VAPOR BARRIERS

Moisture Migration — Concrete Slab-on-Ground Construction

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SYNOPSIS

Concrete slab-on-ground has become a widely used method of construction. Moisture migration from such slabs is of importance primarily because of its effect on certain types of floor coverings.

This study reports data on 141 specimens cast from 29 mixes covering a wide range of concrete quality. The program included exposure conditions varying from water-in-contact to drying only, as well as the effect of admixtures, vapor barriers, and gravel capillary breaks. Several different test procedures were studied in the course of the investigation.

Good correlation was found between moisture migration and water—cement ratio (w/c), flow increasing directly with w/c. Admixtures had little effect on moisture migration measured by these methods. Vapor barriers and gravel capillary breaks produced little or no change in the measured flow at early ages, but reduced the flow at later ages.

The superior resistance to moisture migration of good quality concrete, relative to that of lower quality concrete, was amply demonstrated in this study regardless of time or type of exposure. Analysis of the data established that outflow measurements rather than inflow measurements properly evaluate moisture migration at early ages. The outflow measurements indicated that rate of moisture loss at early ages is 4 to 10 times the flow through the concrete.

INTRODUCTION AND BACKGROUND

Initially the extensive use of concrete slab-on-ground as a method of construction was employed in warm and dry areas, and asphalt tile was the common floor covering. Later, less permeable coverings were adopted and slabs were also constructed in areas with less favorable soil and climatic conditions. These circumstances have placed greater emphasis on the need for information dealing with moisture migration through concrete slabs.

The keen interest and the need for technical information regarding concrete slab-on-ground is evidenced by five reports on the subject issued since 1955 by the National Academy of Sciences—National Research Council through the Building Research Advisory Board.

"Slab-on-Ground Construction for Residences," NAS-NRC Publication 385 (June 1955),(1)* discusses site preparation, need for capillary breaks and vapor barriers, slab design, and insulation. The report terminates with 10 research recommendations indicating the need for much technical information.

"Vapor Barrier Materials for Use with Slab-on-Ground Construction," NAS-NRC Publication 445 (May 1956),(2) is a report describing required properties of vapor barriers and pertinent test methods to evaluate these properties.

"Effectiveness of Concrete Admixtures in Controlling Transmission of Moisture Through Slabs-on-Ground," NAS-NRC Publication 596 (July 1958),(3) describes a test procedure to evaluate the effectiveness of admixtures on moisture control. The committee knew of no admixture that

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*Numbers in parentheses refer to references at end of paper.

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would be sufficiently effective to replace either a vapor barrier or granular base where such protection was needed.

"Design Criteria for Residential Slabs-on-Ground," NAS-NRC Publication 657 (March 1959),(4) recommends a procedure for analysis of structural slabs. The committee delineated four major types of slabs and recommended particular types for various combinations of site and climatic conditions.

"Protection from Moisture for Slab-on-Ground Construction and Habitable Spaces Below Grade," NAS-NRC Publication 707 (February 1959),(5) describes site preparation and also use of capillary breaks, vapor barriers, and good quality concrete for controlling moisture. It also includes recommendations regarding insulation and finish floor coverings.

The purpose of all of these BRAB reports was to provide information that would be helpful to the Federal Housing Administration in establishing Minimum Property Standards on this subject and in defining needed research activities.

Although there are numerous references in the literature to moisture migration through construction materials, few of these are directly applicable to concrete. One of the most comprehensive investigations is that made by Professor C. E. Lund at the University of Minnesota for the U.S. Navy Bureau of Yards and Docks.(6) The study included three different types of concrete over six different types of soil. Two admixtures, two surface coatings, and a moisture barrier were studied. This investigation showed the advantage of using high quality concrete and of providing a capillary break beneath the slab. None of the admixtures or surface treatments was beneficial. Heavy asphalt-impregnated and laminated felt was a very effective moisture barrier.

A study by the Forest Products Laboratory for the Housing and Home Finance Agency(7) included the use of capillary breaks and vapor barriers beneath the slab. However, only one specimen was provided for each of six test conditions, and this fact, together with some apparent inconsistencies, seriously limits the usefulness of the data.

Kocataskin and Swenson(8) used both water and water vapor test procedures to evaluate waterproofing additives in lean (1:6 and 1:7) portland cement mortars. They found that an integral bituminous emulsion was an effective waterproofing material, when tested by the water vapor procedure, and that ammonium stearate was effective in the leaner mortar. When tested under saturated conditions with 32 centimeters of water on the disk, none of the waterproofing additives was beneficial.

Powers, Copeland, Hayes, and Mann(9) have discussed the permeability of cement paste and have shown the advantage of low water–cement ratio and continued moist curing in reducing permeability.

A recent article by Griffin and Henry(10) is concerned primarily with salt contamination of concrete, but concludes that water-vapor transmission increases with an increase in water–cement ratio.

Tests and experience have shown that difficulties normally encountered with concrete floors on grade can be largely eliminated by adherence to good construction practice. The recommendations of the Building Research Advisory Board as given in reference 5 provide good advice. Careful selection of site, provision for proper drainage, and observance of the fundamental rules for making concrete will eliminate most of the problems. However, the fact that concrete contains water which it loses upon drying, and that under certain conditions some water will pass through it, poses a problem that can be only partially alleviated by good construction procedures.

The concern over moisture migration through or from a concrete slab is not with respect to its effect on the slab, but its effect on resilient tile, wood or other flooring, rusting of metal, etc. Retention of water or passage of water through concrete is generally not detrimental to the concrete. The concrete slab should be moist cured for several days after casting, and strength and impermeability of the concrete are both further improved by longer curing. On the other hand, the concrete surface should be relatively dry prior to installation of most floor coverings. Under usual construction practice, floor coverings are installed within a few weeks after the concrete slab has been cast, entrapping much of the original mix water in the concrete, which later contributes to buckling of wood floors and affects adversely the adhesives used with some of the resilient tile. Under these conditions, the moisture *outflow* from the surface of the concrete at early ages is more important than the relatively stable moisture *flow through* the concrete at later ages.

A review of the literature indicates that moisture migration has been reported as *inflow* to certain types of specimens and *outflow* from other types. After extended exposure periods these values tend to become equal; but the outflow after only short exposure periods is much higher than the inflow. *Outflow* is the total moisture leaving the surface of the concrete slab, and consists of loss of mix water due to drying in addition to the moisture passing through the slab. Most of the outflow from concrete slabs measured during the first few weeks results from moisture losses due to drying. Only small quantities of moisture pass *through* good quality concrete or through slabs protected by efficient vapor barriers.

A testing program was initiated covering variables believed pertinent to the study. Initial tests were made on slabs cast over a compacted soil base with and without a four-inch-gravel capillary break directly beneath the slab. The use of various vapor barriers was also included. The quality of concrete was varied over a wide range with both sand-gravel and expanded shale aggregates. In later test series the compacted soil base was eliminated and slabs were exposed directly to either water vapor or water-in-contact. Several admixtures reported as possibly effective in reducing moisture migration were included. This report is based on 141 specimens cast from 29 concrete mixes. Erratic data, usually accompanied by leakage, eliminated some other specimens. A Type I cement that was a blend of several brands was used in all concretes.

The testing program developed into three major series. The initial testing procedures were not entirely satisfactory, but were improved as the program progressed. In the first series, concrete slabs were cast over soil, or soil plus gravel, in 16-gallon containers, with a water level maintained 16 inches below the bottom of the slab. In the second series, concrete specimens were cast in the top of 14-quart pails as suggested by a Building Research Advisory Board Committee.(3) Two modifications of the recommended procedures were necessary before satisfactory results were obtained. In the third series, difficulties encountered in the first two series were eliminated by casting specimens in one-gallon cans and testing in a closed system. These various specimens, procedures, and results are described for each series.

Flow is reported in grains per hour per square foot. If the flow in pounds of water is desired the values shown should be divided by 7000.

SERIES I

Test Procedure

The first of the various test procedures was developed in collaboration with representatives of a government housing agency. As a representative condition for preliminary study, it was decided that the concrete slab should be 16 inches above water level, on a clay soil subbase, and that a gravel capillary break and vapor barriers should be included as variables.

The test specimens and procedures were similar to those used by the Forest Products Laboratory.(7) Metal containers 26 inches high and 14 inches in diameter were painted with rust inhibitor and fitted with glass water column gages as shown in Fig. 1. A 4-inch layer of coarse gravel was placed in the bottom and covered with expanded metal lath and filter paper to provide a water reservoir to facilitate water adjustments. The containers were filled with clay soil compacted at optimum moisture content to maximum density. Half of these containers had a 4-inch layer of ⅜ to 1-inch gravel and two layers of cheesecloth above the soil. Ten of the 24 containers had a 4-inch metal extension which clamped over vapor barriers of 4-mil polyethylene or 55-pound roofing felt.

Four-inch-thick concrete slabs 13.5 in. in diameter were cast in the top of each container. These slabs included both normal weight and lightweight concretes of a wide range of cement contents. Concrete mix and strength data are given in Table 1. One specimen from each concrete was cast on the soil and another was cast on the gravel. A ¼-inch annular space between the concrete and painted metal container was filled with an asphaltic rubber sealing compound after the concrete had hardened. In addition, 10 specimens from the 0.70 w/c sand-gravel concrete (five on soil, and five on gravel) were cast above two different vapor barriers.

Moisture migration was determined by measuring the water required to maintain a water surface in the glass column 16

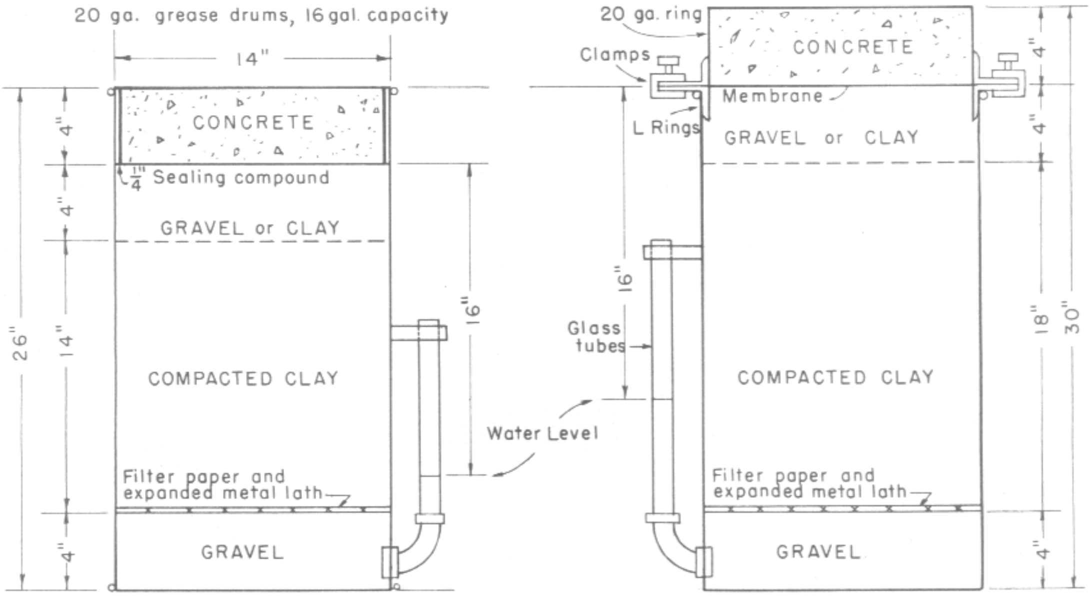
TABLE 1—MIX DATA AND PHYSICAL PROPERTIES — SERIES 1 CONCRETES

Mix No.	W/C	Cement Content		Unit Wt, lbs/cu ft	Air Content, %	Slump, in.	Comp. Str., psi at 28 days	E x 10⁶, psi at 28 days
		lbs/cu yd	bags/cu yd					
Sand-Gravel Concrete								
A	0.51	438	4.7	152.3	1.2	2.9	5300	4.1
B	0.62	376	4.0	152.1	1.4	2.9	4200	4.0
C	0.70	332	3.5	151.4	1.4	2.5	3200	3.7
D	0.89	290	3.1	149.5	1.4	3.1	2060	2.3
Expanded Shale Concrete								
E	—	571	6.1	96.7	3.7	1.9	6100	2.4
F	—	463	4.9	95.0	3.8	1.8	4360	2.5
G	—	385	4.1	92.6	4.0	1.4	2820	2.1

inches below the bottom of the concrete slab. Erratic readings, which were soon observed, were attributed to entrapped air in the soil or gravel and to changes in barometric pressure. These 340-lb specimens were tipped periodically to remove the entrapped air, especially after rapid changes in barometric pressure. Tests were continued for 16 months when stable flows were obtained. These specimens were tested in an environment controlled to 73 F and 30 percent relative humidity.

Series I Results and Discussion

Considerable difficulty was encountered with these specimens due to the unknown quantities of water absorbed by the system, to leakage, and to the barometric effect that caused large variations in the water level. Of the 50 specimens cast in this series, only 24 stabilized to the extent that data were considered to be reliable. The remaining 26 specimens were discarded and no other reference is made to them in this report. As a result of this experience (and also re-



Without Vapor Barrier

With Vapor Barrier

Fig. I — FPL-Type Moisture Migration Apparatus.

sults from Reference 7), this test procedure is not recommended for moisture migration studies. Another objection to this test method, as will be discussed later, is that the test measures the inflow to the total system and not outflow from the surface. However, the effects of the gravel capillary break and of the vapor barriers appear to be established reliably, as is discussed in the following sections.

Fig. 2 shows the moisture inflow for the sand–gravel concrete slabs of various water–cement ratios cast over soil with and without a gravel capillary break. The initial inflows were erratic but became more consistent after the specimens were tipped to remove entrapped air. After 16 months the flows varied only from 1.1 to 1.8 grains per hour per square foot for the various specimens, with the concretes of higher water–cement ratios having higher flows at all ages. The gravel layer reduced the flow by 10 to 25 percent.

Fig. 3 shows the effect of vapor barriers on moisture inflow with and without gravel capillary breaks for concrete of 0.70 w/c. The two vapor barriers, 4-mil polyethylene and 55-lb roofing felt, gave similar results, and the curves shown represent averages of both types.

The gravel capillary breaks reduced the inflow both with and without the vapor barrier. The vapor barrier plus gravel layer greatly reduced inflow during the entire test. Examination after completion of the test showed that a layer of free water had collected between the soil and polyethylene film. Almost continuous patterns of carbonated material were formed on the concrete side of the polyethylene above the gravel. The specimens protected by the 55-lb roofing felt showed less moisture between the vapor barrier and soil, but the roofing was decomposed, tore easily, and was partially coated with slime and mold.

The top surface of one of the felt vapor barrier specimens was coated with polyester two months before the end of the test. The measurements indicated no reduction of inflow during this time; but when the slabs were removed from the containers and immersed in water to determine the percent of saturation, this specimen was 64 percent saturated compared to the other three specimens which were only 46 percent saturated. This result shows that an impervious coating on the top surface caused the moisture content to increase in the concrete, and that this occurred even with the vapor barrier above a gravel layer. The six slabs above the polyethylene film were only 37

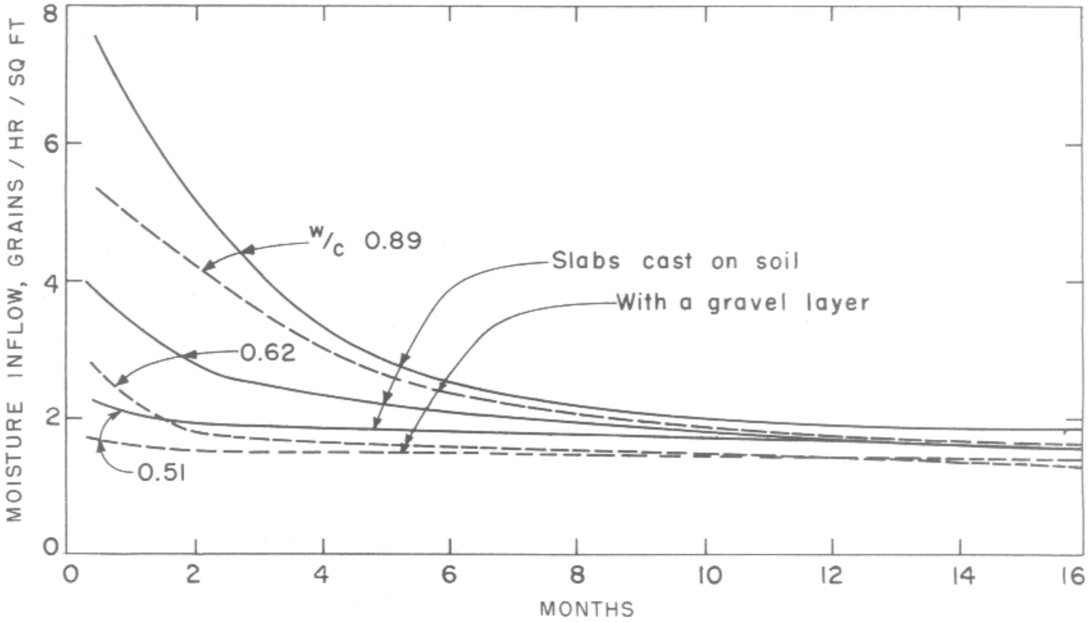


Fig. 2 — Effect of Water—Cement Ratio and Gravel Layer. Series I

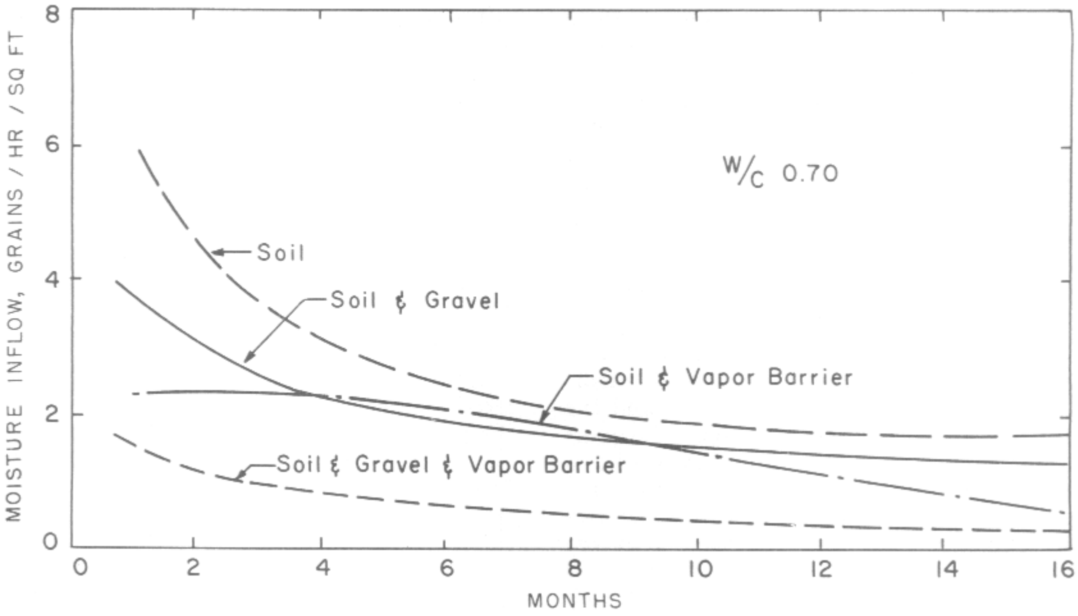


Fig. 3 — Effect of Gravel and Vapor Barrier. Series I

percent saturated at the end of the test. Six slabs without vapor barriers were from 67 to 73 percent saturated.

Lightweight aggregate concretes showed considerably less flow (Fig. 4) than most of the sand–gravel concretes. The slabs cast over soil showed reduced inflow with increasing cement content. This relationship was not well defined for the companion slabs cast over soil with a gravel capillary break, as all of the curves fell into a relatively narrow band. Comparison of the curves of Fig. 4 reveals the advantage of the gravel capillary break, particularly for slabs with lower cement content.

SERIES 2

Test Procedures

The second series of tests was conducted using a test procedure suggested by Building Research Advisory Board Subcommittee II on admixtures.(3) Galvanized pails of 14-quart capacity were fitted with two openings and a metal screen covered by filter paper upon which concrete was cast, as shown by Fig. 5. Concrete samples cast in the upper portion of the pail could be tested either with water in contact with the slab, or with the concrete exposed to water vapor. The first phase of this test procedure did not prove satisfactory because of the generation of hydrogen gas within the assemblage due to a reaction of the zinc in the galvanized lining. This difficulty was overcome by coating all interior metal parts (pail, screen and supports) with epoxy resin. Three groups of specimens were tested using this modified BRAB-type procedure.

This series consisted of five concrete mixes of different w/c ratios with and without a polyethylene vapor barrier. Important properties of mixes are given in Table 2.

Two additional vapor barriers, 32-mil ABS plastic and 55-lb roofing felt, were also included with specimens of 0.45 and 0.55 w/c. Epoxy resin was used to attach the vapor barriers to the sides of the pail. The pail above the vapor barrier was coated with cup grease as a means of obtaining a seal between the concrete and container for the first four concretes, while epoxy resin was used as a more positive seal for the 0.41 w/c concrete. Wax was placed in the preformed groove around the periphery of the concrete after seven days curing.

Concrete slabs of 0.45 and 0.55 w/c were first exposed to water vapor for 50 days in an environment controlled to 73 F and 30 percent relative humidity. Freshly boiled and cooled water was added to a depth of

TABLE 2—MIX DATA AND PHYSICAL PROPERTIES—SERIES 2 CONCRETES

Mix No.	W/C	Cement Content		Unit Wt, lbs/cu ft	Air Content, %	Slump, in.	Comp. Str., psi at 28 days	E x 10^6, psi at 28 days
		lbs/cu yd	bags/cu yd					
H	0.45	478	5.1	153.6	1.9	1.5	6820	5.0
J	0.55	465	5.0	150.0	1.6	8.0	5120	4.6
K	0.68	282	3.0	140.8	6.2	7.8	—	—
L	0.99	284	3.0	147.0	1.0	7.4	1300	—
M	0.41	507	5.4	151.2	4.0	1.5	6680	4.2

Admixtures: K = AEA-1, M = AEA-2.

two inches in the bottom of the pail, leaving an air space between the water and the bottom surface of the concrete. The glass water columns were capped to prevent loss of moisture. At the end of this period the pails were completely filled with water and all entrapped air was carefully removed from beneath the slab. Testing continued for 165 days in a room controlled at 73 F and 50 percent relative humidity. Moisture migration was determined by weight loss while the specimens were exposed to water vapor, and by measuring the water added (inflow only) while the specimens were subjected to water-in-contact.

Concretes of 0.68 and 0.99 w/c were tested with water-in-contact for 138 days, then a portion of the water was drained out and the test with water vapor only was continued for another year. Companion specimens were subjected to water vapor exposure for 50 days.

To obtain an estimate of water loss due to drying only, additional specimens were cast, cured seven days, and then sealed on the bottom and sides with several coats of polyester resin. These specimens were stored beside the others in the 50 percent relative humidity room and were weighed periodically for 500 days.

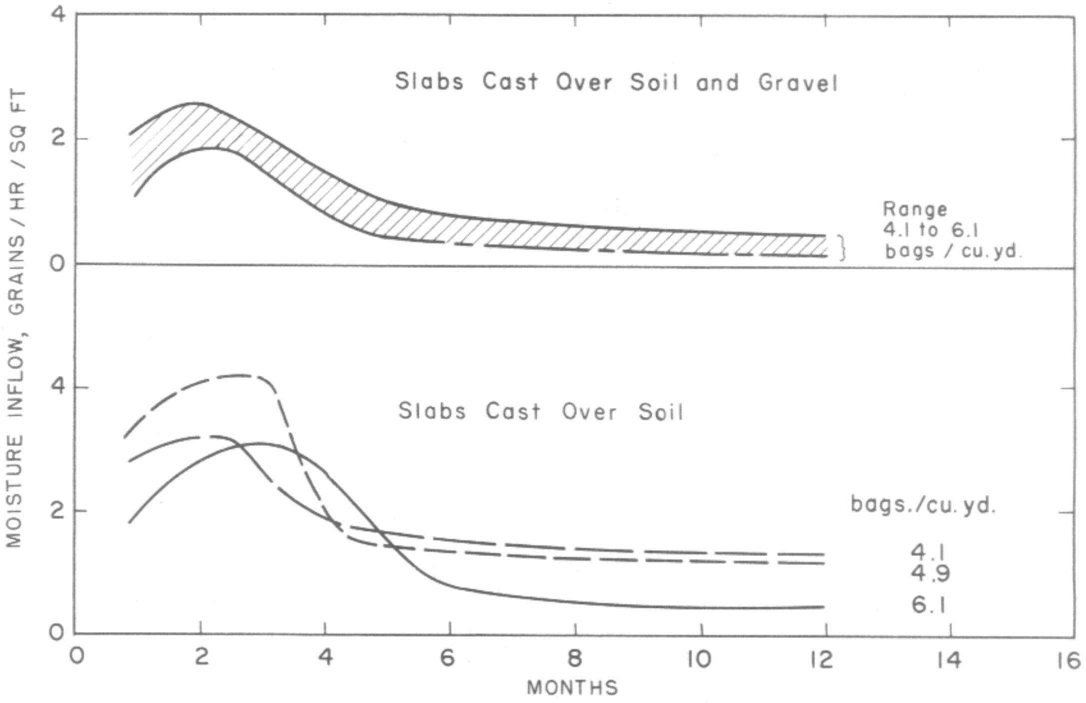


Fig. 4— Effect of Cement Content and Gravel Layer for Lightweight Concrete. Series I

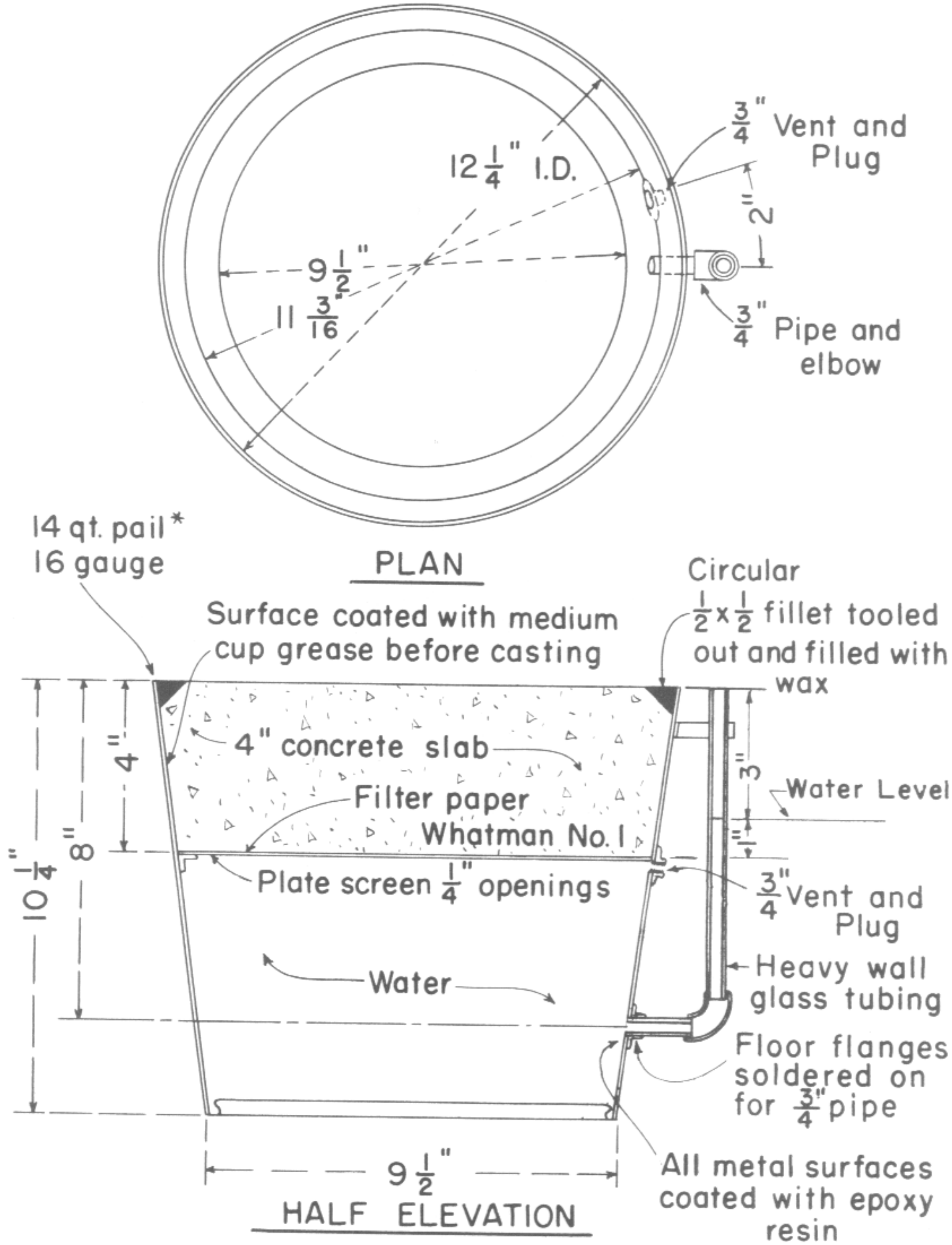


Fig. 5 — Moisture Migration Test Apparatus.
Series 2

*Dimensions of pail need not be exactly as shown.

As testing of this series continued, it became apparent that a small amount of leakage was occurring in a few of the specimens. All specimens with obvious leakage were discarded, and a further attempt was made to refine this particular testing procedure.

A portion of the program was repeated using nine specimens of concrete at 0.41 w/c, with and without vapor barriers, and with the slabs sealed in the pails with epoxy resin.

To eliminate any possibility of water loss by gravity from the fresh concrete and to produce a more uniform bottom surface, 55-lb roofing felt was placed on top of the metal grid and the edges were sealed with cup grease. The upper four inches of the containers was also coated with cup grease. After the concrete had cured three days, the slabs, vapor barriers, and metal grids were removed from each container. All slabs were weighed, then new vapor barriers were attached at the edges of five slabs with epoxy resin. Polyethylene was attached to three slabs, and 55-lb roofing felt was attached to two slabs. After the epoxy had hardened, the upper four inches of each container was cleaned and coated with epoxy, and while the epoxy was still tacky each slab was carefully fitted into its own container. As soon as the epoxy had set, freshly boiled and cooled water was added to each container. After another three days of curing under polyethylene film, wax was placed in the periphery ring and freshly boiled and cooled water was added to bring the water level in the glass tube to three inches below the top surface. All air entrapped on the lower surface of the concrete was removed through the vent, using a bottle brush.

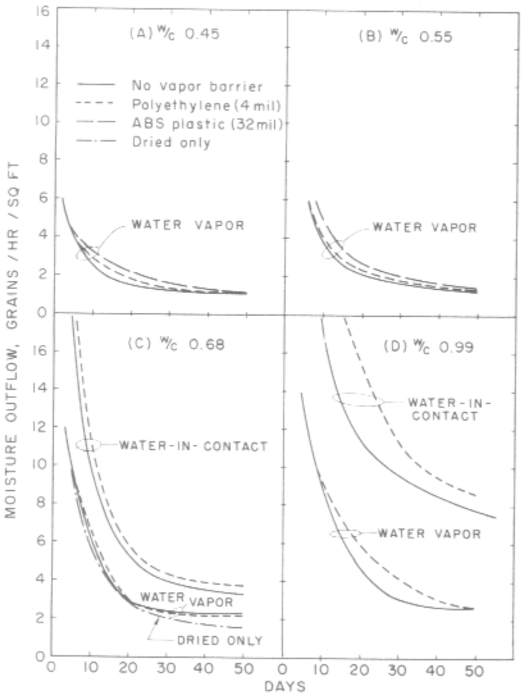


Fig. 6 — Effects of Water—Cement Ratios and Vapor Barriers Under Various Exposures. Series 2

TABLE 3—MOISTURE OUTFLOW FROM SPECIMENS WITHOUT VAPOR BARRIER—SERIES 2—AGE 50 DAYS

W/C	Moisture Outflow, grains/hr/sq ft	
	Water Vapor	Water-in-Contact
0.45	1.0	—
0.55	1.2	—
0.68	2.2	3.3
0.99	2.6	7.8

Moisture outflow was computed from the sum of the water added to maintain the constant head plus any loss in weight from the specimen. Water was added daily and weights were taken weekly. Control specimens were coated with polyester on the sides and one surface to determine the moisture loss due to drying only.

Series 2 Results and Discussion

Test results obtained during the first 50 days of the various exposures (Fig. 6), show that outflow increased as w/c increased. During the first few weeks high flows were measured on all specimens, but, at age 50 days, outflow had reduced to the rates shown in Table 3. Specimens exposed with water-in-contact had considerably greater outflow than those exposed to water vapor.

There appeared to be little difference in flow between specimens that were drying only (Fig. 6c) and those that were exposed to water vapor. This indicates that with water-vapor exposure the loss from the surface was due almost entirely to loss of original mixing water, with very little moisture passing through the slab.

Outflow from specimens cast on vapor barriers was generally slightly greater at early ages than from specimens without vapor barriers. This apparent anomaly occurs because the major portion of the water loss at early ages is due to evaporation of the mix water. When vapor barriers were not used, more mix water drained from the fresh concrete into the pail thereby reducing the water content and w/c ratio in these slabs. However, at later ages, these vapor barriers reduced the flow for water-in-contact exposure. After the initial exposure of 50 days to water vapor, the specimens with 0.45 w/c were subjected to water-in-contact. At age seven months, these specimens had stabilized with the following values for *inflow:*

Without vapor barrier	0.7	grains/hr/sq ft
Polyethylene (4 mil)	0.5	" " " "
ABS Plastic (32 mil)	0.3	" " " "
55-lb roofing felt	0.3	" " " "

Fig. 7 summarizes the outflow for specimens of 0.41 w/c air-entrained concrete for the first 80 days exposure to drying at 73 F and 50 percent relative humidity. No difference in flow was found for the specimens without vapor barriers and with 6-mil polyethylene, but slightly higher flow was obtained when 55-lb roofing felt was used. The major portion of water lost from the surface was due to drying of the slab.

The moisture outflow from concretes of three w/c ratios and exposure conditions but without vapor barriers are compared in Fig. 8. The moisture flow increased rapidly with increased water—cement ratio. Specimens were tested with water-in-contact for 130 days, at which time outflows were 5.6, 3.0, and 0.8 grains for concretes of w/c of 0.99, 0.68, and 0.41, respectively. After excess water was drained from the pail, testing was continued for another 370 days with water-vapor only in contact, resulting in final flows of only 1.3 and 1.1 grains for the 0.99 and 0.68 w/c concretes. After 500 days exposure the 0.41 w/c slabs and the 0.68 w/c slabs subjected to drying only had flows of less than 0.4 grains/hr/sq ft.

SERIES 3

Test Procedures

The third series of tests was conducted to obtain better correlation for some of the variables included in the first two series and to clarify some inconclusive data. This series included 17 concretes having a wide range in quality obtained by varying the w/c ratio from 0.41 to 0.89, with additional variations in both cement content and slump as shown in Table 4. Several admixtures were used including two air-entraining agents, two calcium chloride solutions, butyl stearate, and two water reducing agents.

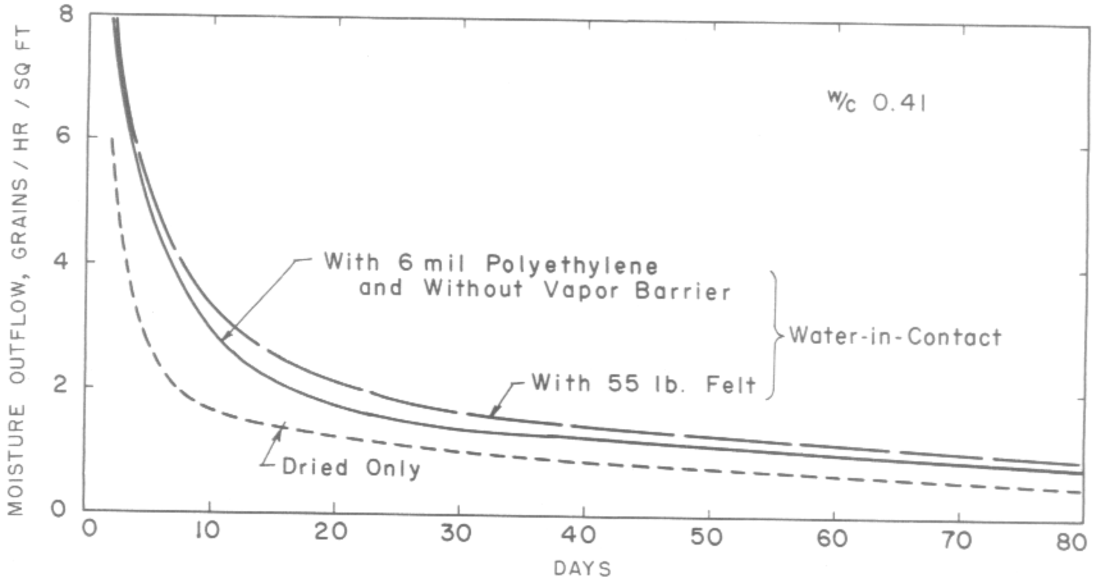


Fig. 7 — Moisture Migration from Good Quality Concrete. Series 2

Four-inch-thick concrete slabs were cast in the bottom of epoxy-coated triple-seal one-gallon paint cans (6½ in. diameter by 7 in. high) and sealed to the sides of the can by placing the concrete against fresh epoxy polysulfide compound. The concrete was cured for seven days, then the bottoms were cut out of the cans to expose the surface of the concrete and a bead of epoxy resin was added around the rim, as illustrated for two of the specimens in Fig. 9. As soon as this bead had hardened, specimens were prepared for the three exposure conditions of drying only, water vapor, and water-in-contact, in a room controlled at 73 F and 50 percent relative humidity. Some cans were sealed with no added water, to provide a measurement of water loss due to drying only. The remaining cans were partially filled with water and the lids sealed with epoxy; half of these specimens were stored in this position, on grids, and were subjected to water-in-contact. The other specimens were inverted so that the concrete was exposed to water-vapor only.

In addition, 11 specimens from a single concrete mix (No. 17) were cast on vapor barriers installed in the two-compartment cans shown in Fig. 9. Seven specimens included 4-mil polyethylene and four specimens had 32-mil ABS plastic vapor barriers. After curing, these specimens were tested with water in contact with the vapor barrier. The moisture outflow from all specimens was determined by weighing.

Series 3 Results and Discussion

Fig. 10 summarizes the data obtained from the third series by correlating moisture *outflow* with w/c after 7, 28, and 180 days. Quite consistent data were obtained. The figure shows that (1) flow increased directly with w/c, (2) flow decreased as exposure conditions varied from water-in-contact to water vapor to drying-only condition, and (3) flow decreased with exposure time. The highest flows were ob-

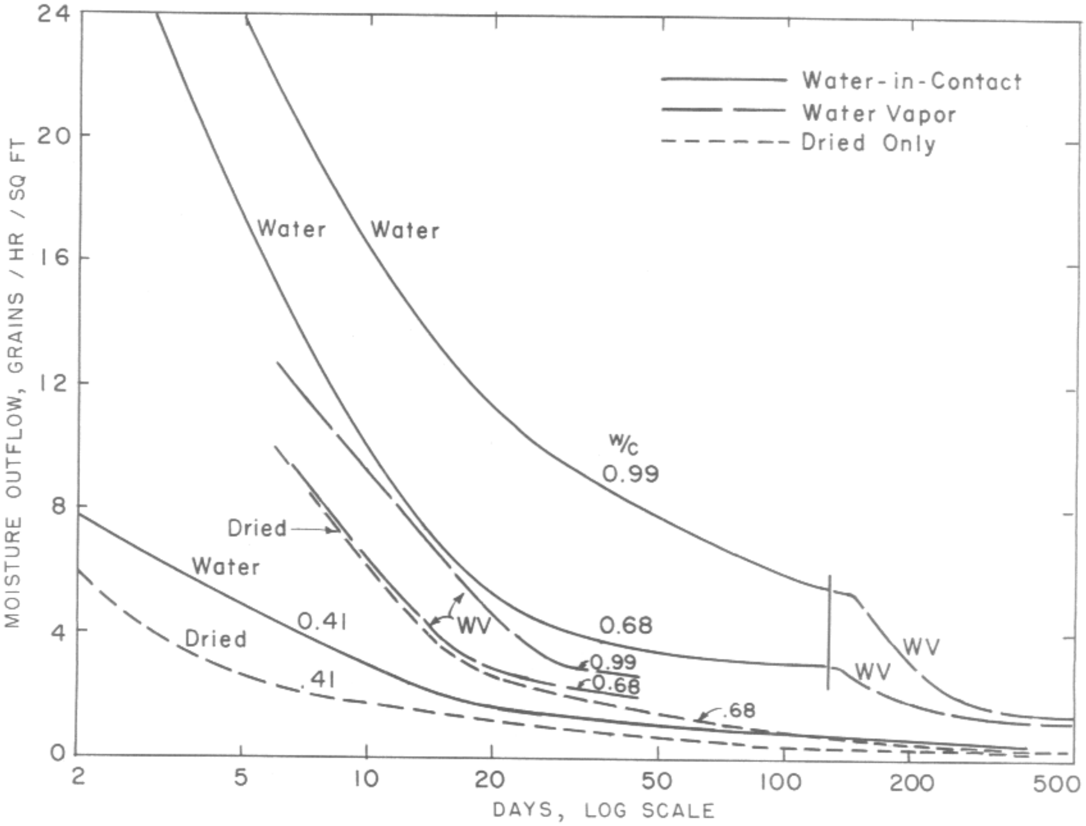


Fig. 8 — Moisture Migration at Various Water—Cement Ratios and Exposures. Series 2

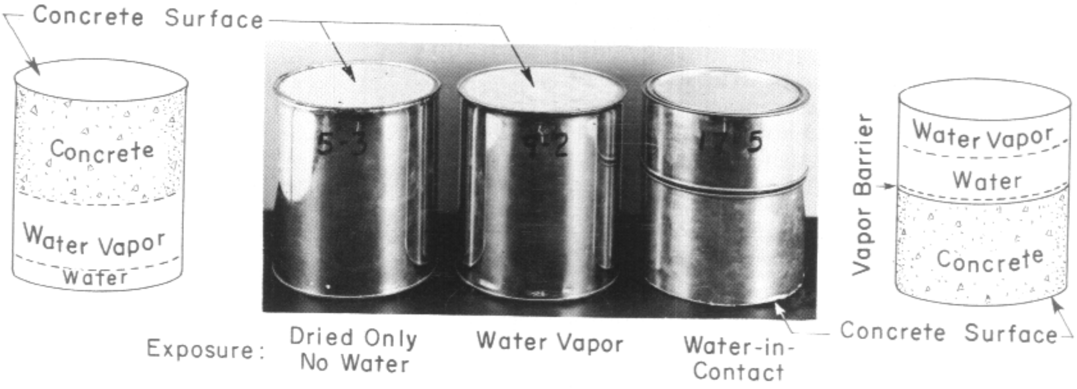


Fig. 9 — Gallon Paint Cans Used for Series 3 Tests.

tained for high w/c concretes at early ages when the slab was in direct contact with water. In addition, the data show that at low w/c little or no difference in flow occurred at early ages regardless of the exposure condition.

Several individual relationships derived from Fig. 10 (and Table 5) are illustrated in Figs. 11, 12, 13, and 14. Fig. 11 compares the *outflow* of moisture from slabs made at different w/c when exposed to water-in-contact. Flow increased rapidly with increasing w/c, but diminished with age. Fig. 12 shows similar data for specimens exposed to water vapor only. The same general relationships of higher flow with higher w/c and decreasing flow with increasing duration of exposure are apparent. Although moisture outflow for the two exposure conditions (water and water vapor) was essentially the same at low w/c, there was a great difference in flow at high w/c. The moisture outflow due to drying only, shown in Fig. 13, is the rate at which the mix water evaporated from the surface when exposed to 50 percent relative humidity air. These outflows were only slightly different from the outflows from companion specimens exposed to water vapor at early ages, but decreased to less than 50 percent after 365 days exposure.

A comparison of outflows for the three exposure conditions at w/c of 0.40, 0.60 and 0.80 are shown in Fig. 14. The severity of the exposure produced only small absolute differences at low w/c; the outflow with water-in-contact was only 0.4 grains/hr/sq ft after one year exposure. High w/c concretes, however, had wide differences in outflow for the different exposure condi-

TABLE 4—MIX DATA AND PHYSICAL PROPERTIES—SERIES 3 CONCRETES

Mix No.	W/C	Cement Content		Unit Wt, lb/cu ft	Air Content, %	Slump, in.	Comp. Str., psi at 28 days	Admixture
		lb/cu yd	bags/cu yd					
4	0.41	681	7.2	149.0	1.7	4.5	7460	None
16	0.43	545	5.8	140.2	6.6	4.4	5080	AEA-3
15	0.44	558	6.0—	143.6	4.5	4.6	5740	AEA-4
13	0.44	578	6.2	149.2	2.0	3.6	8020	Hydroxylated carboxylic acid
14	0.45	560	6.0	144.6	3.5	5.0	6940	Lignosulfonic acid
1	0.48	567	6.0	147.3	1.6	5.0	6320	None
11	0.50	568	6.0+	147.9	2.7	4.9	5960	2% Butyl stearate
10	0.50	514	5.5	147.3	2.5	3.0	5850	Calcium chloride sol.
17	0.50	455	4.9	138.9	7.0	5.2	4280	AEA-3
12	0.51	569	6.0	148.7	1.5	4.2	6670	2% Calcium chloride
2	0.56	457	4.9	147.4	2.0	2.0	5260	None
3	0.67	386	4.1	145.9	2.3	3.7	3350	None
6	0.69	303	3.2	144.8	4.5	2.5	2930	AEA-4
5	0.70	294	3.1	140.5	6.5	4.2	2510	AEA-3
7	0.84	304	3.2	146.2	2.2	1.6	2410	Calcium chloride sol.
9	0.84	305	3.2	146.9	1.6	1.5	2200	2% Calcium chloride
8	0.89	302	3.2	145.7	1.7	2.6	2060	2% Butyl stearate

tions. After one year, substantial quantities of water were still passing through the slabs of 0.80 w/c, as indicated by flows of 2.5, and 1.1 for water-in-contact and water vapor, respectively. Although the drying-only condition indicated high flow at early ages, this reduced to 0.5 grains after one year.

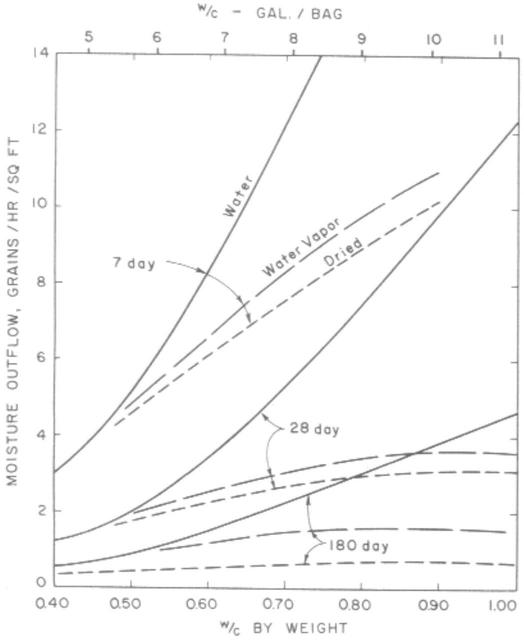


Fig. 10 — Correlation of Moisture Migration with Water—Cement Ratio, Type of Exposure, and Days Subjected to Exposure.
Series 3

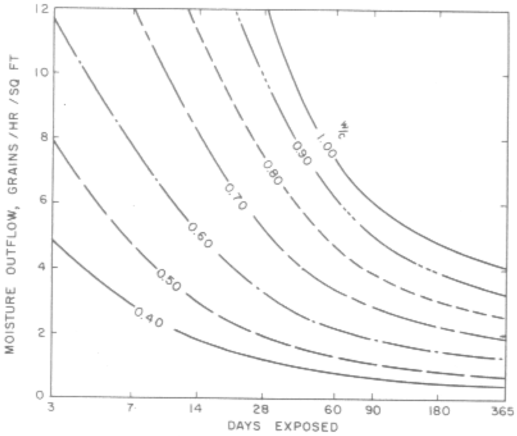


Fig. 11 — Moisture Migration with Water in Contact.
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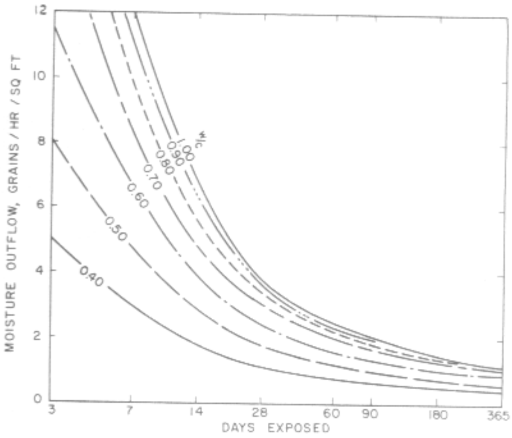

Fig. 12 — Moisture Migration with Water Vapor in Contact.
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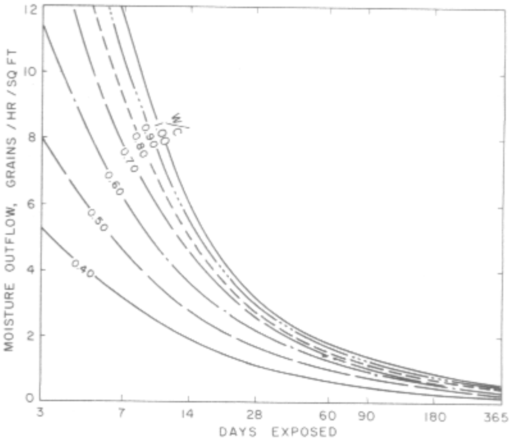

Fig. 13 — Moisture Migration Due to Drying Only.
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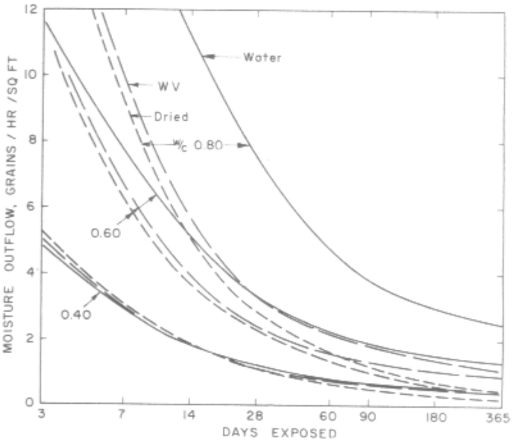

Fig. 14 — Moisture Migration at Various Water—Cement Ratios and Exposures.
Series 3

Fig. 15 provides a comparison between concretes with and without admixtures. The numbers and letters above the plotted points indicate the concrete mixes described in Tables 2 and 4. Concretes without admixtures are (1), (2), (3), (4), and (L). Data from three concretes (L, K and M) from Series 2 are included with the 17 concretes of Series 3. It is apparent that all of the points lie close to the average curves, indicating that these admixtures had no appreciable effect on moisture migration when compared with plain concretes of the same w/c. This conclusion, based on the 90-day test results of Fig. 15, was found to apply at all ages.

In addition to the above tests, specimens from concrete mix No. 17 were cast in two-compartment paint cans fitted with vapor barriers. Both 4-mil polyethylene film (7 specimens) and 32-mil ABS plastic sheeting (4 specimens) were tested with water in contact with the vapor barrier as shown in Fig. 9. Fig. 16 compares outflow from these specimens with the outflows obtained from specimens without vapor barriers. Although both vapor barriers reduced the outflow for water-in-contact, the 4-mil film was less effective than the 32-mil sheeting. Neither vapor barrier, however, eliminated entry of water into the concrete as indicated by both higher outflow from the slab and higher percent saturation at the end of the test, as shown by Table 6.

TABLE 6—MOISTURE OUTFLOW AND PERCENT SATURATION OF 0.50 W/C CONCRETE AT AGE ONE YEAR

Test Condition	Moisture Outflow, gr/hr/sq ft	Degree of Saturation, %
Water in contact with concrete	0.73	81
Water vapor in contact with concrete	0.66	76
Water in contact with 4-mil polyethylene	0.45	53
Water in contact with 32-mil ABS plastic	0.32	51
Drying only—No water added to can	0.29	50

TABLE 5—MOISTURE MIGRATION FOR CONCRETES OF SERIES 2 AND 3

Days	Exposure	Moisture Migration, grains/hr/sq ft at w/c valves shown						
		w/c=0.40	0.50	0.60	0.70	0.80	0.90	1.00
3	W*	4.8	7.8	11.6	20.4	27.0	33.0	43.8
	WV	5.0	8.0	11.5	17.0	21.0	24.4	27.2
	D	5.2	8.0	11.4	16.3	19.2	21.2	22.8
7	W	2.9	4.7	7.7	11.8	16.4	21.5	27.0
	WV	3.0	4.8	6.7	8.4	9.8	11.0	12.4
	D	3.1	4.6	6.1	7.6	9.0	10.2	11.5
14	W	1.8	3.0	5.0	8.1	11.1	14.4	18.2
	WV	1.8	2.9	3.9	4.8	5.6	6.3	6.8
	D	1.9	2.8	3.7	4.6	5.0	5.5	6.0
28	W	1.2	1.9	3.3	5.3	7.5	9.9	11.8
	WV	1.1	1.8	2.9	3.0	3.4	3.6	3.8
	D	1.1	1.7	2.3	2.6	2.8	3.0	3.2
60	W	0.8	1.3	2.2	3.4	4.7	6.1	7.4
	WV	0.8	1.2	1.6	2.0	2.2	2.4	2.5
	D	0.7	1.1	1.3	1.5	1.6	1.7	1.8
90	W	0.7	1.1	1.9	2.9	3.8	5.0	6.0
	WV	0.7	1.0	1.4	1.7	1.8	1.9	2.1
	D	0.5	0.8	1.0	1.1	1.2	1.3	1.4
180	W	0.5	0.9	1.5	2.2	3.0	3.9	4.8
	WV	0.5	0.8	1.1	1.3	1.4	1.4	1.5
	D	0.3	0.5	0.6	0.6	0.7	0.8	0.9
365	W	0.4	0.7	1.3	1.9	2.5	3.3	4.1
	WV	0.4	0.6	0.9	1.0	1.1	1.1	1.1
	D	0.2	0.3	0.4	0.4	0.5	0.5	0.5

*W = Water-in-contact.
WV = Water vapor.
D = Dried only.

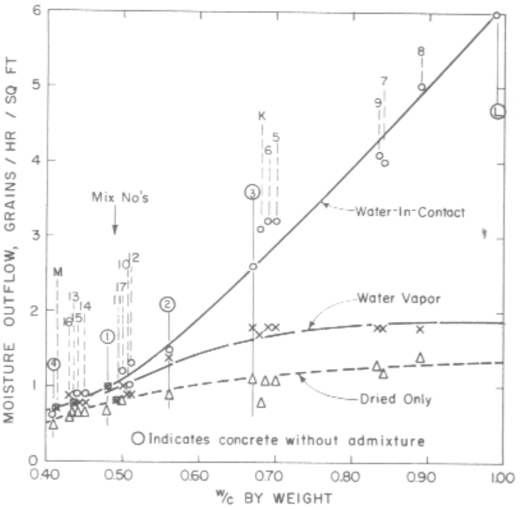

Fig. 15 — Comparison of Concretes With and Without Admixtures After 90 Days Exposure. Series 2 and 3

SUMMARY AND CONCLUSIONS

The principal conclusions drawn from this study on moisture migration from 4-inch-thick concrete slabs are:

(1) Flow varies directly with the water-cement ratio of the concrete. The w/c ratio controls the flow but of course the values obtained vary with time exposed, type of exposure (Fig. 10), and method of measurement (*i.e.* outflow or inflow).

(2) Moisture migration *through* good quality concrete was less than 0.3 grains/hr/sq ft; but the flow through low quality concrete often exceeded 2.0 grains.

(3) The *outflow* or rate of moisture loss from the surface of the same concretes, however, is much higher at early ages — approximately four times the above values at 28 days, and ten times at seven days. This outflow at early ages is the flow that contributes to the problems encountered upon installation of floor coverings.

(4) After extended exposure periods, exceeding one year under the constant temperature and humidity conditions of these tests, *inflow* and *outflow* will become equal; at that time stabilized moisture migration *through* concrete is attained.

(5) On the basis of concretes of equal w/c, the admixtures used neither contributed to, nor detracted from, the measured flow to any appreciable degree (Fig. 15).

(6) A gravel capillary break between the clay soil and concrete slab reduced the inflow by 10 to 25 percent (Figs. 3 and 4).

(7) Vapor barriers below concrete slabs normally reduce moisture migration (Figs. 3 and 16). However, moisture migration may be increased at early ages when seepage of excess mix water to the subbase is retarded by the vapor barrier (Figs. 6 and 7).

(8) Application of an impervious barrier (such as floor tile) on a partially dried concrete surface reduced evaporation but increased the moisture content of the concrete when moisture was available below the slab. This occurred even when a vapor barrier was used.

REFERENCES

1. "Slab-On-Ground Construction for Residences," National Academy of Sciences — National Research Council, Washington, D.C., *Publication 385* (1955), 50 pages.
2. "Vapor Barrier Materials for Use with Slab-On-Ground Construction and as Ground Cover in Crawl Spaces," National Academy of Sciences — National Research Council, Washington, D.C., *Publication 445* (1956), 23 pages.
3. "Effectiveness of Concrete Admixtures in Controlling Transmission of Moisture Through Slabs-on-Ground," National Academy of Sciences — National Research Council, Washington, D.C., *Publication 596* (1958), 32 pages.
4. "Design Criteria for Residential Slabs-On-Ground," National Academy of Sciences — National Research Council, Washington, D.C., *Publication 657* (1959), 73 pages.
5. "Protection from Moisture for Slab-On-Ground Construction and Habitable Spaces Below Grade," National Academy of Sciences — National Research Council, Washington, D.C., *Publication 707* (1959), 67 pages.

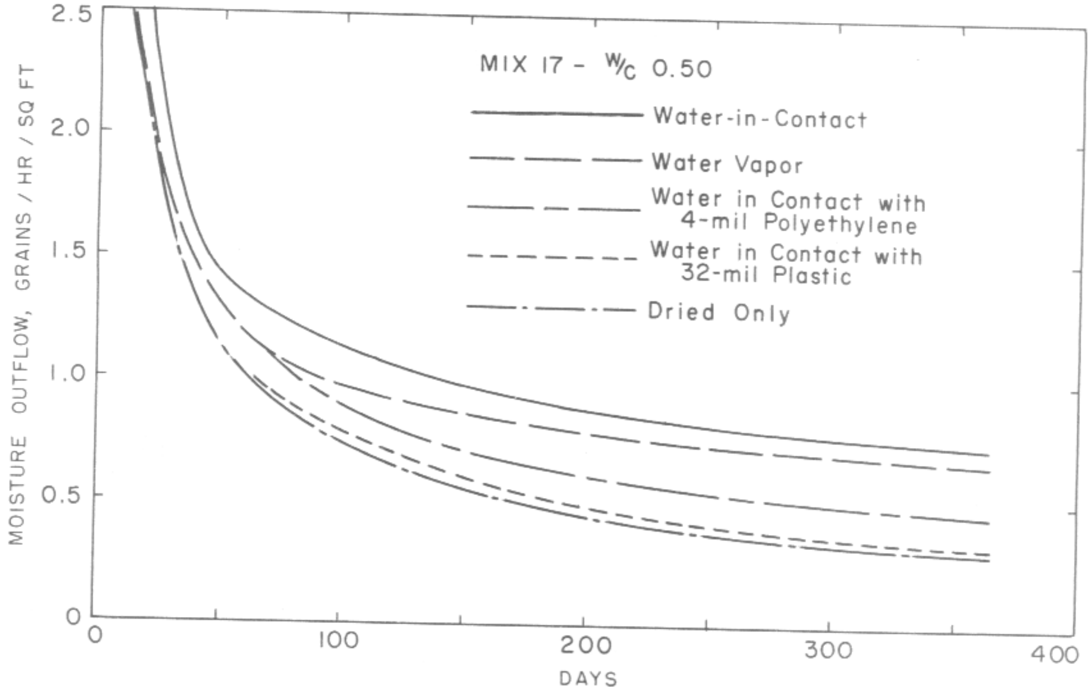

Fig. 16 — Effect of Vapor Barriers.
Series 3

6. Lund, C. E., "Moisture Migration and Vapor Permeability of Concrete Storehouse Floors," University of Minnesota, Institute of Technology, Minneapolis, Minnesota, *U.S. Navy Contract NOy 73218, Summary Report* (June 15, 1955), 51 pages.

7. "Moisture Migration from the Ground," Housing and Home Finance Agency, Washington, D.C., *Housing Research Paper No. 28* (April 1954), 13 pages.

8. Kocataskin, F., and Swenson, E. G., "Methods for Rating Concrete Waterproofing Materials," *ASTM Bulletin,* pages 67-72 (April 1958).

9. Powers, T. C., Copeland, L. E., Hayes, J. C., and Mann, H. M., "Permeability of Portland Cement Paste," *Journal of the American Concrete Institute* (November 1954); *Proceedings,* **51,** 285-298 (1954-55); *PCA Research Department Bulletin 53.*

10. Griffin, D. F., and Henry, R. L., "Integral Sodium Chloride Effect on Strength, Water Vapor Transmission, and Efflorescence of Concrete," *Journal of the American Concrete Institute* (December 1961); *Proceedings,* **58,** 751-772 (1961).

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