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BY

F. KOCATASKIN AND E. G. SWENSON

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Methods for Rating Concrete Waterproofing Materials

by F. KOCATASKIN and E. G. SWENSON

In an attempt to develop reliable test methods for evaluating the effectiveness of concrete waterproofers, it was found that a combination of saturated and unsaturated permeability tests is necessary, the latter covering more than one humidity condition

THE USE OF waterproofing admixtures or surface treatments for mortars and concrete has become widespread in recent years. Although the benefits to be derived from their use are questioned by many concrete experts, there has been no serious attempt to develop separate methods for rating the effectiveness of these materials for each of the various conditions that can exist in the field.

Waterproofing admixtures or surface treatments have been mainly associated with prevention of liquid flow through concrete. The prevention of dampness and the stopping of rain penetration are also claimed for many materials. Of added interest is the possible effect of such agents in reducing efflorescence, staining, and frost damage on exposed mortar or concrete.

The problems involved in properly evaluating these materials concern: (*a*) the various types of moisture situations; (*b*) the various types of waterproofing materials on the market; (*c*) the variation in the constituents and composition of the concrete; (*d*) the reactions of waterproofing materials with different cements; and (*e*) the influence of waterproofing materials on other properties of the concrete, such as strength and durability. Comprehensive investigations with integral or surface waterproofing materials involve mainly tests with water pressure and absorption (**1,2,3,4,5,6**).[1] But the development of a reliable test procedure involving all possible problems has not appeared in the literature. The present investigation was therefore undertaken to serve as a basis for the establishment of a simple but satisfactory series of test methods.

Initial Considerations

Structure of Concrete and Nature of Moisture Flow

Hardened concrete is a solid containing a gel pore system, an aggregate pore system, both usually very fine, and a cement-paste pore system that varies with water-cement ratio, degree of compaction, degree of hydration, and type of cement. Aggregate pores and gel pores play only a minor role in the transport of moisture. The cement paste pores are scattered capillary pockets and channels, some isolated, some interconnected. Their size varies from very fine to very large. They are responsible for the degree of permeability of concrete (**7,8**).

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E. G. SWENSON, associate research officer, Materials Section, Division of Building Research, National Research Council of Canada, and formerly assistant professor in chemistry at the University of Saskatchewan, is currently in charge of cement and concrete research and the author of several papers in this field.

NOTE.—DISCUSSION OF THIS PAPER IS INVITED, either for publication or for the attention of the authors. Address all communications to ASTM Headquarters, 1916 Race St., Philadelphia 3, Pa.

[1] The boldface numbers in parentheses refer to the list of references appended to this paper.

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Under isothermal conditions water may be transferred through this porous system by vapor flow for low moisture contents and by liquid flow for saturated conditions. For partially saturated conditions both mechanisms are believed to operate simultaneously.

Under nonisothermal conditions these situations may be complicated by the influence of temperature gradients between different parts of the concrete. They may be further complicated by osmotic pressures or electrical potentials. In the present study, however, these additional effects as well as other accidental means for water transfer through concrete, such as cracks, honeycombing, and joints, will not be taken into consideration.

Theory of Moisture Flow

The theory of moisture flow in porous media has been developed in analogy with heat transfer (**9,10,11**). It uses the concept of potential and the general equation of flow is given for the one dimensional case as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\psi)\,\frac{\partial \psi}{\partial x}\right] \ldots\ldots (1)$$

where:

θ = the moisture content at point x, at the time t,
ψ = the moisture potential at point x, at the time t, and
$K(\psi)$ = the permeability function.

The potential ψ represents the specific free energy of the moisture. For practical application it may be expressed either in terms of hydraulic pressure P or in terms of vapor pressure p, as convenience demands.

A direct solution of the general flow equation is not possible, and it is necessary to determine experimentally the function $K(\psi)$, relating permeability to moisture potential.

In the case of steady-state flow, the general equation is simplified, can be integrated once, and takes the form:

$$q = K(\psi)\,\frac{d\psi}{dx} \ldots\ldots\ldots (2)$$

For the saturated steady-state flow this is the well-known Darcy's formula:

$$q = K\,\frac{\Delta P}{\Delta x} \ldots\ldots\ldots (3)$$

For the unsaturated steady-state flow, and regarding vapor pressure as the potential:

$$q = K(p)\,\frac{dp}{dx} \ldots\ldots\ldots (4)$$

[2] Tentative Method of Test for Compressive Strength of Hydraulic Cement Mortars (Using Portions of Prisms Broken in Flexure) (C 349-54 T), 1955 Book of ASTM Standards, Part 3, p. 136. Method of Test for Tensile Strength of Hydraulic Cement Mortars (C 190-49), 1955 Book of ASTM Standards, Part 3, p. 188.

In the case of transient flow only simple problems like capillary absorption or drying by evaporation can be solved with certain assumptions. For capillary absorption, for instance, assuming:

$$\theta = \gamma\cdot\epsilon\cdot x, \qquad K(\psi) = K,$$

$$\frac{\partial(\partial\psi/\partial x)}{\partial/x} = \frac{f}{x}$$

where:

γ = density of water,
ϵ = porosity of the medium, and
f = suction force,

the equation may be integrated and the well-known capillarity formula obtained:

$$\gamma\cdot\epsilon\cdot\frac{dx}{dt} = K\cdot\frac{f}{x}, \qquad \gamma\cdot\epsilon\cdot x^2 = 2K\cdot f\cdot t,$$

$$\theta^2 = (2\gamma\cdot\epsilon\cdot K\cdot f)t = K_c t \ldots\ldots (5)$$

The coefficient K_c, known as the capillarity-coefficient, is a function of the porosity, permeability, and suction of the medium. Therefore it is not a constant; it depends upon the initial moisture condition of the medium.

These considerations show that the effects of material properties upon moisture flow may be reflected through the coefficients K, $K(p)$, and K_c. For correct evaluation of integral or surface waterproofing materials on the basis of their effectiveness in decreasing the flow of moisture in concrete, it is necessary to study their influence on these coefficients for the whole range of the variation of the latter. The usual hydrostatic flow test or the simple absorption test would appear to be insufficient. It is clear that proper evaluation can be achieved only by a series of tests to cover the various situations that can occur.

Selection of Waterproofing Materials and Preparation of Test Specimens

From commercially available groups, four integral and three surface waterproofing materials were selected as representative:

Admixture 1—Accelerator type (calcium chloride solution).
Admixture 2—Water-repellent type (ammonium stearate paste).
Admixture 3—Bituminous emulsion.
Admixture 4—A paste of siliceous and organic composition.
Surface waterproofing material 1—Cement grout (water-cement ratio, 0.75).
Surface waterproofing material 2—Cement base paint (water-paint ratio, 0.75).
Surface waterproofing material 3—Silicone resin solution (5 per cent silicone).

A type I Canadian cement was used. It is referred to as cement X.

Two mortar compositions were selected: mortar A was fairly rich and with a low water content; mortar B was a lean mix with a high water content. The sand used was one which has a good service record. Its specific gravity in the saturated surface-dry condition was 2.6. Separate sieve sizes were blended to give the following percentages passing each sieve size (the latter in parentheses: 100 per cent (No. 4), 80 per cent (No. 8), 60 per cent (No. 16), 35 per cent (No. 30), 15 per cent (No. 5), 5 per cent (No. 100), and 0 per cent (pan). Table I gives the proportions of the mixes as used in the test specimens.

TABLE I.—MIX PROPORTIONS USED IN TEST SAMPLES.

Constituents	Mix A	Mix B
Aggregate-cement ratio (weight)	6.17:1	7.44:1
Water-cement ratio (weight)	0.62:1	0.78:1
Density of fresh mortar, g per liter	2340	2300
Cement content, g per liter	300	250
Sand content, g per liter	1855	1855
Water content, g per liter	185	195
Air content, per cent by volume	1.6	2.2

Preparation of test specimens was as follows:

(*a*) *Specimens With Integral Waterproofing Materials.*—Small cylindrical specimens 4 in. in diameter and 1 in. thick were made from these mixes, with and without each of the selected admixtures. Additional specimens were made for supplementary tests for compressive strength, tensile strength and shrinkage, according to ASTM standards.[2] All specimens were cured in near 100 per cent relative humidity conditions at 23 C, demolded, stored in water for 6 days, then placed in a room conditioned at 50 per cent relative humidity and 23 C to the age of 28 days. Identification of the specimens was provided by a code, the first letter referring to the mortar, the number to the admixture, and the third letter to the cement, for example A0X, A1X, etc. Where the middle term is zero no admixture was used. Duplicate specimens were used for each test and their mean values are reported throughout.

(*b*) *Specimens With Surface Waterproofing Materials.*—All surface waterproofers are intended to be painted on surfaces with smooth textures and without large pores. Since mortar A met these requirements, it was used in these tests. The size, shape, preparation, and curing of the specimens were the same as for the series containing integral waterproofing materials. Surface waterproofings were applied at the age of

28 days on one face of the specimens. After this the specimens were cured an additional 14 days at 50 per cent relative humidity before tests were started. For identification, a letter-number code was used, the letter indicating surface, the number referring to the waterproofer, for example, S0, S1, S2, etc. The case of S0 means that no waterproofer was applied.

Experiments and Results

Specimens with Integral Waterproofing Materials

The Unsaturated Permeability Test.—In this investigation unsaturated permeability refers to the case where moisture flow occurs as the result of an appreciable vapor pressure gradient in the material. The degree of unsaturation would naturally be different for different conditions of test. The usual dry-cup procedure for measuring the vapor permeance of building materials (**12,13**) was found suitable for measuring unsaturated permeability and was adopted with slight modification to accommodate the relatively thick specimens. The specimens were mounted on aluminum dishes, which were filled with a desiccant (calcium chloride) and the sides sealed with wax. These dry cups were stored in chambers in controlled constant temperature and constant humidity conditions. Owing to the difference of vapor pressures outside (p) and inside ($p_0 = 0$), moisture diffused through the pores of the mounted specimens into the dish and was taken up by the desiccant. At steady-state conditions the rate of moisture flow, q, was determined from the weight gains of the dish. It may be noted that by storing several dry cups in different humidity conditions p, corresponding values of q could be determined.

The law of vapor permeability previously given as

$$q dx = K(p) dp$$

can be expressed, with q = constant for the steady-state flow, as

$$qx = \int_0^p K(p) dp \quad \text{.......}(6)$$

But it is not possible to carry out the integration without knowing the function $K(p)$. However, as it was possible to obtain values of q for given values of p experimentally by the dry-cup test, these experimental values of q, if multiplied by x, plotted against p, and connected by a smooth curve would represent the $\int_0^p K(p) \cdot dp$ function. By graphical differentiation, it is possible then to derive the unknown permeability function $K(p)$.

To determine the influence of admixtures on the unsaturated permeability of concrete, duplicate specimens from all control and test series were tested by the dry-cup method at 50, 80, and 100 per cent relative humidities. Figure 1 shows the permeability functions obtained by the graphical differentiation method from results of these tests. As seen from Fig. 1, admixtures 1 and 4

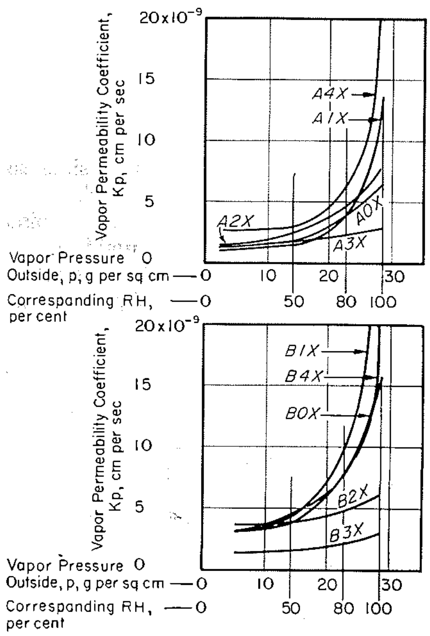

Fig. 1.—Vapor permeabilities of mix A, with and without admixtures.

NOTE.—A in first graph refers to the rich mix with low water cement ratio. B in second graph refers to the lean mix with high water-cement ratio. The middle numbers refer to the admixtures, the zero term indicating no admixture (reference). The last term, X, refers to the cement used.

were not effective; they increased the permeability. Admixture 2 was effective in one mix, and admixture 3 in both mixes. In this and the following graphs the data points are not shown for any of the curves since the results are based on proprietary materials the exact compositions of which are not known. The curves should therefore be interpreted in a qualitative way. For this reason also much of the data is not included in this paper.

A special case of unsaturated permeability will be obtained when a concrete is subjected to liquid water on one surface and to free air on the other surface. Dense concretes with their extremely fine pores offer such a great resistance to liquid flow that the concrete will dry out by evaporation to the air and a condition of partly saturated and partly unsaturated permeability will occur (**14**). The flow will be influenced by both the coefficients of saturated and unsaturated permeabilities. As results of investigations show, however, most integral waterproofing materials have no appreciable effect on the first coefficient (saturated permeability). Therefore, the function of the second coefficient $K(p)$ (unsaturated permeability) is also expected to reflect the effects of integral waterproofing materials for this special case of composite permeability. Experimental evidence was provided by a series of so-called inverted wet-cup tests, in which specimens of each series were mounted on aluminum dishes, as for the vapor permeability test. The dishes were filled with 1 to 2 in. of water, the sides sealed with wax and the dishes inverted, bringing the water to the top of the specimens. Pairs of these inverted wet cups were stored in still air at 50 per cent relative humidity, leaving their bottom surfaces free for evaporation. After steady-state conditions were reached, rates of moisture flow were determined from weight losses of the dishes. The results, not recorded here, were closely similar to those on Fig. 1 on vapor permeability.

The Saturated Permeability Test.—In this study saturated permeability refers to the case where moisture flow occurs as the result of a hydrostatic pressure gradient in a specimen in which the degree of saturation is determined by the condition of test. Apparatus suitable for determining saturated permeability under a small head has been described elsewhere (**15,16**). The basic apparatus used in the present study is shown schematically in Fig. 2. To

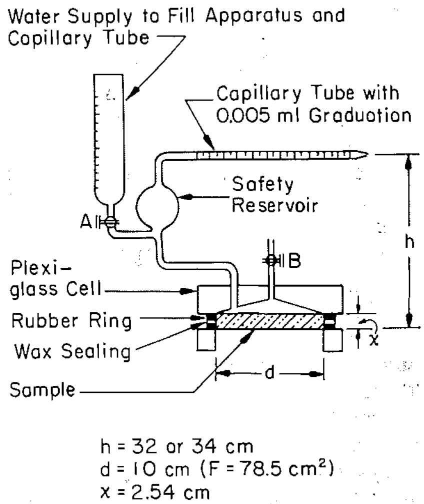

Fig. 2.—Saturated permeability apparatus.

avoid the complications introduced by evaporation at the exposed face, the apparatus was stored in a room controlled at near 100 per cent relative humidity and 23 C. The apparatus was designed to maintain a constant hydraulic head on the specimen by means of a horizontal capillary tube, and to allow measurement of flow into the specimen through observation of the miniscus in the capillary tube. Measurements were begun when droplets became visible at the exposed surfaces and were taken each day for one week.

Experimental results show that if the conditions producing flow are maintained over a substantial period, there is a continuous decrease in the permeability of the concrete. Explanations have been given in terms of expansion of cement particles due to further hydration, swelling of the cement and aggregate colloids due to wetting, clogging of the pores by products of the chemical combination of bicarbonates in water with the free lime of cement, retardation of flow due to the establishment of an electrical potential, retardation of flow due to osmotic pressures, etc. For practical purposes, it seemed sufficient to follow this change in permeability up to seven days, at which time it became practically constant.

Duplicate specimens from all control and test series were tested for saturated permeability under the conditions described above. The permeability coefficients calculated from the rates of flow using Darcy's formula are plotted in Fig. 3 against time, using semilogarithmic coordinates for convenience. Before comparing the results obtained from test series with those obtained from control specimens, it was necessary to know how much variation was to be expected between specimens of the same composition, but prepared from different batches. Therefore, additional duplicate specimens were prepared from additional batches of mixes A0X (rich mix) and B0X (lean mix), and these were tested for permeability in the same manner. The results of these additional series are shown in Fig. 3 as curves A0XR and B0XR. (These batches of the same composition were carried out to check reproducibility.)

Comparing the results, it is seen that permeabilities from all test series fall within the range of their control mixes. Thus none of the admixtures has shown any markedly beneficial properties. This result is in essential agreement with the conclusions reached by other investigators.

The Capillary Absorption Test.—No special apparatus was needed for this test. The specimens were stored until equilibrium was reached at 50 per cent relative humidity and then weighed and set in contact with water from one surface. The amount of absorption was measured by taking weights at intervals. The square of the weight gain was plotted against time to give straight lines of the form:

$$\theta^2 = K_c \cdot t + a$$

It was assumed that a represented the first amount of water necessary to wet the surface. The slopes, K_c, of these straight lines were determined. The same procedure was repeated for 0 per cent relative humidity equilibrium conditions. The values of K_c obtained for 0 per cent and 50 per cent equilibrium relative humidity conditions are plotted in Fig. 4. It was possible to draw a suitable curve through these two points and through the $K_c = 0$ point at 100 per cent relative humidity, assuming the same general shape as given for absorption isotherms of porous materials, and thus obtain the whole variation of the capillarity coefficient. The thickness of the specimens was shown to influence the results of the capillary absorption test. Therefore the tests were not prolonged beyond the appearance of the first wet spots on the opposite surfaces of the specimens.

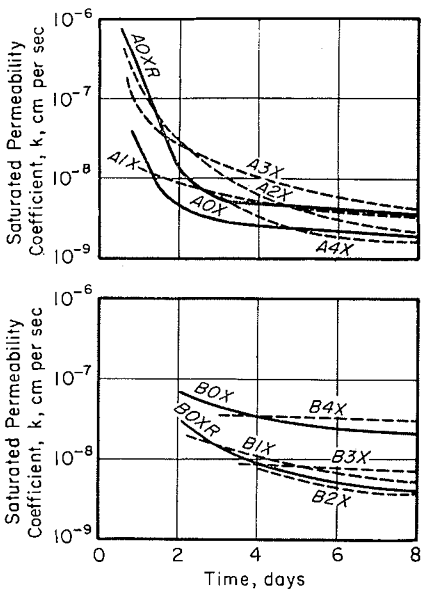

Fig. 3.—Saturated permeabilities of mixes A and B, with and without admixture.

To investigate the influence of waterproofing admixtures, duplicate specimens from all test and control series were tested in the described manner. Figure 4 shows the curves of capillarity coefficients obtained. Admixture 1 is shown to have no effect on capillarity. Admixtures 2 and 3 were very effective in reducing capillarity; admixture 4, however, gave higher absorption values.

Additional Tests.—Certain properties of the cement and mortars, other than permeability, were expected to be modified by the admixtures. Several supplementary tests were made to check such effects, and their results may be summarized as follows:

(*a*) The calcium chloride admixture accelerated the setting time of the standard cement paste very considerably (initial set 55 min, final set 70 min); the other admixtures did not affect the set (initial set 180 to 220 min, final set 230 to 285 min).

(*b*) The workability of the mortar, as measured by the time of vibration necessary for complete compaction, was improved by the stearate admixture; the calcium chloride or siliceous admixtures did not affect workability; the bituminous emulsion gave very poor workabilities;

(*c*) The 28-day compressive strengths were not significantly affected by the calcium chloride, stearate, and siliceous admixtures; the bituminous emulsion decreased the compressive strength by 20 per cent.

(*d*) The 28-day tensile strengths were not affected by the calcium chloride and stearate admixtures; the bituminous and siliceous admixtures, however, improved tensile strengths considerably, 315 and 310 psi, respectively, as compared with 231 psi for the mix containing no admixture.

(*e*) Shrinkage data on the various mixes were obtained on 1 by 1 by 5 in.

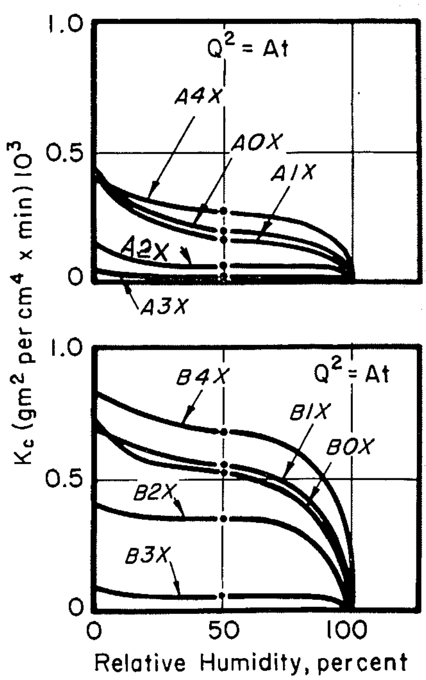

Fig. 4.—Capillary coefficients of mixes A and B, with and without admixtures.

NOTE.—Code designations are the same as for Figs. 1 and 3.

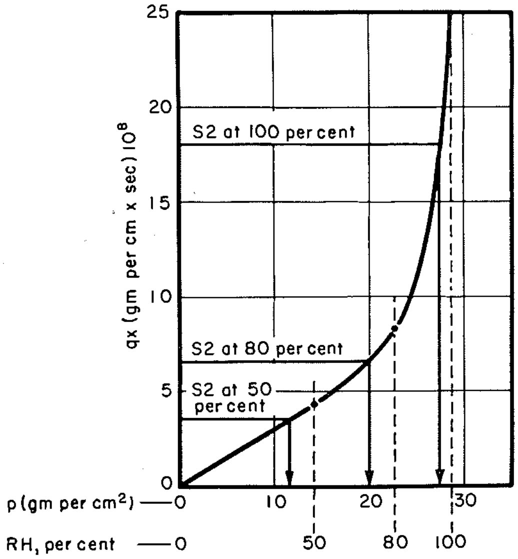

Fig. 5.—Use of flow data for uncoated specimen in determining P_1 values for rating surface coatings S2.

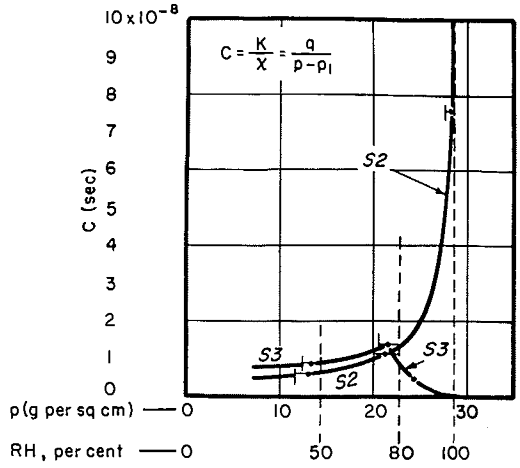

Fig. 6.—Vapor conductances of surface coatings S2 and S3.

mortar bars cured for 11 days at 100 per cent relative humidity and 73.4 F, and then conditioned at 50 per cent relative humidity and 73.4 up to 60 days. The slight but possible adverse influence of integral waterproofing materials on drying shrinkage is illustrated by the following results: A0X (no admixture)—0.071 per cent, A1X— 0.087 per cent, A2X—0.086 per cent, A3X—0.077 per cent, and A4X—0.094 per cent.

The data in the preceding sections are for the rich mix only. Data for the mix B showed similar trends.

Specimens with Surface Waterproofing Materials

The Unsaturated Permeability Test.—The dry-cup test was carried out in the same manner as described previously. The rates of moisture flow were determined for 50, 80, and 100 per cent relative humidity conditions at the painted side of the specimens. Test results obtained from the uncoated series S0 were used to plot the qx curve of the uncoated concrete (Fig. 5). With the aid of this curve and with the experimental results of the coated series, it was possible to obtain the moisture conductances of the surface waterproofing films, which will subsequently be referred to as paint films.

It was considered that a partial pressure drop $p-p_1$ would be attained in the paint film, resulting in a smaller pressure drop p_1-p_0 in the concrete than it would have experienced in the uncoated state. Therefore the rate of flow q_1 obtained for the painted specimen would be smaller than the rate of q of the unpainted specimen. q_1 was determined experimentally. To find p_1, use was made of Fig. 5. A horizontal line was drawn from the point q_1x to its intersection of the qx curve. Then a vertical line was drawn leading down to the p_1 value. The pressure p_1 was determined by this procedure for each of the cases and the moisture conductance of the paint film was calculated from the equation:

$$C = \frac{q_1}{p - p_1}$$

and plotted against $p_m = (p + p_1)/2$, giving three points, one for each of the three tests at 50, 80, and 100 per cent relative humidities. The three points were connected by a curve and the moisture conductance of the paint film was obtained for the whole range of vapor pressures. Only the results for points S2 and S3 are shown in Fig. 6 since S1 (cement paste) had no apparent effect in moisture flow. The curves show that:

(*a*) paint S2 gave decreased flow rates; the curve of conductance had the same general shape as the curve of the unsaturated permeability coefficient of concrete; and

(*b*) paint S3 gave decreased flow rates, especially at higher humidities; the curve of vapor conductance follows the curve of paint S2 up to 80 per cent relative humidity, but at higher humidities, instead of rising to higher values, it drops to a very low value at 100 per cent relative humidity. This shows the remarkable effect of the silicone waterproofer at higher humidities.

The special test of unsaturated permeability with water and air on the two sides of the specimens was carried out by the inverted wet-cup metho d as described previously. The paint film was applied (*a*) to the wet side, and (*b*) to the dry side. Results of tests (*a*) again showed excellent agreement with the results of dry-cup tests; results of tests (*b*) showed no benefit except for the silicone waterproofer S3. This would indicate that the cement-base waterproofing materials were beneficial when they were painted on the upstream side but apparently not beneficial when they were painted on the evaporation side.

The Saturated Permeability Test.—The test was carried out in the same manner as for the specimens containing integral waterproofing materials. The results showed that paints S1 and S2 did not affect the rates of permeability at all. Paint S3, on the contrary, showed no leakage under the small head of water during the seven days of the test. As a matter of interest, a higher water pressure of 30 psi was applied resulting in definite leakage. After the specimens had leaked for one night and had become saturated, the pressure was decreased to its original small value. After that the leakage stopped again. It can be concluded that paint S3 was very effective against small water pressures.

The Capillary Absorption Test.—The capillary absorption at 50 per cent relative humidity equilibrium conditions was determined from the initial inflow measurements in the saturated permeability apparatus. The fact that paint and concrete represented two different layers made it impossible to establish a simple theory and to determine a coefficient of absorption as described previously. Figure 7 shows the rates of absorption obtained for the series S0, S1, S2, and S3. As seen from this figure, S1 and S2 decreased capillarity and increased the time of complete water penetration through the 1-in. specimens. For S3 water had not penetrated the sample to any extent even after 7 days.

Discussion and Conclusions

The test methods used in this investigation, taken together, showed promise as a means of evaluating integral and surface waterproofing materials. The results show clearly that reliance on one single test is not adequate. The materials tested showed to no advantage in the saturated permeability test. However, this test may have some merit where filler-type or pozzolanic admixtures are used. The unsaturated permeability test appeared to make clear distinction between certain types of waterproofings and could be related to certain field situations. In practical testing it may not be necessary to apply both the dry-cup and the wet-cup methods unless field conditions warrant it. The capillary absorption test gave a good indication of the over-all effectiveness of waterproofings in cases where concrete is subjected to short periods of contact with moisture, with intermediate drying intervals.

The water repellent and bituminous admixtures showed up favorably in all the tests except the saturated permeability test. The calcium chloride admixture showed no beneficial effects in this study, apparently because the cement used did not respond to the usual accelerating action of calcium-chloride on hydration.

The cement-base paints provided varying degrees of benefit when painted on the side of the specimen subjected to wetting. The silicone application had a very significant influence on moisture flow.

The differences obtained with waterproofing agents used in these studies indicate that the combination of tests described provides a simple and useful means of evaluating such materials on the basis of the different field problems which may be anticipated.

The tests, however, were limited to isothermal conditions and to relatively early ages of concrete. The influence of age and temperature gradient, as well as durability and corrosion resistance properties, require additional investigation before final conclusions can be drawn.

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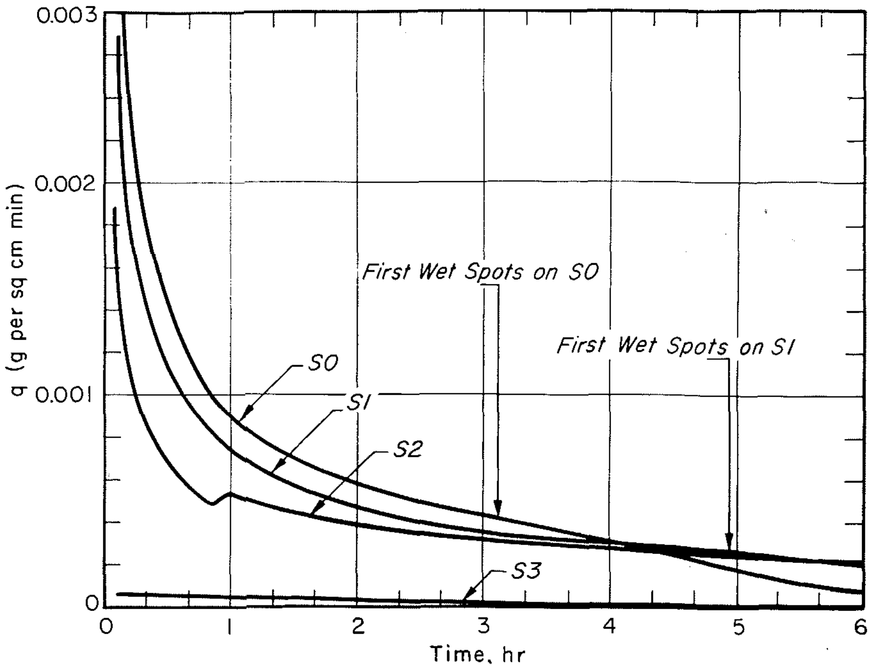

Fig. 7.—Capillary flow with surface coatings S1, S2, and S3; compared with uncoated specimen S0

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