from the conditioning chamber and placed in a hydrostatic core holder which allowed confining pressures up to 3,500 psi (24 MPa) to be applied to the outer periphery of the specimen through a water-tight jacket. The top surface of the specimen was then subjected to an injection pressure of 3,000 psi (20 MPa) and outflow from the bottom face monitored using a capillary pipette. Specimens were left under pressure for a minimum of 48 hours. The permeability in darcys (m^2), was then calculated from the outflow rate, in cm^3/sec, using equation 3:

\[
    k = \frac{\mu \cdot Q}{A \cdot dp/dx}
\]

Where:
- \( k \) = permeability, in darcys (m^2)
- \( \mu \) = viscosity of fluid, 1 cp (0.001 Pa·s) for water
- \( Q \) = outflow rate, in cm^3/sec (m^3/s)
- \( A \) = average cross sectional area perpendicular to line of flow, in cm^2 (m^2)
- \( dp/dx \) = pressure gradient along line of flow, in atmosphere/cm (Pa/m).

**Air Permeability**

Air permeability measurements were carried out after hydraulic permeability testing was concluded. As permeability to gases is strongly dependent on the moisture content of the specimen, all test specimens were oven-dried at 140°F (60°C) to constant weight prior to testing. Constant weight was taken at that point beyond which weight losses were less than 0.5 grams per specimens per 48-hour period.

Standard API procedures were followed. The "Hassler" type permeameter used for these tests is shown in Fig. 2. The 4x8-inch (100x200-mm) concrete test specimen was sealed into the cell by application of an external pressure to a rubber boot surrounding the periphery of the specimen. Air was introduced through a source valve to the upstream face of the sample. After steady-state was achieved the upstream and downstream pressures were recorded. Flow rate was determined by measuring the pressure drop across a calibrated orifice located a short distance downstream of the sample. Permeability, in darcys (m^2), was then calculated using equation 4:
Where:

\[ k_g = \frac{2 \cdot \mu \cdot Q_g \cdot P_b \cdot L}{A \cdot (P_2 - P_1)} \]  

(4)

- \( k_g \) = gas permeability, in darcys (m^2)
- \( \mu \) = gas viscosity, in centipoise (Pa•s)
- \( Q_g \) = gas flow rate, in cm^2/sec(m^3/s)
- \( P_b \) = barometric pressure, in atmospheres (Pa)
- \( P_1 \) = inflow (upstream) pressure, in atmospheres (Pa)
- \( P_2 \) = outflow (downstream) pressure, in atmospheres (Pa)
- \( A \) = Average cross-sectional area perpendicular to line of flow, in cm^2(m^2)
- \( L \) = Length of flow path, in cm(m)

Rapid Test for Permeability to Chloride Ions (RCPT)

This test procedure was developed as a rapid means of assessing permeability of concrete to chloride ions. Full details of the development, application, and limitations of the method have been given by Whiting(17). Briefly, a potential of 60Vdc is applied across a 4-in. diameter x 2-in. thick slice of concrete which has been conditioned by vacuum saturation. After six hours under test, the total charge passed through the specimen (in Coulombs) is obtained by integration of the current passed through the specimen during the 6-hour test period. As a measure of permeability the test is indirect. Its utility lies in the relationships developed between charge passed and long-term measurements of chloride intrusion into companion concretes. Such correlations have been developed(17) and were used to develop the relative permeability rankings shown in Table 7. The procedure is therefore semi-quantitative, more significance being attached to the permeability "class" into which the results fall than to the absolute value of charge passed. This test has been adopted as AASHTO Designation: T277-83 (Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete).

Chloride Ion Penetration

The amount of chloride ion penetrating into test concretes in a given period of time was measured using a technique similar to that described in AASHTO Designation: T 259-80 (Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration). Briefly, concrete test specimens, in the form of 12x12x3-in. (300x300x75-mm) slabs, were ponded with a 3\% solution of sodium chloride for a period of 90-days. At the end of this time period, the solution was removed and samples of concrete were taken using a 1-in. (25-mm) diameter rotary hammer drill. Previous work(17) has shown that triplicate drill samples taken from 1/16 in. to 1-5/8 in. (2 to 40 mm) give a good representation of the total
amount of chloride entering the slab. The samples are analyzed for total chloride ion content (by weight of concrete) using acid digestion and a potentiometric titration procedure.

Porosity

The technique chosen for measurement of the total porosity of the specimen was helium porosimetry. The small molecular size and inertness of the helium molecule make it an ideal penetrant for cementitious systems having restricted pore openings and significant surface activity. The principle of the method is based on Boyle's Law for isothermal gas expansion, given as equation 5:

\[ P_1V_1 = P_2V_2 \]  

A known volume of gas \( V_1 \) at a pressure \( P_1 \) is expanded into an unknown volume \( V_2 \), where a final pressure \( P_2 \) is established. The resultant pressure is then used to calculate the unknown volume. In the porosimeter used, the unknown volume \( V_2 \) is the sum of the volume of void space in the specimen \( V_v \) plus the dead volume (volume without test specimen \( V_d \)) of the porosimeter, minus the bulk volume \( V_b \) of the specimen. Porosity, in percent, can then be expressed as:

\[ P = 100 \cdot \left[ \frac{V_2-V_d}{V_b} + 1 \right] \]  

Porosity measurements were performed on the same specimens immediately following the air permeability measurements. Following the porosity measurements, tests for volume of permeable voids were carried out, as described in the next section.

Volume of Permeable Voids

This series of tests was carried out in accordance with ASTM Designation: C 642 (Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete). The method consists of drying the specimens at 212 to 230°F (100 to 110°C) to constant weight, immersion of the specimens in water at 70°F (21°C), until uptake of water is minimized, then boiling the specimens for 5 hours and subsequently obtaining weights in water and air. In this method the "volume of permeable void space" is defined as that void volume which is emptied during the specified drying and filled with water during the subsequent immersion and boiling. Any voids which do not empty during drying, or which do not fill with water during wetting, would not be included in the pore space measured by this method.
The volume of permeable voids ($V_p$) is calculated from equation 7 as:

$$V_p = \frac{C - A}{C - D} \cdot 100$$  \hspace{1cm} (7)

Where:

- $V_p$ = volume of permeable voids, %
- $A$ = weight of oven-dry sample in air, gm.
- $C$ = weight of sample in air after immersion and boiling, gm.
- $D$ = weight of sample in water after boiling, gm.

RESULTS AND DISCUSSION

Presentation of Test Data

Test data are presented in Table 8. All values represent the average of triplicate specimens. For mixtures 1 and 2, prepared at very low w/c ratios, the amount of water flowing through the test specimen during testing for hydraulic permeability was not measurable.

Also shown in Table 8 are average coefficients of variation for the sets of triplicate specimens for each test procedure. For the permeability tests, coefficients of variation range from 7.9% for the RCPT to 20.9% for hydraulic permeability. These statistics are in the range to be expected for these techniques (17, 18) and illustrate the variability to be expected with permeability testing in general. Scatter in results of "static" tests involving measurement of porosity and void volumes is much lower, as might be expected for these less complicated procedures.

Effects of Mix Composition and Curing

For the mixtures tested in this investigation the variable having the greatest effect on permeability was the w/c ratio. This is illustrated in Fig. 3 for the series of RCPT tests. Mixtures prepared with very low w/c ratios, less than 0.30, showed very low to negligible permeabilities. Above a w/c ratio of 0.5, permeability would be classified as "high" using the guidelines established for this test (Table 7). It is of interest that the values measured for mixture 1 (containing silica fume) are within the same range as those measured on polymer-impregnated concretes in a previous study(17). The relationships between w/c ratio and permeability are logarithmic, as illustrated in Fig. 4 and 5, for RCPT and hydraulic permeability, respectively. The greatest change in permeability (per unit change in w/c ratio) occurs at lower values of w/c ratio. Fig. 6 illustrates that the amount of
permeable voids also show a greater increase at lower w/c ratios. At intermediate values of w/c ratio there is less of an effect of increased water content on volume of permeable voids.

The fairly good fit obtained using the logarithmic relationships between hydraulic permeability and w/c ratio in Fig. 5 indicates that this function may be used to extrapolate values for w/c ratios where hydraulic permeabilities could not be experimentally determined. Using the data for 7-days of moist curing, the relationship can be expressed as follows:

\[ Y = -4.518 + 5.119X \]  

Where:

- \( Y \) = log\(_{10}\) of hydraulic permeability (μdarcys)
- \( X = 1 + \log_{10}(w/c) \)

Extrapolation to a w/c of 0.26 yields a hydraulic permeability of 4x10\(^{-11}\) darcys (3.9x10\(^{-22}\)m\(^2\)). This is indeed a very small value, which would be difficult to accurately determine using a direct water flow test. The rapid test, in this instance, offers an alternative to standard flow testing for concretes of very low permeability.

These data also illustrate the beneficial effects of early moist curing on reduction of permeability. In nearly all cases, maintaining moist conditions for seven days after casting resulted in reductions in permeability and void volumes. The benefits of initial moist curing become greater as w/c ratio is increased, as can be seen by examination of the divergence in the fitted lines in Fig. 3 through 5. At a w/c ratio of 0.75, there is a fivefold decrease in permeability as initial moist curing is increased from 1 to 7 days. Similar trends have been noted by Gaerty and Freeman(4). In their studies the effects of moist curing were even more substantial, as tests were performed 21 days after the initial cures. For their tests there was a tenfold decrease in permeability between the 1 and 7 day cures.

Comparison of Techniques

Although the effects of mix design variables on permeability are certainly important, much of this information has already been disseminated in a general sense. There is an appreciation that lowering w/c ratio will decrease permeability, and that increasing the length of moist curing will result in a more impermeable concrete. While this study helps to quantitatively define these relationships, a more unique aspect of the research concerns comparisons between the various tests techniques. While each technique measures a separate parameter, it was expected that there should be some underlying commonality between results when compared over a variety of concretes. To establish relationships between the
techniques chosen for evaluation, regression analyses were carried out. This consisted of fitting the data to the best linear relationships using a least-squares approach. In many cases, transformations of the variables were necessary to linearize the data sets. Results of such analyses are presented in Table 9. This table represents what may be termed a "correlation matrix". In this first column the techniques used as independent (X) variables are listed. The dependent (Y) variables, upon which the X variables are regressed, are shown in the top row of the table. The values shown represent correlation coefficients ($R^2$) for the various relationships. Values in parentheses represent standard errors of estimate, expressed as a percent of the mean Y value.

Analyses were not carried out on every possible combination of variables, only on those where relationships developed might prove useful in future test programs. For instance, the RCPT allows results to be obtained in approximately 3 days, as opposed to over 90 days for standard ponding tests. Therefore, it is of interest to evaluate how well long-term permeability can be predicted by the RCPT results.

For the majority of comparisons made, the association between the two variables (as measured by the correlation coefficient) is quite good. Many of the relationships exhibit correlation coefficients of 0.95 or greater. The usefulness of the RCPT in ranking of concretes with respect to their long-term permeabilities to chlorides is confirmed in this study. A correlation coefficient of 0.99 was obtained for this relationship (Fig. 7). Standard error of the estimate was approximately 10 percent. The RCPT also offers a reasonable estimate of hydraulic permeability (Fig. 8), the correlation being only slightly worse than for the previous comparison. The RCPT is not as good a predictor of air permeability, here the correlation coefficient is 0.95 and, more importantly, the standard error is close to 30 percent. The differences in mechanism of mass transfer between the two tests may help explain this. Ionic transfer, which occurs in the RCPT and ponding tests, must occur through solutions contained within the pore system. Thus, this transfer most likely occurs through the same pathways as does saturated liquid flow. The air permeability measurements were carried out on dried concretes, where pathways for flow of air molecules may be available that would be restrictive to flow of liquid.

The relationships between porosity, void volume, and the various permeability tests are also of interest, as porosity and void volume can be obtained fairly rapidly using simple tests procedures. Results indicate that the test for volume
of permeable voids (ASTM C 642) shows reasonable correlation with a number of the more time consuming permeability tests. Its standard errors, however, are higher than those obtained using the RCPT, thus some sacrifice of precision must be expected. Additionally, when time needed for oven-drying and cooling subsequent to boiling are taken into account, a full C 642 test would take nearly 5 days to complete, as compared to three days using the RCPT. On the other hand, capital investment in equipment is less for C 642, and a larger number of specimens could be tested simultaneously. In any case, these data do indicate that rapid test procedures, such as the RCPT or ASTM C 642, can be used as measures of relative permeability, although the tests do not measure "permeability" as conventionally defined.

SUMMARY

The importance of mix design variables and curing with respect to concrete permeability have been confirmed. To achieve watertight, impermeable concretes, low water-to-cementitious ratios and moist curing should be employed. If concrete is not moist cured for at least seven days, permeabilities may increase fourfold or more. By restricting w/c ratios to a maximum of 0.4, concretes with permeabilities low enough to withstand significant hydrostatic pressures can be achieved.

Concretes designed to attain low permeability should be tested prior to actual construction. Several rapid test procedures may be utilized. This research has demonstrated that the rapid chloride permeability test (RCPT) offers a reliable means for quickly assessing the relative permeabilities of a variety of concretes. As an alternative, simple absorption-based test procedures, such as ASTM C 642 may also be employed, although total test time is greater and predictability is less than for the RCPT.

ACKNOWLEDGEMENTS

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REFERENCES


4. Gaerty L. and Freeman, R.J., "Permeability of Concrete", New Zealand Concrete Construction, pp 3-6 (March 1986).


16. AASHTO Designation: T259-80 (Resistance of Concrete to Chloride Ion Penetration).


### TABLE 1--CONVERSION* TABLE FOR PERMEABILITY** UNITS

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<th>darcy</th>
<th>millidarcy</th>
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<th>m²</th>
<th>Meiners</th>
<th>ft/day</th>
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</table>

* To convert from units in column at left to units at top multiply by indicated factor.

** Conversions given are appropriate for cases of saturated, steady-state flow. For units associated with diffusion processes, or with relative, empirical test procedures, no direct conversions are available.
**TABLE 2—COMPOSITION OF CEMENT BLEND**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_3S$, %</td>
<td>59.1</td>
</tr>
<tr>
<td>$C_2S$, %</td>
<td>14.8</td>
</tr>
<tr>
<td>$C_3A$, %</td>
<td>8.1</td>
</tr>
<tr>
<td>$C_4AF$, %</td>
<td>7.8</td>
</tr>
<tr>
<td>Alkali (as Na$_2$O)</td>
<td>0.68</td>
</tr>
<tr>
<td>$SO_3$, %</td>
<td>3.0</td>
</tr>
<tr>
<td>MgO, %</td>
<td>2.5</td>
</tr>
<tr>
<td>Loss on Ignition, %</td>
<td>1.8</td>
</tr>
<tr>
<td>Insoluble Residue, %</td>
<td>0.2</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>3.09</td>
</tr>
<tr>
<td>Blaine Fineness ($m^2/gm$)</td>
<td>374</td>
</tr>
</tbody>
</table>

**TABLE 3—SILICA FUME COMPOSITION**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica, %</td>
<td>92 - 93</td>
</tr>
<tr>
<td>Carbon, %</td>
<td>4 - 5</td>
</tr>
<tr>
<td>$Fe_2O_3$, %</td>
<td>0.1 - 0.50</td>
</tr>
<tr>
<td>CaO, %</td>
<td>0.10 - 0.15</td>
</tr>
<tr>
<td>Al$_2$O$_3$, %</td>
<td>0.20 - 0.30</td>
</tr>
<tr>
<td>MgO, %</td>
<td>0.10 - 0.20</td>
</tr>
<tr>
<td>MnO, %</td>
<td>0.008</td>
</tr>
<tr>
<td>K, %</td>
<td>0.10</td>
</tr>
<tr>
<td>Na, %</td>
<td>0.10</td>
</tr>
<tr>
<td>S, %</td>
<td>0.10</td>
</tr>
<tr>
<td>Volatiles at 105°C, %</td>
<td>0.8</td>
</tr>
<tr>
<td>Average particle size, $\mu m$</td>
<td>0.1</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.07</td>
</tr>
<tr>
<td>Blaine Fineness ($m^2/gm$)</td>
<td>5115</td>
</tr>
</tbody>
</table>

*As reported by manufacturer.*
### TABLE 4—AGGREGATE PROPERTIES

<table>
<thead>
<tr>
<th>Source</th>
<th>Grading - % Retained on Sieve size Indicated</th>
<th>Fineness Modulus</th>
<th>Bulk Specific Gravity - SSD</th>
<th>Absorption - % by wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eau Claire, Wisc. Sand</td>
<td>No. 4 8 16 30 50 100</td>
<td>3.10</td>
<td>2.66</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>% 4 19 33 63 92 99</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milan, Ill. Stone</td>
<td>3/4 in. 3/8 in. No. 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 50 100</td>
<td>2.64</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>
### TABLE 5—CONCRETE MIX PROPORTIONS AND CHARACTERISTICS

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Quantities, lb. per cu yd*</th>
<th>Admixture(s)</th>
<th>W/C Ratio**</th>
<th>Slump**** (in.)</th>
<th>Air Content %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750 1266 1738 222</td>
<td>Microsilica - 100 lb/yd³</td>
<td>0.258</td>
<td>4.7</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HRWR Type F - 39 fl. oz/cwt***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>750 1330 1824 216</td>
<td>HRWR Type F - 20 fl. oz/cwt</td>
<td>0.288</td>
<td>3.5</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>642 1320 1809 257</td>
<td>WR Type A - 3.4 fl. oz/cwt</td>
<td>0.401</td>
<td>3.5</td>
<td>2.3</td>
</tr>
<tr>
<td>4</td>
<td>550 1336 1831 276</td>
<td>--</td>
<td>0.502</td>
<td>3.7</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>500 1332 1828 300</td>
<td>--</td>
<td>0.600</td>
<td>4.2</td>
<td>1.8</td>
</tr>
<tr>
<td>6</td>
<td>413 1363 1864 311</td>
<td>--</td>
<td>0.753</td>
<td>4.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>

---

* To convert from pounds per cubic yard to kilograms per cubic meter multiply by 0.594.

** For Mixture No. 1 expressed as ratio of water to cementitious material (cement plus silica fume).

*** To convert from fl. oz/cwt to ml/kg, multiply by 0.652.

**** To convert from inches to millimeters, multiply by 25.4
TABLE 6--COMPRESSIVE STRENGTH OF CONCRETE SPECIMENS AT 90 DAYS

<table>
<thead>
<tr>
<th>MIXTURE</th>
<th>Compressive Strength - psi*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 day moist cure</td>
</tr>
<tr>
<td>1</td>
<td>15,250</td>
</tr>
<tr>
<td>2</td>
<td>11,540</td>
</tr>
<tr>
<td>3</td>
<td>6,530</td>
</tr>
<tr>
<td>4</td>
<td>5,090</td>
</tr>
<tr>
<td>5</td>
<td>5,110</td>
</tr>
<tr>
<td>6</td>
<td>3,580</td>
</tr>
</tbody>
</table>

* To convert from psi to MPa multiply by 6.895 X 10^-3

TABLE 7--RAPID CHLORIDE PERMEABILITY TEST
INTERPRETATION OF RESULTS

<table>
<thead>
<tr>
<th>Relative Permeability</th>
<th>Charge Passed (Coulombs)</th>
<th>Type of Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>&gt;4,000</td>
<td>High water-cement ratios ( \geq (0.6) )</td>
</tr>
<tr>
<td>Moderate</td>
<td>2,000 to 4,000</td>
<td>Moderate water-cement ratios ( (0.4 \text{ to } 0.5) )</td>
</tr>
<tr>
<td>Low</td>
<td>1,000 to 2,000</td>
<td>Low water-cement ratios &quot;Iowa&quot; dense concrete</td>
</tr>
<tr>
<td>Very Low</td>
<td>100 to 1,000</td>
<td>Latex modified concrete Internally sealed concrete</td>
</tr>
<tr>
<td>Negligible</td>
<td>&lt;100</td>
<td>Polymer impregnated concrete Polymer concrete</td>
</tr>
<tr>
<td>Mix* No.</td>
<td>W/C</td>
<td>Cure Time</td>
</tr>
<tr>
<td>----------</td>
<td>-----</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 day</td>
</tr>
<tr>
<td>1</td>
<td>0.26</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>2</td>
<td>0.28</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
<tr>
<td>6</td>
<td>0.75</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 days</td>
</tr>
</tbody>
</table>

**Coefficient of Variation - %** 7.0 12.9 20.9 14.0 2.5 2.4

* See Table 5 for description of mixtures.

** To convert from μDarcy to m² multiply by 9.87 x 10⁻⁷.

*** Permeability too small to measure.
### TABLE 9—CORRELATION MATRIX

<table>
<thead>
<tr>
<th>-X-</th>
<th>RCPT</th>
<th>Ponding</th>
<th>Hydraulic</th>
<th>Air</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCPT</td>
<td>1</td>
<td>0.99</td>
<td>0.97</td>
<td>0.95</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(9.8)</td>
<td>(13.0)</td>
<td>(28.1)</td>
</tr>
<tr>
<td>Air</td>
<td>----</td>
<td>0.94</td>
<td>0.75</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(21.10)</td>
<td>(51.1)</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>0.97</td>
<td>0.95</td>
<td>0.91</td>
<td>0.96</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(19.2)</td>
<td>(19.4)</td>
<td>(150)</td>
</tr>
<tr>
<td>Vol. Voids</td>
<td>0.97</td>
<td>0.99</td>
<td>0.93</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(19.0)</td>
<td>(17.6)</td>
<td>(41.7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(23.6)</td>
<td>(3.7)</td>
</tr>
</tbody>
</table>

**NOTE:** Upper values are correlation coefficients. Lower values are standard errors of estimate (expressed as percent of mean value).
Fig. 1--Hydraulic permeability test apparatus

Fig. 2--Air permeability test apparatus
Fig. 3--Effect of w/c ratio on RCPT results

Fig. 4--Lineralized relationship between w/c ratio and RCPT
Fig. 5--Lineralized relationship between w/c ratio and hydraulic permeability

Fig. 6--Relationship between w/c ratio and volume of permeable voids
Fig. 7--Relationship between results of rapid and 90-day chloride ponding tests

Fig. 8--Relationship between results of RCPT and hydraulic permeability tests