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MOISTURE MIGRATION FROM THE GROUND

Changes and new developments in building construction during the past few decades have brought about an increasing need for control of moisture which often migrates upward from the ground. Crawl-space-type basementless houses, formerly built mostly in mild southern climates where condensation of moisture was not a problem, are now being built in increasing numbers in northern latitudes. Concrete slab-on-ground floors, which formerly were constructed chiefly in semiarid southwestern areas of the United States, are now commonly used in almost every part of the United States, for both houses and commercial buildings. The recent trend to gas- and oil-fired heating plants in dwellings has resulted in a large amount of clean space in basements, which the homeowner can make good use of only if the basement is kept reasonably dry by preventing ground moisture from migrating into it.

The purpose of this paper is to discuss the theory of moisture migration, the common ways or forms in which it gains access to the building, and to suggest practical methods by which builders and homeowners may prevent or reduce moisture migration.

Forms of Moisture Migration

There are three general ways or forms by which ground moisture may gain access to a building: leakage, capillarity, and vapor migration. Any of these may occur separately or simultaneously. Moisture originating in the ground should not be confused with that which condenses out of the air on cold floor slabs and walls, particularly during hot, humid summer weather, although ground moisture and condensation moisture may occur simultaneously.

Failure to control moisture migration from the ground often results in serious damage to the building. It may cause rotting of wood joists and sills in crawl-space-type houses, excessive dampness in basements, rotting of wood framing in walls, blistering of exterior paint, deterioration of adhesives bonding floor finish material to slab-on-ground floors, rusting of tools, and deterioration by mildew of rugs, furnishings, shoes, and clothing.

Natural Laws of Moisture Migration[1]

Moisture migrates in obedience to natural physical laws, many of which are well known to engineers and others with scientific training.

● This paper reviews current theory and existing knowledge on the subject of migration of moisture from the ground, and reports recent research studies on this subject. The control of moisture originating in the ground beneath buildings has become more important because of the trend to concrete slab-on-ground floor construction, often associated with "ranch"- or "rambler"-type houses, and to the increased use of basements for habitable purposes.

Data, based on recent studies of laboratory specimens simulating slab-on-ground construction, are presented and recommendations for control of moisture migration from the ground are suggested.

Recent research studies on slab-on-ground construction reported herein were sponsored by the Housing and Home Finance Agency and performed at the Forest Products Laboratory, Forest Service, U. S. Department of Agriculture, Madison, Wis., under Housing Research Project O–T–29. H. W. Eickner, engineer, and R. F. Blomquist, chemist, were in charge of the laboratory work and compilation of data, under the general direction of R. F. Luxford, engineer.

This paper was prepared by William A. Russell, Chief, Technical Standards Unit, Division of Housing Research, Housing and Home Finance Agency.

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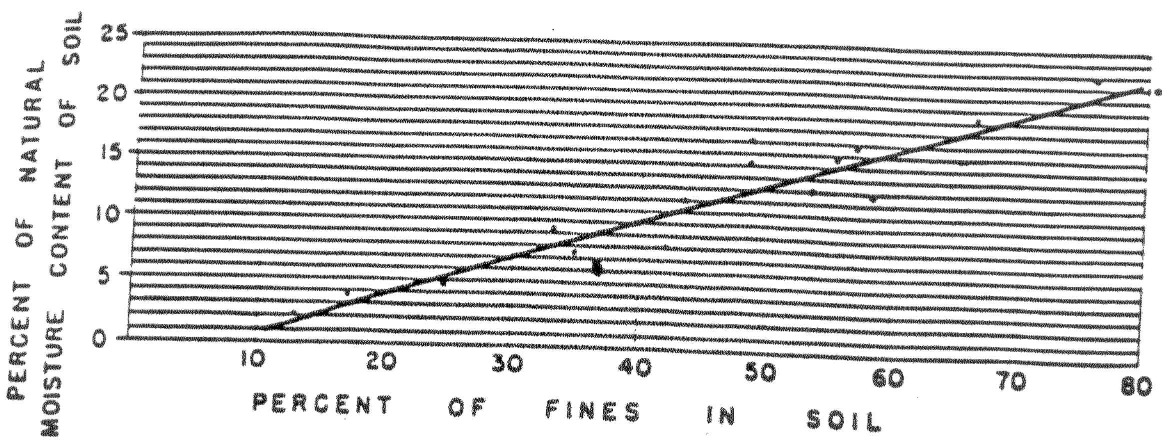
[1] "Moisture Migration, a Survey of Theory and Existing Knowledge," by P. F. McDermott, research engineer, Johns-Manville Research Laboratories, published in *Refrigerating Engineering*, August 1941.



SOIL SAMPLES TAKEN FROM CRAWL SPACES OF FOUR BUILDINGS - 16 SAMPLES

NOTE: FINES = SILT + CLAY + COLLOIDS
SILT IS SMALLER THAN 1/480 INCHES
CLAY AND COLLOIDS ARE STILL SMALLER

Figure 1.—Relationship of natural moisture content to fineness of soil.

These include the laws of gravity, hydraulic pressure, surface tension of liquids, vapor pressure, absorption, adsorption, evaporation of liquids, condensation of gases, and other physical laws governing the behavior of liquids and gases.

Leakage

Moisture migration in the form of leakage needs little explanation. It is simply liquid water moving from a higher to a lower elevation due to the force of gravity. It is evidenced either by free water appearing on the inner surface of basement walls and floors, or by damp spots when the leakage is less severe. It often causes damp or flooded crawl spaces when the crawl-space floor is below the grade of the surrounding yard. Leakage is caused by free water which finds its way through cracks or openings, honeycombed concrete, porous masonry units, imperfect water-resistant coatings, or poorly constructed water-resistant membranes.

Capillarity

Capillarity is often spoken of as "wick action" because it is similar to the action of a lampwick. Unlike leakage, where water moves from a higher to a lower elevation under the influence of gravity, moisture may travel by capillarity from a lower to a higher elevation, as in the case of the lampwick where fluid rises from the base of the lamp to the top of the wick. Scientists have found that the force which causes a capillary movement is the result of tension on the surface of the liquid when it is confined in a very small tube or channel. Cell walls in plants and trees, and the small spaces between particles of earth composed of silt and clay, form capillary-sized tubes and channels which induce moisture to travel through them by capillary action.

The amount of moisture that can be transmitted from the ground by capillary action is often underestimated. Tests[1] indicate that the natural moisture content of soil varies in direct relation to the fineness of the soil, as shown in figure 1.

Sieve analysis and determination of natural moisture content of 16 typical soil samples, plotted in figure 1, varied progressively from 4 percent moisture for soils having 20 percent fines to 23 percent moisture for soils having 80 percent fines. As used herein, "fines" are defined as soil particles composed of silt, clay, and colloids which are less than 1/480 inch in size. Other tests of laboratory specimens of soils containing 56 percent fines showed moisture constantly rising to the surface by cap-

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[1] HHFA Reprint No. 1. *Crawl Spaces.* Available from U. S. Government Printing Office, Washington 25, D. C. Price 15 cents.

illarity, and evaporating at the average rate of 12.1 gallons per 1,000 square feet per 24 hours, when the water table was maintained 30 inches below the surface of the specimens.

The distance which water will rise by capillarity above the water table [4] is also usually underestimated. The idea, held by many, that a high water table only a few feet below the surface is necessary to produce appreciable rise of capillary moisture is not borne out by tests. Core borings made in soils having 50 to 80 percent fines showed the same straight-line relation between fines and natural moisture content of the soil near the surface, regardless of whether the water table was 8 feet or 20 feet below the ground surface. It is doubtful that this rise is due to simple capillary action. What appears to be capillary action may well be a combination of capillarity, adsorption, and gaseous diffusion.

The conclusions which seem to be indicated by the above data with regard to migration of moisture from the soil by capillary action are that a large amount of moisture would be transmitted for an average soil having 50 percent or more fines. This would be true even when the water table is as much as 20 feet below the surface, which most authorities would call a low water table. Moreover, capillary action usually takes place 24 hours a day, day after day, over the whole area of a crawl space, basement, or slab-on-ground floor, so that a large amount of moisture may migrate into a building by capillary action alone.

Vapor Migration From the Ground

Moisture in the form of water vapor may also migrate from the ground into a building. Because water vapor is an invisible gas, this form of moisture migration is less understood than other types. It is only in the last decade that engineers and builders have learned of the necessity of protecting buildings from the harmful effects of moisture that migrates in the form of vapor into floor, wall, and roof areas of buildings, and then condenses into liquid water, which causes damage.[5]

Water vapor acts in accordance with the physical laws of gases, which can no more be "wished" away than can the physical law of gravity. One of these laws is that vapor will travel from one area to another whenever a difference of vapor pressure exists between the two, unless an impervious vapor barrier exists between them.[6] The water vapor with which we are dealing here is not pure water vapor but rather a mixture of two gases—water vapor and air. The amount of water vapor which air can absorb is limited for any given temperature of the air and water vapor mixture, and as the temperature is raised, the ability of the air to absorb more moisture increases. When air at any given temperature has absorbed all the water vapor it can hold, it is said to be saturated with water vapor or to have 100 percent relative humidity. If the air contains only half as much water vapor as it can hold at a given temperature, it is said to have 50 percent relative humidity.

Any good text on heating or ventilating contains tables of vapor pressures for various temperatures and relative humidities. Table 1, which is based on data published by General Electric Co., is such a table. It will be noted in this table that vapor pressure increases not only with temperature but also as the relative humidity increases.

Table 1.—Vapor pressure for various temperatures and relative humidities, in pounds per square inch

[Based on General Electric Co. data]

Dry bulb temperature	Relative humidity (in percent)									
	100	90	80	70	60	50	40	30	20	10
°F.										
100	0.946	0.851	0.757	0.662	0.568	0.474	0.378	0.284	0.189	0.095
90	.690	.621	.551	.482	.414	.344	.275	.207	.138	.069
80	.506	.455	.405	.357	.303	.253	.202	.152	.101	.051
75	.429	.386	.343	.300	.258	.214	.172	.129	.086	.043
70	.362	.326	.290	.253	.217	.181	.145	.108	.072	.036
65	.305	.274	.244	.213	.183	.153	.123	.091	.061	.030
60	.256	.230	.205	.179	.153	.128	.102	.077	.051	.026
55	.214	.193	.171	.149	.128	.107	.085	.064	.042	.021
50	.178	.160	.142	.124	.107	.089	.071	.053	.036	.018
45	.147	.132	.118	.103	.088	.073	.059	.044	.029	.015
40	.122	.110	.098	.085	.073	.061	.049	.037	.024	.012
35	.100	.090	.080	.070	.060	.050	.040	.030	.020	.010

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[4] Upper limit of ground which is saturated with water, such as the surface of the water in a well.

[5] *Condensation Control in Dwelling Construction*, published by HHFA and available from the U. S. Government Printing Office, Washington 25, D. C. Price 25 cents.

[6] "A Theory Covering the Transfer of Vapor Through Materials," by Frank B. Rowley, director, Engineering Experiment Station, University of Minnesota, published in *Transactions of American Society of Heating and Ventilating Engineers*, vol. 45, 1939.

Let us examine a concrete slab-on-ground floor resting on 4 to 6 inches of coarse gravel, which would act to interrupt capillarity, to see under what conditions there would be a tendency for moisture to migrate from the soil beneath in the form of water vapor. Let us first consider a typical winter condition where the air in the house is maintained at 70° F. and 30 percent relative humidity.[6] From table 1, the vapor pressure in the room above the slab would be 0.108 pound per square inch. Assuming the house to be heated by warm air or conventional radiators, the air in the house would be losing heat to the slab which, in turn, would be losing heat to the ground below. Measurements by several investigators have shown that a temperature of 60° F. would be realistic for the ground or gravel course just below the slab. Since moisture is constantly being fed up to the area just beneath the slab by capillarity, we would expect the relative humidity of airspaces in the gravel course beneath the slab to be high, possibly approaching saturation. From table 1, the vapor pressure of air at 60° F. completely saturated with water vapor would be 0.256 pound per square inch, which is more than twice the vapor pressure of the air in the room above. Theoretically, vapor would travel upward through the slab even if the relative humidity below the floor were decreased to 50 percent, in which case the vapor pressure from table 1 would be 0.128 pound per square inch. This is still 0.02 pound per square inch higher than the vapor pressure in the room above.

Conversely, during humid summer weather, when the temperature and humidity are both high in the room above the slab, vapor pressure would be higher in the room than beneath the slab, with a consequent vapor pressure downward.

Laboratory Measurements of Vapor Migration

In order to get some factual information on the migration of water vapor through a concrete slab-on-ground floor, and on the effectiveness of vapor barriers, a limited exploratory study, sponsored by the Housing and Home Finance Agency, was made at Forest Products Laboratory, Madison, Wis. While these studies were preliminary, and consisted of only one test specimen for each slab construction, they support the theory that vapor migrates through the slab in easily measurable quantities, due to a difference in vapor pressure.

Description of Specimens

Six cylindrical galvanized-iron tanks, 34 inches high and 1 square foot in cross section, were constructed. Each of these was equipped with a water-gage glass for determining the height of the water table, and a filler tube through which water could be added to maintain a constant water level, as shown in figure 2. A 4-inch-thick concrete slab was poured flush with the top of each tank. Miami-type loam was placed to a depth of 26 to 30 inches to represent the subsoil under a slab-on-ground floor, and various membranes and capillary breaks were placed beneath the slabs prior to pouring them as described in detail below.

TANK 1—26 inches soil, 4 inches coarse washed gravel (1 inch), 1 layer, untreated kraft paper (65 pounds per 3,000 square feet), 4-inch concrete slab. The kraft paper was for the purpose of preventing filling of gravel spaces by grout and is not considered to be a vapor barrier.

TANK 2—26 inches soil, 4 inches coarse washed gravel (1 inch), 2 layers 15-pound asphalt-saturated felt, hot asphalt mopped between layers, 4-inch concrete slab.

TANK 3—26 inches soil, 4 inches coarse washed gravel (1 inch), 1 layer 15-pound asphalt-saturated felt, 4-inch concrete slab.

TANK 4—26 inches soil, 4 inches coarse washed gravel (1 inch), 1 layer of 45-pound smooth-surface roll roofing, 4-inch concrete slab.

TANK 5—26 inches soil, 4 inches coarse washed gravel (1 inch), 1 layer 15-pound asphalt-saturated felt, 4-inch concrete slab. 1 : 3 : 5 mix to which 2 parts of an integral waterproofing admixture containing hydrated lime and calcium stearate were added to 94 parts of cement.

TANK 6—4-inch-thick concrete slab poured directly on 30 inches of soil, no membrane or gravel course.

The membranes were sealed to the walls of the tanks with a hot-melt asphalt cement. Con-

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[6] "Humidity Conditions in Modern Houses," by Robert C. Reichel in HOUSING RESEARCH No. 6, October 1953, published by HHFA. Available from U. S. Government Printing Office, Washington, D. C. Price 35 cents.

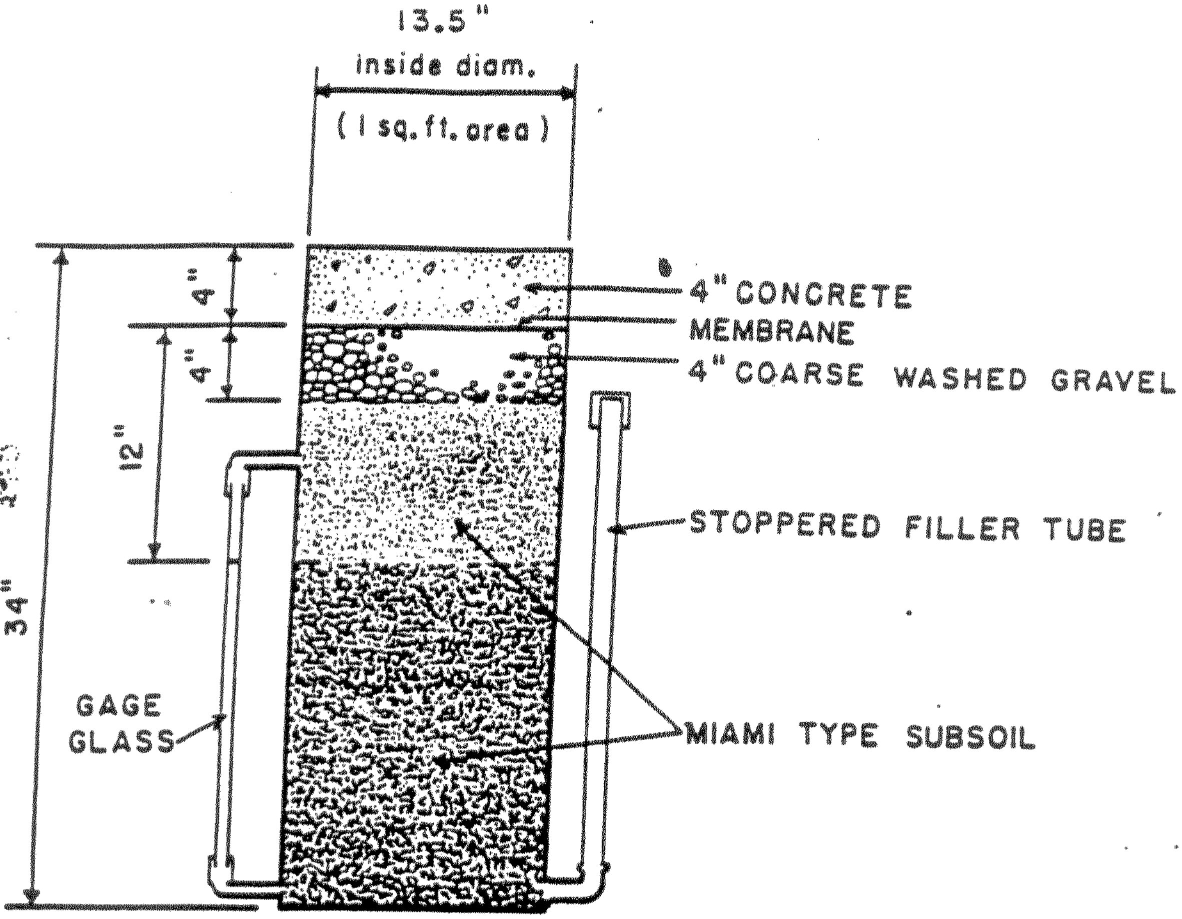

Figure 2.—Diagrammatic sketch of cylindrical tank specimens.

crete mix was 1 part cement, 3 parts sand, and 5 parts ½- to ¾-inch gravel.

Test Procedure

Water was added to all tanks through the filler tubes to bring the water level to a point 1 foot below the bottom of the slabs as observed on the water-gage glasses attached to the side of each tank. The tanks were then placed in a temperature-and-humidity-controlled room. For the first week after pouring the slabs, the temperature was controlled at 80° F. and the humidity at 97 percent relative humidity. Following this, the temperature was controlled at 80° F. and the humidity at 30 percent relative humidity for the remainder of the test period of approximately 150 days (22 weeks). Figure 3 shows specimens undergoing test.

At intervals of approximately 2 weeks, sufficient water was added to the tanks to maintain the water level at 1 foot below the bottom of the slabs, as observed on the gage glasses. The average amount of water which had to be added, reduced to a daily basis, is shown in table 2.

Analysis of Results

It must be assumed that the amount of moisture, shown in table 2 for each tank, traveled upward and found its way out of the tank through the slab, since this was the only way in which moisture could escape from the tank. A study of the relative daily amounts of water escaping reveals the following:

1. *Effect of Membranes.*—Considering Tanks 1 through 4, which were identical specimens except for the membranes, the amount of moisture passing through the slabs was directly proportional to the vapor permeability of the membrane. Tank 4, which had a highly imperme-

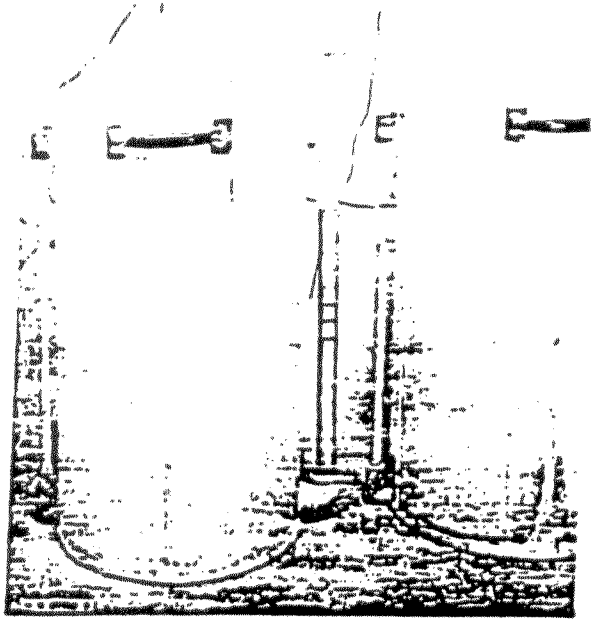

Figure 2.—Specimens undergoing test.

able 45-pound roll roofing membrane,[7] lost the least moisture, the loss being only one-tenth as much as that shown by Tank 1, which had no membrane. Tank 2, which had a membrane consisting of two layers of 15-pound asphalt-saturated felt, mopped with hot asphalt between, showed approximately half as much loss as did Tank 3 which had a single layer of 15-pound asphalt-saturated felt.

2. *Effect of Admixture.*—Tank 5 was identical with Tank 3, except that an integral waterproofing admixture was added to the concrete of Tank 5. Both tanks had 4 inches of coarse gravel beneath the slab to interrupt capillarity, and both had a membrane consisting of a single layer of 15-pound asphalt-saturated felt. Almost twice as much moisture passed through the slab specimen containing the integral waterproofing admixture as passed through the slab specimen without an integral waterproofing admixture. The indication is that the addition of an admixture of the type used increases the permeability of the concrete rather than decreases it.

Table 2.—Average water added per day in 2-week periods to maintain water-table level at 1 foot below bottom of slabs cast in top of metal tanks which were observed in a room maintained at 80° F. and 30 percent relative humidity.

Date of period	Cubic centimeters per day					
	Tank 1. 4 inches gravel, no membrane	Tank 2. 4 inches gravel, 2 layers 15-pound felt mopped between	Tank 3. 4 inches gravel, 1 layer 15-pound felt	Tank 4. 4 inches gravel, 1 layer 45-pound roll roofing	Tank 5. 4 inches gravel, 1 layer 15-pound felt, integral concrete admixture	Tank 6, no gravel, no membrane
1951						
4/9 to 4/23	13.5	(¹)	(¹)	(¹)	(¹)	9.8
4/23 to 5/7	7.6	(¹)	(¹)	(¹)	(¹)	9.1
5/7 to 5/21	6.7	3.2	2.3	1.1	9.3	6.2
5/21 to 6/4	6.9	3.0	1.9	1.6	10.7	3.3
6/4 to 6/18	3.6	1.4	3.3	0	9.0	3.2
6/18 to 7/2	9.1	3.5	3.7	1.9	9.1	6.4
7/2 to 7/16	13.5	.9	0	0	6.2	3.0
7/16 to 7/30	11.0	1.7	9.3	.7	3.7	2.8
7/30 to 8/13	11.0	2.8	9.2	0	7.0	4.7
8/13 to 8/27	12.7	1.8	2.0	1.4	5.7	3.2
8/27 to 9/17	9.0	1.7	2.0	1.2	4.3	2.8
Average 5/7 to 9/17	9.3	2.3	3.7	.9	7.2	4.3
Average gallons per day per 1,000 square feet	2.45	.58	.87	.24	1.80	1.13

¹ No water added because water-table level was high during this initial adjustment period.

3. *Effect of Gravel.*—Tank 1 was identical with Tank 6 except that Tank 1 had 4 inches of coarse gravel beneath the slab to interrupt capillarity, while the slab of Tank 6 was poured directly on the Miami loam subsoil with the coarse gravel omitted. Neither specimen had a vapor-barrier membrane beneath the slab. More than twice as much moisture passed through the slab of Tank 1, where capillarity was interrupted by 4 inches of coarse gravel beneath the slab, as passed through the slab of Tank 6 where no gravel was present to interrupt capillarity. In the case of Tank 1, it must be assumed that the moisture traveled upward from the top of the subsoil in the form of water vapor, since capillary travel was interrupted by the noncapillary coarse gravel beneath the slab. In the case of Tank 6, the moisture was free to rise by capillarity until it reached the bottom of the slab. Since twice as much water passed through the slab of Tank 1 as passed through that of Tank 6, it may be inferred that, under

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[7] HHFA Reprint No. 15, *Durability of Moisture-Resistant Membrane Materials in Contact With the Ground*, provides data on permeability of roll roofing and 15-pound asphalt-saturated felt. Available from U. S. Government Printing Office, Washington 25, D. C. Price 5 cents.

the temperature and humidity conditions of the test, vapor travel through a concrete slab is much more rapid than travel of free water.

However, since these results were obtained from single test specimens, and the gravel course beneath the slab also acts as a thermal break (the value of which will be discussed later), the coarse gravel fill beneath the slab (recommended by most authorities) should be retained until additional test data are developed.

Dr. J. D. Babbitt has pointed out that the migration of water vapor through hygroscopic building materials does not follow Fick's law of diffusion of gases and is much more rapid than the migration of other gases such as oxygen and nitrogen.[8]

This is accounted for by the fact that water vapor is adsorbed and can migrate through materials, in the adsorbed phase. Also, Babbitt points out that the migration of water vapor, unlike that of most gases, increases with the concentration, and that as the concentration approaches saturation, the increase is very rapid. The combination of gaseous and adsorbed diffusion may account for the greater movement of moisture through the slab of Tank 1 as compared with that of Tank 6. This more rapid movement of moisture through the slab of Tank 1 indicates that the air filling the spaces between the gravel beneath this slab has a high relative humidity, probably approaching saturation.

4. *Motive Force.*—Tanks 1 through 5 had a 4-inch coarse-gravel course beneath the slab to interrupt capillary action and to prevent moisture from reaching the slab by capillarity. Despite this, all of these tanks lost moisture, and it must be inferred that the moisture migrated upward through the gravel course in the form of water vapor. Since the tanks were kept in a temperature-controlled room during the period of test, the temperature beneath the slab was the same (80° F.) as the temperature of the air above the slab, and the moisture movement could not have been caused by a difference in temperature. The motive force causing moisture movement must then have been a difference in relative humidities below and above the slabs. The considerable movement of moisture through the slabs, even when a highly impermeable vapor barrier was used, such as that placed beneath the slab of Tank 4, indicates that humidities beneath the slabs were high, probably approaching saturation. Again consulting table 1, it will be seen that the vapor pressure at 80° F. and 100 percent relative humidity would be 0.506 pound per square inch, compared with the vapor pressure of 0.152 at 80° F. and 30 percent relative humidity at which the air above the slab was maintained. The difference of 0.354 pound per square inch between the vapor pressures below and above the slabs would provide a strong motive force in the upward direction.

Electrical Resistance Moisture Tests

During the same 150-day period in which moisture loss from the tanks was being observed, as described above, corollary moisture tests of the concrete slabs were being made. This was accomplished by reading, at intervals during the test period, the electrical resistance in ohms between stainless steel pins embedded in the slabs. To accomplish this, 3/16-inch-diameter stainless steel pins were cast in the slab at the time of pouring. Four pins having ½-, 1-, 2-, and 3-inch embedments were arranged in a 2½-inch-diameter circle around a central pin, which had an embedment of 3 inches. Resistance readings were taken between the central pin and each of the pins having various embedments. Figure 4 shows equipment used in making electrical resistance tests. Table 3 shows initial resistances in ohms, and subsequent ratios of resistance at each test period to initial resistance. The values for the pins having ½-inch embedment are not reported since some of them were found to have loosened and results were erratic.

On examining the values shown in table 3, it will be seen that in all cases resistance increases with time. This does not necessarily mean that there was a proportional decrease in moisture content of the concrete during this entire period, as probably there were certain chemical changes taking place during the slow setting of the concrete which also affected the electrical

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[8] "The Movement of Moisture in Building Materials," by Dr. J. D. Babbitt, Canadian Scientific Liaison Office, published in *Conference Report No. 4, Condensation Control in Buildings*, February 1952, by Building Research Advisory Board, 2101 Constitution Ave., Washington, D. C.

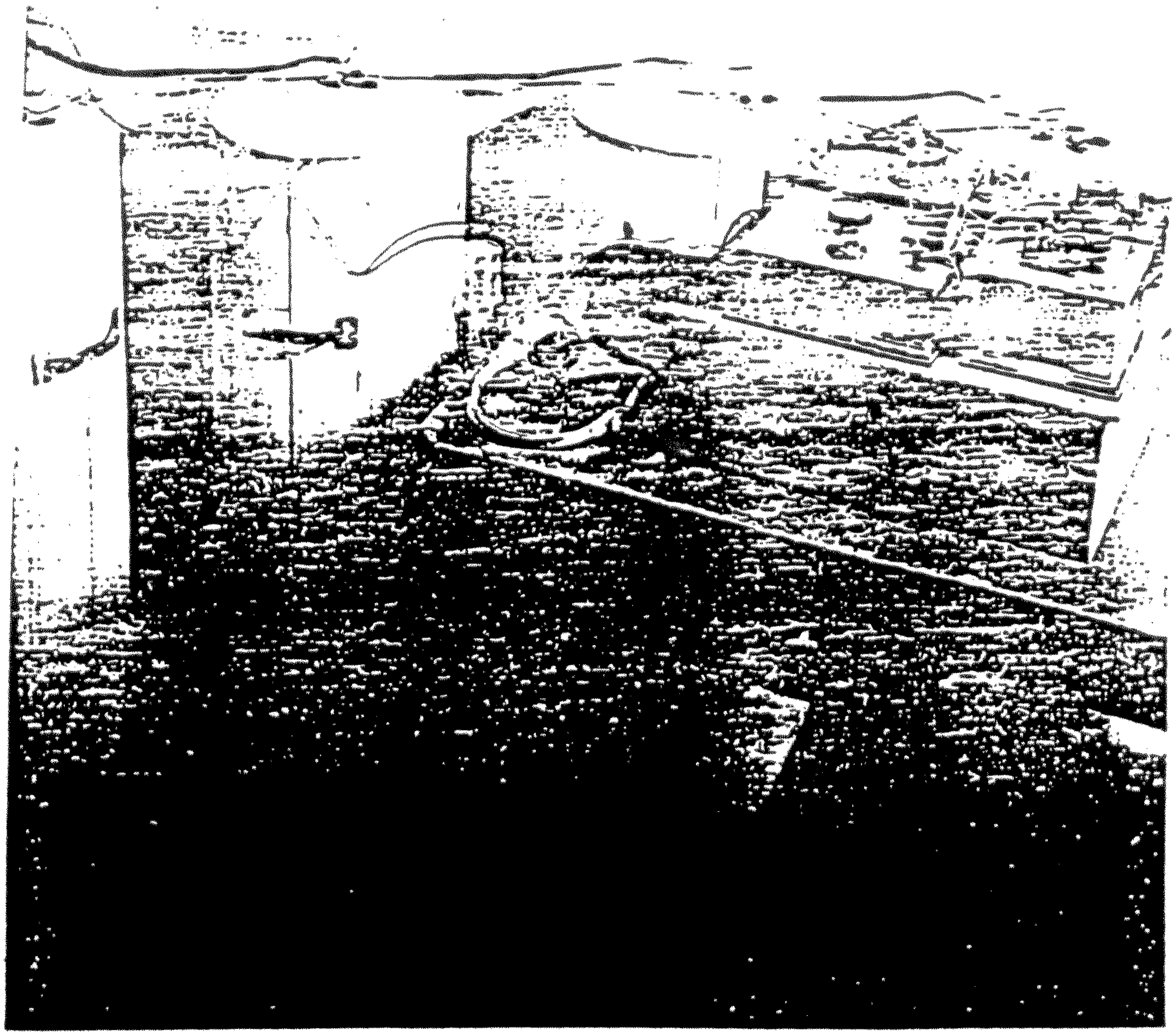

Figure 4.—Equipment used for electrical resistance tests.

Table 1.—Summary of electrical resistance readings between stainless steel electrodes [1] cast in concrete slabs constructed over tanks to simulate slab-on-ground floor construction when exposed to a temperature of 80° F. and 30 percent relative humidity

Tank No.	1-inch depth						2-inch depth						3-inch depth					
	Average initial resistance [2]	Specific resistance [3]					Average initial resistance [2]	Specific resistance [3]					Average initial resistance [2]	Specific resistance [3]				
		10 days	20 days	30 days	90 days	180 days		10 days	20 days	30 days	90 days	130 days		10 days	20 days	30 days	90 days	130 days
	Ohms						Ohms						Ohms					
1	281	3.2	7.3	12.9	22.8	41.2	277	3.0	5.0	7.3	9.9	12.8	221	3.3	3.9	5.4	6.4	9.1
2	306	6.1	8.4	17.7	42.9	93.8	230	4.3	5.4	8.1	13.5	18.9	230	3.4	4.2	6.0	8.7	11.3
3	349	3.3	7.3	13.1	19.6	44.6	281	3.7	4.6	7.3	10.7	13.5	228	3.3	4.0	5.8	8.0	8.6
4	412	4.6	9.7	28.5	62.5	340.0	257	4.3	5.6	9.1	16.0	20.3	203	3.9	5.1	6.4	14.6	21.6
5	238	4.7	9.7	18.6	33.6	66.4	167	4.8	6.3	9.6	12.5	17.0	175	3.4	4.2	5.6	7.6	10.1
6	413	2.5	4.6	7.6	12.2	19.1	326	2.5	3.2	5.2	7.3	9.5	232	2.5	3.1	5.1	8.6	9.3

[1] Readings were taken between a central pin which had a ½-inch embedment and pins having embedments of 1, 2, and 3 inches, arranged in a 2½-inch-diameter circle around the central pin.

[2] The average initial resistance is the average of resistance readings taken on the 1st, 2d, 5th, 6th, and 7th days after pouring the slabs.

[3] Specific resistance values are the ratio of the resistances, at the periods indicated, to the average initial resistance.

resistance of the concrete. If we assume that the highest resistance represents the lowest moisture content, and compare the results of Tanks 1 through 4 (these specimens had only one variable, the type of membrane used) at the end of the 150-day test period with the amount of water passing through the slab as shown in table 2, we find good correlation, as shown in table 4.

Table 4.—Comparison of electrical resistance of Tanks 1 to 4, inclusive, at end of 150 days, with average daily amount of water added to tanks during 150-day test period

[Assuming highest electrical resistance indicates least amount of water passing through the slabs]

Rating	Average daily water added	Electrical resistance (length of electrode)		
		1 inch	2 inches	3 inches
	cc.			
1st—Tank 4	0.9	349.0	30.3	23.6
2d—Tank 2	2.2	95.8	16.9	11.3
3d—Tank 3	3.7	44.6	11.5	9.6
4th—Tank 1	9.3	41.2	12.8	9.1

Tanks 1 to 4 had 4-inch-thick coarse gravel capillary stops, and membranes, as follows:

Tank 4—45-pound roll-roofing.
Tank 2—Two layers 15-pound felt, hot-mopped between.
Tank 3—One layer 15-pound felt.
Tank 1—No membrane.

Note.—Tanks 5 and 6 are not included in this rating comparison since they contained variables other than the membranes.

Tank 4, which had a 45-pound roll-roofing membrane, rated lowest in moisture loss through the slab and driest (highest electrical resistance) in each case. Tank 2, with 2 layers of 15-pound felt, hot-mopped between, rated second. Tank 3, with 1 layer of 15-pound felt, came third; and Tank 1, which had no membrane and which showed the greatest moisture loss through the slab of the four specimens, also had the lowest electrical resistance (highest moisture content) and hence, fourth rating. Tanks 5 and 6 probably are not comparable with the others, since they contained variables other than the membrane used. Gravel was omitted beneath the slab of Tank 6, and an admixture was added to the concrete of Tank 5.

Conclusions

While the data reported in tables 2 to 4 are based on preliminary specimens which do not cover all of the variables encountered in slab-on-ground construction, they are in good agreement with accepted scientific theory and appear to support the following conclusions:

1. Moisture originating in damp soil beneath will move upward through slab-on-ground construction, either by capillary action or in the form of water vapor.
2. The introduction of coarse material, such as [illegible]-inch washed gravel, between the slab and the subsoil, may interrupt capillary action but will not prevent migration of moisture in the form of water vapor.
3. A temperature differential is not necessary to the migration of water vapor.
4. Moisture may travel through a concrete slab more rapidly as water vapor than as liquid water.
5. Membranes which are highly impermeable to water vapor are effective in reducing moisture migration from the ground.
6. The amount of moisture transmitted through a concrete slab-on-ground decreases as the permeability of the membrane decreases.

Discussion of Data

The data reported in tables 2 to 4 were obtained when the top surfaces of the slabs were exposed without any floor covering to an 80° F. and 30 percent relative humidity condition. Placing of a finish floor covering that is bonded to the concrete with an adhesive, most of which are good vapor barriers, would be expected to influence greatly the moisture content of the slabs and the amount of water vapor that would permeate through the different types of slab-on-ground construction. In effect, the adhesive would provide a vapor barrier on the top of the slab, which would reduce the amount of water vapor permeating through to the room above, and probably also would cause a build-up, within the slab, of moisture sufficient to affect adversely the bond of the adhesive to the concrete. Variables in temperature and in humidity conditions, in the ground beneath the slab and in the room above it, also, no doubt, would have an effect on this moisture migration.

Tests of asphalt- and rubber-base adhesives commonly used for bonding floor finish to concrete slabs, indicate that they lose a large portion of their dry bond strength when the concrete becomes damp.[9] This possibly is due to chemical degradation of the adhesive at the junction of the adhesive and the concrete, and may be caused by a reaction, in the presence of water, between alkali in the cement and the resin in the adhesive.

Based on the very limited data shown in table 2, obtained from observation of only one specimen of each construction, 2.45 gallons of water per 1,000 square feet per day would pass through construction of Tank 1, which had 4 inches of gravel under the slab, but no membrane. This would be reduced to 0.97 gallon per 1,000 square feet per day by the addition of a 15-pound asphalt-saturated felt membrane (Tank 3); 0.58 gallon by the addition of 2 layers of 15-pound felt, hot-mopped between (Tank 2); and 0.24 gallon by the addition of one layer of 45-pound roll-roofing (Tank 4).

These quantities of water probably are representative of extreme conditions, since the motive vapor pressure probably is high (0.350 pound per square inch, assuming 100 percent relative humidity beneath the slabs) because of the high temperature of 80° F. in the soil beneath the slabs. This temperature would be approximately that of the ground immediately below a radiant slab which had heating pipes embedded in it. A non-radiant-heated slab, such as that discussed earlier in the paper, with a temperature of 70° F. and 30 percent relative humidity in the air above the slab, and a temperature of 60° F. and 100 percent humidity beneath the slab, would have a motive vapor pressure of approximately 0.148 pound per square inch. Hence, the radiant-heated slab, with the vapor pressure differential of 0.350 pound per square inch, would be expected to result in a much greater migration of moisture upward through the slab than in the case of the non-radiant-heated slab, where the vapor pressure differential is only 0.148 pound per square inch.

Algren has studied the moisture content of soils immediately beneath a radiant-heated slab in terms of conductivity of the soil and found it to have calculated *k*-values ranging from 12.0 to 18.0 B. t. u. per square foot per hour per degree Fahrenheit per inch of thickness.[10] He also made corollary tests of conductivity of soils at various moisture contents. The calculated *k*-values of 12.0 to 18.0, of the soil beneath Algren's test slab, indicate moisture contents of 16 to 23 percent when compared with the *k*-values of the corollary tests at various moisture contents. This indicates that the moisture content of the soil beneath a heated slab remains high, and led Algren to conclude that the moisture content of the soil under a heated concrete slab probably does not change much from season to season. If there is little or no drying out of the soil by the heated slab, than we would expect high humidity conditions in the gravel spaces below the slab, which would tend to increase the vapor pressure, with a consequent increase in moisture transmission through the slab. In other words, adding heating pipes or ducts to the slab would appear to increase the transmission of moisture through the slab, if no vapor barrier was provided.

Petersen[11] has reported that the problem of obtaining completely moistureproof concrete has not been solved except by the use of a vapor barrier. He states that the inherent character of concrete is such that water vapor will readily permeate it. His studies also indicate that many of the integral waterproofing compounds on the market contribute little or nothing to the watertightness of concrete.

Significance of Collected Data

Data collected to date appear to be in agreement with accepted theories of moisture migration, and indicate that this moisture may migrate up through a slab-on-ground floor by hydrostatic pressure, capillarity, or in the form of water vapor.

The one method, on which most authorities are in agreement, of preventing moisture migration through a slab-on-ground floor is the use of a membrane that is impermeable to the passage

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[9] National Bureau of Standards Report BMS 30, *Properties of Adhesives for Floor Coverings*. Available from U. S. Government Printing Office, Washington 25, D. C. Price 10 cents.

[10] "Ground Temperature Distribution With a Floor Panel Heating System," by A. B. Algren, Associate Professor and Head of the Division of Heating, Ventilating and Air Conditioning, Mechanical Engineering Department, University of Minnesota, published in *American Society of Heating and Ventilating Engineers Journal*, May 1948.

[11] "Can Concrete Be Made Moisture-Proof?" by Perry H. Petersen, Director, Materials Division, Structures Research Department, Naval Civil Engineer Research Laboratory, Port Hueneme, Calif., published in *BuDocks Technical Digest No. 23*, April 1952, Bureau of Yards and Docks, Navy Department, Washington 25, D. C.

of both liquid water and water vapor. This barrier, if placed beneath or incorporated in the slab, would be expected to prevent moisture by hydrostatic pressure, capillary action, or in the form of water vapor, from penetrating through the slab. Such a barrier would have to be durable for the life of the building. Also, it should be an exceptionally good vapor barrier, probably approaching the effectiveness of a metal sheet, unless other measures are taken to prevent moisture from reaching the bottom of the slab.

One measure which easily can be taken to prevent hydrostatic pressure beneath the slab is to elevate the bottom of it well above the surrounding yard and to slope the yard around the house to drain away from it. This appears to be especially necessary in colder climates where snow around the building would be melted by heat escaping from the slab. This melted snow water usually would be prevented from draining away from the building, by a dam of frozen snow and ice, and might find its way under the slab unless the slab were sufficiently elevated.

To prevent capillary moisture from reaching the slab, several inches of coarse washed gravel, crushed stone, or slag may be placed beneath the slab to interrupt capillarity. This material should also be above the grade of the yard; otherwise, moisture will drain into the spaces between the gravel, and nullify its effectiveness. The gravel course beneath the slab, when positively drained, also serves as a thermal break between the slab and the ground. This increases the comfort of the slab in winter, in the case of nonheated slabs, since heat absorbed from the room is not dissipated to the ground so rapidly, thus maintaining a warmer floor. In the case of a heated slab, the timelag is reduced, so that a more uniform slab temperature results. This thermal break between the slab and the ground also would be expected to reduce condensation on the slab on hot, humid summer days, since the slab is less apt to be cooled by the ground to the point where it will be below dewpoint temperature.

Algren's work indicates that silt and clay soils have a thermal conductivity (*k*-factor) of approximately 10.0 under normal capillary moisture conditions. Dry coarse washed gravel has been reported by Groeber of Germany to have an average *k*-factor of approximately 2.5. Hence, heat would be transmitted approximately four times as fast through damp soil as through dry coarse washed gravel.

Neither elevating the slab above ground level nor providing a capillary stop beneath it will prevent water vapor from permeating the slab, although each will provide a factor of safety against free water reaching the slab. As previously stated, a highly impermeable membrane appears to be the most reliable method of preventing migration of water vapor.

Recent research [13] sponsored by the Housing and Home Finance Agency has developed data on the permeability and durability of certain roofing materials when used as membranes in contact with the soil, where they are subject to attack by rot fungi. These data indicate that asphalt-saturated felts would not be durable unless protected with coatings of asphalt. Roll roofing, which is heavily impregnated with asphalt, was found (both in accelerated laboratory tests and in 10-year actual use) to be much more effective as a vapor barrier than 15-pound asphalt-saturated felt, and to have good durability as ground cover in a crawl space. Industry is developing membrane materials specially designed for use in contact with the ground. Two of these are now on the market. One is a roll material similar to 55-pound roll roofing, but made with a softer type of asphalt so as to be more flexible and easier to lay than is 55-pound roll roofing. The other is a sheet material, approximately twice the weight of 55-pound roll roofing, which is produced in 4- by 8-foot sheets. We would expect these special membrane materials to be equal or better in durability than 55-pound roll roofing, and to be equally good vapor barriers. No doubt, a good and durable membrane could also be obtained by building up several layers of 15-pound asphalt-saturated felt, solidly mopped with asphalt to protect the felt at all points from attack by fungi. The cost probably would be higher than that of the heavier membrane materials described above.

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[13] HHFA Reprint No. 15, *Durability of Moisture-Resistant Membrane Material in Contact With the Ground*, February 1953. Available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Price 5 cents.

Recommendations

Based on the data developed to date, and allowing some factor of safety to insure durability during the expected life of the building, the following recommendations are offered for controlling migration of moisture from the ground:

Slab-on-ground Construction

1. Where the site is high and well drained, and finish floor is to be asphalt tile, provide a membrane consisting of one layer of 55-pound roll roofing or one of the equally effective and durable new membrane materials, lapped 6 inches, turned up and extending to the top of the slab around all edges, with all laps carefully sealed with hot or solvent-type waterproofing asphalt.

2. Where site has a high water table or is poorly drained, and particularly where it is desired to protect a woodblock or strip floor, or other material that can tolerate little moisture, provide a membrane consisting of two layers of 45- or 55-pound roll roofing, or equally effective and durable new membrane materials, solid mopped between with hot or solvent-type waterproofing asphalt, and turned up to the top of the slab around all edges.

Preferably, membranes should be laid on a base course of well-compacted, coarse washed gravel or crushed stone. This base course should be 4 or more inches thick, and high enough above the surrounding yard to be well drained. Otherwise, drain tiles or other positive means of drainage should be provided. The top of the slab, preferably, should be elevated at least 12 inches above the grade of the surrounding yard, which should be sloped to drain away from the building. Of course, care should be taken to avoid puncturing the slab membrane, and as little water as practicable should be used in the concrete mix.

Basement Slabs

Where it is desired to provide a dry basement, migration of moisture from the soil beneath must be controlled. The problem of controlling moisture through the concrete floor slab is much the same as that previously described for slab-on-ground floors located above the grade of the yard. However, the problem is rendered more difficult by the need for controlling moisture under hydrostatic pressure, as well as moisture migrating by capillarity and vapor travel.

Where below-grade areas, such as those often found in semibasement and split-level houses, are to be developed into useable space, an unusually good membrane should be provided. Two layers of 55-pound roll roofing, or equally effective and durable membrane material, solid mopped between with hot or solvent-type waterproofing asphalt, turned up to the top of the slab around all edges, and sealed to the foundation walls, are recommended.

Masonry walls below grade should be parged with portland cement mortar and coated with hot bituminous waterproofing on the exterior face. Open-joint tile or other positive means of drainage should be provided around the exterior of the house at the level of the footing, to prevent a buildup of hydrostatic pressure. Positive drainage should also be provided for the gravel course under the floor. Both perimeter wall and underfloor drainage should have a connection to a sewer or a dry well, or in the case of sloping sites, to an outfall below the grade of the floor, so that positive drainage will be provided.

Crawl Spaces

Dr. J. D. Diller, of the U. S. Department of Agriculture, Bureau of Plant Industry at Beltsville, Md., has carried on extensive observations of crawl-space cover effectiveness and durability for a period of over 10 years.[13] This work has demonstrated that moisture migration into crawl spaces from the ground beneath can be effectively controlled by simply covering the ground in the crawl space with a durable membrane, such as 55-pound roll roofing.

Sealing or cementing of the laps of crawl-space membranes is not recommended. Many crawl spaces are below the grade of the surrounding yard, where they are subject to occasional flooding during heavy rains, and the open

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[13] Forest Pathology Special Release No. 38, April 1952, obtainable from Plant Industry Station, Beltsville, Md.

[illegible] permit this water to drain off before it causes damage to the house.

When a durable and effective ground cover such as 55-pound roll roofing has been placed in the crawl space, the vents provided in the foundation walls to ventilate the crawl space may safely be closed during cold winter months. This will provide a more comfortable floor during cold weather, and will reduce fuel costs.

Cost

The cost of providing membranes as recommended is moderate. The cost of roll roofing or roll membrane material is 2 to 3 cents per square foot, and the installed cost of the membrane should be 5 to 10 cents per square foot, depending on whether a single or double thickness is required. In view of the protection which a good membrane would provide against deterioration of the house and its furnishings, this cost appears moderate.

Commercial Construction

The problem of preventing moisture migration from the ground is not limited to dwellings. Many modern shops, commercial buildings, and warehouses are constructed with slab-on-ground floors because of the economies inherent in the much heavier permissible floor loadings, and in the ease of material handling by mechanical means. Much of the dampness which causes rusting of tools and metal containers and mildewing of fabrics in storage, no doubt originates in the damp soil beneath the building, and could be reduced by providing a good membrane beneath the floor. This was evidenced by the expensive program of protecting machine tools and ordnance for periods of extended storage after the last War. Most supply officers turn their stock frequently, and often at considerable extra-handling expense, in order to reduce spoilage, much of which is caused by dampness.

In gymnasiums, armories, and drill halls, if cupping and buckling of the wood finish floor is to be avoided, the provision of a good membrane under slabs on the ground supporting wood-strip floors on sleepers is almost a "must."

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