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**MOISTURE CONTENT IN PROTECTED MEMBRANE ROOF
INSULATIONS — EFFECT OF DESIGN FEATURES**

by
Charles P. Hedlin

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Moisture Content in Protected Membrane Roof Insulations—Effect of Design Features

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ABSTRACT: In protected membrane roofs, the thermal insulation is placed above the main waterproof membrane where it is exposed to precipitation. The severity of the wetting problem can be reduced by protective measures.

Fibrous and closed cell plastic insulations, ranging from 150 to 610 mm square and 51 mm thick, were placed on experimental roofs. They were weighed periodically over periods of up to five years.

The results indicate that moisture gains are reduced by increasing deck slope. Sealing the bottom surface significantly reduced moisture gain in a bead polystyrene, but improvement was offset by placing paving stones directly on its upper surface. Slotting the lower insulation surface on a 100-mm-square grid was not found to reduce moisture uptake. Moisture content of some fibrous specimens sealed on the bottom surface and edges remained at less than 4 percent by volume. Others similarly sealed, but with paving stone cover flashed to divert water away from the upper surface, remained at less than 1.5 percent. In most cases, when specimens were placed wet on the roof in winter, significant drying occurred over a period of several months.

KEY WORDS: roofing, thermal insulation, membranes, moisture content, sealing, slotting, water, insulation cellular materials, slope, flashing, drying

One of the functions of a roof is to provide an adequate barrier against heat flow during all seasons of the year. Each of the roofing components adds to the thermal resistance, but, normally, the largest single contribution is provided by the thermal insulation. The thermal resistance of the roof can be calculated by summing component resistances which are obtained by standard tests on dry materials. The accuracy of this method should not be taken for granted in the case of protected membrane roofs as not all the factors affecting thermal performance have been fully investigated. One factor that must be considered is the absorption of moisture by the insulations, since this reduces the thermal resistance and promotes degradation.

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In protected membrane roofs, preformed insulation is often laid loose on the membrane and held in place by gravel or paving stones.^{2,3} Figure 1 illustrates the moisture movement in such a system. Moisture may reach the top surface of the insulation by percolating through the gravel layer. In the case of paving stone cover, some of the moisture falls directly onto the insulation or into the butt joints. A further amount adheres to the underside of the stone, flows along it, and eventually drips onto the insulation. Water flows into the butt joint and down the edges of the insulation. Some of it will also flow into the space between the insulation and the membrane. As described, moisture comes in contact with all surfaces of the insulation.

Extruded polystyrene is used successfully and extensively, and some other types of insulation, for example, bead polystyrene and urethane, are used to a lesser extent. However, the environment is a severe one and limits the number of types that can be employed.

The protection of the insulation from moisture effects can be modified by design. Conditions can be alleviated by promoting water flow to the drains, protecting insulation surfaces against water penetration, and by providing conditions favorable to drying of the insulation, for example, through top surface ventilation.

The effects of some design features were reported earlier.⁴ Additional work was undertaken to obtain further information about some of these features and others. Several insulations were used. Their susceptibilities to moisture attack differ widely, for example, their permeabilities to moisture movement. A knowledge of the capabilities of protective features, based on experience with insulations with diverse physical properties, may be useful in assessing the extent to which such measures can be applied. The work was not intended as a general test of the performance of thermal insulations.

The work was confined to the question of how to keep insulations dry. The consequences of high moisture contents, for example, on thermal resistance and insulation decay, are of crucial importance but constitute subjects too large to be treated in detail here.

FIG. 1—Flow of water around the insulation in a protected membrane roofing system

²Handegord, G. O. and Baker, M. C., "Application of Roof Design Principles," *Canadian Building Digest*, National Research Council, Division of Building Research, No. 99, March 1968.

³Baker, M. C. and Hedlin, C. P., "Protected-Membrane Roofs," *Canadian Building Digest*, National Research Council of Canada, Division of Building Research, No. 150, June 1972.

⁴Hedlin, C. P., "Moisture Attack on Insulations in Protected Membrane Roofing," Research Paper No. 634 (NRCC 14590) of the Division of Building Research, National Research Council, Ottawa, Ont., Canada.

Experimental Methods and Results

Sets of measurements involving four different treatments were carried out.

1. Moisture gains on a deck slope of approximately 1 in 48 were compared with those on a deck slope of 1 in 12.

2. The lower surface, edges, or both, were sealed by adhering coatings of low moisture permeability to them. This was an asphalt-coated base sheet having a weight of about 1.9 kg m^{-2} .

3. Specially prepared paving stones were used to divert precipitation away from the insulation surfaces. The insulations were sealed with coated base sheet on the edges and bottom surface.

4. The bottom surfaces were slotted to encourage drainage.

In general, the results are compared within each group, for example, moisture gains on a 1 in 48 slope versus a 1 in 12 slope, gains in specimens with sealed surfaces versus those without sealed surfaces, assuming that other conditions were the same. However, variations in the material existed even from the same batch, and the exposure conditions certainly varied.

In addition, the results of two sets of measurements on winter drying of wet insulations are reported.

Following are some details of the work:

1. The materials used were glass fiber having a density of approximately 145 kg m^{-3} wood fiber (275 kg m^{-3}), perlite fiber (185 kg m^{-3}), urethane (32 kg m^{-3}), and bead polystyrenes of several different densities.⁵ Extruded polystyrene was not included. Unless otherwise indicated, the glass fiber specimens had a factory-applied vapor barrier. This was used as the lower surface.

2. In all cases, specimens were placed loose on the membrane. No measurements were made with specimens adhered to the roof membrane.

3. All moisture contents are given as percent of gross volume.⁶ Harmful effects, such as loss of thermal resistance and decay, are likely to bear an approximate relationship to this quantity. It is widely used and is a fairly unambiguous measure of moisture content.

The moisture contents were determined periodically by removing the specimens from the roof, weighing them, and computing the result, using the measured gross volume and the initial weight.

4. The measurements were begun with insulations at the as-received moisture content, and all values given are changes from those levels. Tests showed that initial values were near zero for glass fiber, polystyrenes, and urethane, and approximately 2 and 4 percent by volume for perlite fiber and wood fiber insulations, respectively.

⁵To convert kg m^{-3} to lb ft^{-3} , divide by 16

⁶To convert moisture contents in percent of gross volume to percent weight, multiply by 997 divided by insulation density (kg m^{-3}) or by 62.3 divided by insulation density (lb ft^{-3}).

5. With the exception of one set of measurements involving surface sealing, which was made at Ottawa, the results were obtained at the outdoor experimental facilities of the Division of Building Research, National Research Council of Canada, in Saskatoon (Fig. 2). Monthly precipitation, plotted in Fig. 3, was measured at the Saskatchewan Research Council's

FIG. 2—Outdoor exposure site of the Division of Building Research at Saskatoon, Sask.

FIG. 3—Monthly precipitation totals Sept. 1969 to Dec. 1974 at the Saskatchewan Research Council's Climatological Reference Station at Saskatoon.

Climatological Reference Station, approximately 1.5 km from the site of these experiments.

Specimens were exposed on four structures. The first three are located at Saskatoon.

- (a) The main outdoor experimental building is 24 by 6.1 by 4.1 m high. The specimens were placed in a portion of the roof consisting of a wood deck covered with a four-ply asphalt organic felt membrane. The slope is nominally 1 in 48.
- (b) A small structure, 2.4 by 4.8 m, and about 2 m high, has a deck slope of 1 in 12. Several types of asphaltic membranes cover the deck.
- (c) A concrete slab, 2.4 by 7.2 m, stands about 0.25 m above the ground surface. It has a slope of 1 in 48 and is covered with polyethylene sheet material.
- (d) The roof of a laboratory building in Ottawa was also used. The deck was nominally "flat."

6. The environmental conditions for the insulation are determined by the weather on the outside, the controlled interior temperatures of the structures (21°C) and the roof design.

Deck Slope

Two sets of measurements were made to assess the effect of deck slope on moisture gain.

1. Specimens of glass fiber, wood fiber, perlite fiber, and urethane were placed on the deck having a slope of 1 in 12. No surface protection was added to them. They were placed on the membrane or on a 20-mm-thick layer of pea gravel and were covered by paving stones with a 20-mm ventilation space above the insulation surface or by a gravel layer 30 to 40 mm thick.

From the beginning of the study, in 1969, until June 1971, only one 150-mm-square specimen from each treatment was weighed. Thereafter, three additional specimens were weighed, one of which was 150 mm square, another 300 by 610 mm, and the third 610 by 610 mm.

The results are plotted in Fig. 4, where the points were obtained by a simple averaging of the moisture contents for those cases where more than one specimen was used in a given treatment. The below zero values for two of the glass fiber treatments were due to surface erosion caused by removal of gravel when weighing them.

In the first four years, the moisture content of glass fiber remained low, with the exception of two peaks that resulted from rain storms. The urethane remained at less than 1 percent by volume throughout, wood fiber reached a maximum value of about 8 percent, and perlite fiber reached a maximum value of over 15 percent by volume. They were then placed on a deck having a slope of 1 in 48 for the period 30 May to 19 Sept. 1973. Many of the

FIG. 4—Moisture contents of glass fiber, wood fiber, perlite fiber, and polyurethane insulations on a deck with a 1 in 12 slope.

specimens showed a marked increase in moisture content. The rainfall had not been unusual when compared with that for the two preceding years. The reduced deck slope was assumed to be largely responsible. Moisture levels fluctuated. After having become wet, however, the wood fiber and perlite fiber remained at relatively high moisture contents even after being returned to the 1 in 12 slope.

Moisture contents were also measured on 150-mm-square specimens exposed on the deck of the main building where the slope was 1 in 48. The average and maximum values for both sets of results (from the 1 in 12 and the 1 in 48 slopes) over the period 1969 to 1974 are given in Table 1a. During that interval the specimens on the 1 in 12 slope had lower moisture contents than those on the 1 in 48 slope. The ratios of the average moisture contents (MC) for the pairs of values, that is, MC on 1/48/MC on 1/12 range from about 2 to 10.

2. A second set of measurements was made involving the same 1 in 12 and 1 in 48 deck slopes. The 1 in 12 group spent the period 30 May to 19 Sept. 1973 on a 1 in 48 slope. Two specimens were used in each treatment. One was 150 mm square and the other 300 by 610 mm in size. All were sealed by adhering a polyethylene-backed rubberized asphalt to the 51-mm edges. The other surfaces were unsealed.

TABLE 1(a)—Moisture contents of insulations in volume, percent, on deck slopes of 1 in 48 and 1 in 12, average (avg) and maximum (max) values, 1969–1974.

		Glass Fiber		Wood Fiber		Perlite Fiber		Urethane	
		1/48	1/12	1/48	1/12	1/48	1/12	1/48	1/12
Stone cover	avg	22	3.0	32	4.0	23	9.5	3.5	0.4
	max	64	34	62	11	62	43	13	2.0
Stone cover on gravel ^a	avg	6.2	2.7	6.9	1.2	4.5	0.1	0.6	0.1
	max	32	40	15	3.2	17	0.9	3.9	0.2
Gravel cover	avg	...	...	51	5.6	30	12	5.1	0.4
	max	...	...	63	20	71	50	17	1.0
Gravel cover on gravel ^a	avg	...	...	40	1.4	9.8	2.9	1.2	0.2
	max	...	...	65	6.1	39	12.3	3.7	0.3

^aTo April 1973 only.

The results are given in Table 1b. With one exception, the ratios, MC on 1/48/MC on 1/12 for the pairs of average moisture contents ranged from unity to more than 10, indicating, as the first had done, that the increased slope reduced the moisture content.

In these measurements:

1. The 1/12 slope did not prevent moisture content peaks from occurring as a result of precipitation.
2. The moisture contents varied widely with the type of insulation; however, in all cases, the increased slope reduced the moisture contents. They ranged from about 10 to 50 percent if these are the 1/48 slope.
3. The moisture contents on the 1/12 slopes were still high enough to cause some physical damage to the wood fiber and perlite fiber, for example, delamination, mold growth, and loss of strength.

Surface Sealing

The results of three tests follow.

1. Eleven specimens of bead polystyrene, each 610 by 610 by 51 mm, were used in a test of the effectiveness of bottom surface sealing. They were of three different densities, 16, 26, and 32 kg/m³. Their bottom surfaces were either sealed with coated base sheet adhered with asphalt, or left unsealed. They were placed on the roof of the outdoor experimental building and were

TABLE 1(b)—Moisture contents, in volume, percent, of edge-sealed specimens on deck slopes of 1 in 48 and 1 in 12, average (avg) and maximum (max) values, April 1973–May 1975.

		Glass Fiber ^a		Wood Fiber		Perlite Fiber		Urethane	
		1/48	1/12	1/48	1/12	1/48	1/12	1/48	1/12
Stone cover	avg	50	8.0	28	1.3	51	5.6	1.5	0.3
	max	78	41	41	3.6	75	9.7	2.6	0.6
Gravel cover	avg	...	...	39	4.4	47	21	0.3	0.3
	max	...	...	48	8.5	75	58	0.8	0.6

^aNo vapor barrier.

covered with paving stones which either rested directly on their upper surfaces or were raised to provide a 20-mm air space for ventilation. The moisture contents after two years are given in Table 2. The results suggest that the bottom surface sealing had a marked effect on the moisture gain. The 0.7 percent average for the sealed specimens with top side ventilation was much lower than the 5.9 percent average for those that were unsealed but ventilated. However, when top side ventilation was eliminated by placing the paving stone on the insulation surface, the effect of sealing was largely nullified. The effect of ventilation is also evident in the results for the unsealed specimens as the moisture contents with the stone on the insulation surface average about 2.5 times those for the ventilated specimens.

With no ventilation, top surface sealing would probably have improved the result. It would have prevented evaporation of moisture from the insulation but would also have prevented top side entry. Compared with top side ventilation, however, that solution would seem to be a poor one; it means added cost and is a sandwich type of construction, thus forfeiting an important advantage of the protected membrane roof system.

2. Specimens of glass fiber, wood fiber, perlite fiber, and urethane insulations were sealed only at the edges and were placed on decks with a 1 in 12 and a 1 in 48 slope. These were the results used in the section on deck slope. It was not evident that this treatment was a significant deterrent to the moisture accumulation.

3. Specimens of wood fiber, perlite fiber, and urethane, 410 by 410 by 51 mm thick, were sealed with coated base sheet both on their bottom surfaces and edges, but the top surfaces were left unsealed. Two specimens of each type were exposed on the roof of the Environmental Laboratory of the Division of Building Research, National Research Council of Canada in Ottawa. Triangular paving stones, supported on pedestals, provided a top cover but permitted ample ventilation. The specimens were so placed that a butt joint in the paving stones crossed each of them diagonally, and water dripped directly onto them (Fig. 5).

The changes in moisture content, thickness, width, and length are shown in Fig. 6. The values are averages for the two specimens of each. The

TABLE 2—Moisture contents of bead type polystyrene, in volume, percent, after two years' exposure with and without bottom surface sealing, with paving stone cover.

Density, kg/m ³	Sealed		Unsealed	
	Top Ventilated	No Top Ventilation	Top Ventilated	No Top Ventilation
16	0.4	7.9	3.5	15.9
26	1.3	11.3	8.0	16.8
32	0.3		6.2	17.9
Avg MC	0.7	9.6	5.9	15.1

FIG. 5—Wood fiber, perlite fiber, and polyurethane insulations with bottom and edge sealing exposed at Ottawa.

moisture content gains have not exceeded 4 percent by volume during the three years of observation. This is about the same as the measurements at Saskatoon.

The survival of the wood fiber and perlite fiber depends on their continued ability to shed water from their upper surfaces and on the integrity of the surface seal. If either should fail and allow moisture to penetrate into the insulation, they would be destroyed. Their top surfaces are showing small cracks due to wetting and drying, but so far these have not apparently had a serious effect.

Flashing

If roof drainage is adequate, it can be virtually ensured that water will not come in contact with the insulation. Then, apart from hygroscopic absorp-

tion, the insulation will remain dry. To achieve this in protected membrane roofing requires a special top cover and surface protection for the insulations.

Specimens of glass fiber, wood fiber, perlite fiber, and urethane were bottom and edge sealed with coated base sheet. The upper corner was chamfered (Fig. 7). Paving stones were designed so that water would be diverted away from the upper surface by means of a flashing. This was done using perimeter troughs emptying at a drip tab at each corner, or with a drip edge around the perimeter of the stone. The stones rested flat on the insulation (Fig. 7*b*), or were supported on stringers, or were corrugated to provide ventilation (Figures 7*a,c*). Roof slope was approximately 1 in 48.

With these arrangements, the moisture content gains of six glass fiber specimens over a two-year period averaged 0.5 percent by volume, and the maximum value was 1.5 percent. For two wood fiber, perlite fiber, and

FIG. 6—Moisture contents and dimensional changes of bottom surface- and edge-sealed wood fiber, perlite fiber, and polyurethane specimens exposed at Ottawa.

FIG. 7—Three flashing arrangements designed to prevent precipitation from reaching the top surface of the insulation. Bottom and edge surfaces were sealed.

urethane specimens, the average and maximum gains were 0.6 and 1.0 percent, 0.4 and 0.9 percent, and 0.2 and 0.4 percent, respectively. The last mentioned deformed significantly due to bottom side restraint combined with insulation expansion at the top surface.

The insulations remained dry under these conditions. However, immersion due to deck flooding for an appreciable period of time would probably make them wet; hence, good drainage is essential.

Slotting for Drainage

Specimens of a urethane and three bead polystyrenes (610 mm square and 51 mm thick) were placed on decks having slopes of 1 in 48. In some, slots 6 mm deep and 13 mm wide were cut on a 100-mm-square grid on the bottom surface to improve drainage. All were covered with paving stones resting on the insulation. The tests were run for one to two years, and the insulations were weighed several times. Final values are given in Table 3.

In only one case were the moisture contents of slotted specimens lower than those of the unslotted ones. Thus, these values suggest that the slotting did not significantly improve the result.

Moisture Loss From Insulation

A major concern in the design of protected membrane roofs is to maintain a low moisture content through favorable balance between gain and loss. Drying rates, therefore, may be important. In summer, this is

TABLE 3—Moisture contents for slotted and unslotted insulations, volume percent, number of specimens in brackets—paving stones rested on the insulation surfaces in all cases.

Insulation	Density, kg m ³	Slotted	Unslotted	Length of Test, Year
Bead polystyrene	29	8.7(2)	3.4(2)	1
Bead polystyrene	16	7.6(2)	7.9(2)	1
Bead polystyrene	32	6.7(2)	17.9(1)	2
Urethane	28	10.3(2)	11.3(2)	1

accomplished when warm, dry air flows over the insulation surface. In winter the temperature gradient can produce a vapor pressure gradient which drives moisture toward the cold surface. If ventilation exists, it may escape.

Specimens, 600 by 600 by 51 mm, of wood fiber, perlite fiber, glass fiber, and urethane, with no surface protection, were wetted and then placed on the roof of the main outdoor experimental building at Saskatoon in winter. Paving stones covered the insulations, but a 20-mm ventilation space was provided (Fig. 8).

The first set, including four specimens each of glass fiber, wood fiber, and perlite fiber, were exposed on 29 and 30 Dec. 1970. The moisture contents ranged from 0 to 60 percent by volume. The changes in moisture content

FIG. 8- Winter drying of wet insulations on an experimental protected membrane roof.

with time are shown in Fig. 9. A second set, including four specimens each of urethane and wood fiber board, were exposed on 23 Jan. and 4 Feb. 1974, respectively. Those results are given in Fig. 10.

Drying usually occurred. In the first set, glass fiber dried somewhat more rapidly than the wood fiber and perlite fiber. All of the glass fiber reached dryness within 100 days, whereas a substantial amount of moisture remained in both of the wettest specimens of the other two. In the second group, the initial moisture contents were lower and the drying effects were less pronounced. The wood fiber specimens approached equilibrium at about 10 percent and urethane at about 3 percent moisture by volume. It is apparent, in the case of the wood fiber board in the second run, that substantial amounts of moisture had entered, probably through its bottom surface. The results demonstrate that drying can take place, but the latter set indicates that insulation may take up moisture in the winter even at low temperatures if the surfaces are not protected.

In the foregoing, some very high moisture contents have been quoted. Clearly, many of these far exceed acceptable limits. It is normally assumed that thermal insulation remains dry in service. In the protected membrane roofing system this is not likely to be so because of the intimate contact that usually exists between insulation and precipitation. Almost any gain in moisture produces a corresponding loss in thermal resistance. Also, depending on the insulation, physical degradation may result from too much moisture. The maximum acceptable figure is a matter of judgement and may differ for different insulations. Without presuming to set a figure, it may be said that gains in excess of few percent by volume will probably cause a reduction in performance that is unacceptable.

Conclusions

Most commonly employed designs of protected membrane roofs produce environments that encourage moisture increases in the insulation. These

FIG. 9—Moisture contents of wet glass fiber, perlite fiber, and wood fiber insulations on a protected membrane roof in winter.

FIG. 10—Moisture contents of wet wood fiber and polyurethane insulations in a protected membrane roof in winter.

results and those reported earlier⁴ demonstrate the effect of some protective design measures in producing lower moisture content gains by insulations. Despite the wide differences in their physical properties, the insulations used in these studies usually showed the same qualitative response to a given measure.

1. Probably the most severe moisture attack occurs when the insulation is placed on the membrane and covered by a paving stone (or an equivalent) which allows water to reach the insulation but prevents it from evaporating from the upper surface of the insulation.

2. Provision of top surface ventilation by supporting the paving stone above the insulation or by using a gravel cover results in moisture contents that are significantly lower than when the paving stone rests directly on the insulation surface.

3. Moisture contents on the 1, 12 slope were 10 to 50 percent of those on the 1:48 slope. However, the increased slope did not prevent the occurrence of high moisture contents in the fibrous insulations and some damage to them.

4. Sealing insulation surfaces with an impermeable membrane—bottom surface on some insulations, bottom and edge on fibrous insulations—coupled with top surface ventilation resulted in a marked improvement for all of the insulations except glass fiber which did not adequately shed water from its upper surface.

5. The addition of flashing to the stone top cover to direct water away from the top surface of the insulations, combined with surface sealing and ventilation kept moisture gains to about 1 percent by volume over the period of test.

These are experimental results. The periods of time involved are short compared with the life expectancy of a roof. Further, no attempt has been made to assess the cost of applying the measures on a practical scale. Emphasis has been placed on the effects of design features on the moisture gains of insulation. The question of criteria for judging acceptable moisture content has not been included but should eventually be answered to employ a system such as this where it is normal for insulations to gain and lose moisture.

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