NEW WETTING CURVES FOR COMMON ROOF INSULATIONS

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Specimens of common roof insulations were placed in an apparatus that maintained an air temperature of 4°C (40°F) and 75 percent relative humidity (RH) above the insulation, and 29°C (85°F) and 100 percent RH (or 70 percent RH) below. The specimens were periodically removed from this apparatus, weighed, wrapped in a thin plastic film and then tested in a thermal conductivity instrument with its top plate maintained at about 4°C (40°F) and its bottom plate at about 29°C (85°F). After a specimen's insulating ability was determined in this instrument according to the ASTM C 518-76 procedure, it was returned to the apparatus for further wetting. Some insulations accumulated moisture rapidly, but others gained very little moisture even after years of testing.

The ratio of a material's wet thermal resistivity to its dry thermal resistivity, expressed as a percentage, is termed its thermal resistance ratio (TRR). As moisture accumulates in a material, its TRR decreases. Graphs of TRR vs. moisture content were developed for fiberboard, perlite, cork, gypsum, insulating concrete, cellular glass, fibrous glass, expanded polystyrene, extruded polystyrene, urethane/isocyanurate, foamed-in-place urethane and phenolic insulations. TRR vs. moisture content equations have also been developed for each material. Insulation with a TRR of 80 percent or less is, by our definition, 'wet' and unacceptable. The moisture content at which the TRR equals 80 percent is tabulated for these materials.

KEYWORDS

Insulation, moisture, roofs, thermal resistance, vapor, wetting.

BACKGROUND

Twelve years ago at the Fifth Conference on Roofing Technology, Tobiasson and Ricard presented the paper "Moisture Gain and its Thermal Consequence for Common Roof Insulations."[1] The objective of those tests was to establish the effect of thermally induced vapor pressure gradients, such as are present in roofs, on insulation specimens. Early tests at CRREL[2] were conducted by immersing insulation specimens in water at room temperature, but Hedlin[3] had shown that foam plastic insulations gain much more moisture when subjected to thermally induced vapor pressure gradients than when soaked under isothermal conditions. Since there is often a significant temperature gradient through roofs, isothermal soaking is not a realistic test condition for predicting the installed performance of insulations in roofs.

The insulation wetting test program had not been completed when Reference 1 was written. Tests continued for several years on materials that wet very slowly, such as extruded polystyrene and cellular glass. Additional materials were added to the test program (e.g., gypsum and lightweight concrete) and as new materials became available (e.g., phenolic) they were also tested.

The findings in Reference 1 are being used by many individuals to estimate the insulating ability of in-place roof insulation. They obtain samples of insulations from roofs, often in conjunction with roof moisture surveys,[4] and then measure the moisture content of the insulation by drying it in an oven at about 49°C (120°F) until a constant weight is reached. Using the graphs in Reference 1 that relate the moisture content of insulations to their insulating ability, an indication of the in-place thermal performance of roofs is obtained.

When taking samples from roofs, one must separate the insulation and its facers from other components of the roof since the relationships in Reference 1 are based on the dry weight of the insulation and its facers. Once an insulation facer is adhered to a substrate or a membrane is adhered to an insulation facer, it is usually very difficult to separate the insulation and its facers from those components. Even if this can be done, some hot asphalt has entered the facer, causing wight gain that introduces errors. It would have been better (at least for this practical use of our information) to remove the insulation facers from the insulation specimens and present the moisture contents as a function of the dry weight of the insulating material only. That has been done in this paper. Consequently, the moisture content-insulating ability relationships herein for lightweight insulations with relatively heavy facers (e.g., urethane, isocyanurate and fibrous glass) are different from the relationships in Reference 1. Other relationships have also changed because the data base has been enlarged.

Another concern that developed from the first paper was caused by presentation of moisture contents as a percentage of dry weight, not as a percentage of volume. Use of weight-based water contents confuses some individuals since moisture contents in excess of 100 percent or even 1000 percent are possible. A weight-based moisture content of 1000 percent simply means that the water in the sample weighs 10 times as much as the dry sample. That is certainly possible for a lightweight material such as 16 kg/m^3 (1 pcf) expanded bead polystyrene foam (EPS).

However, a "high" weight-based moisture content of 50 percent may be quite damaging to a relatively heavy material such as perlite, while a lightweight material such as EPS would not suffer much from a weight-based moisture content as "low" as 50 percent.

Some individuals have suggested that this problem can be avoided by presenting moisture contents as a percentage of volume instead of dry weight. Unfortunately this requires users to measure both weights and volumes of samples taken from roofs. Since measuring the volume of such samples is very difficult, we continue to feel that the most useful form is to present water contents as a percentage of dry weight. However, we have also explained how to convert to volume-based moisture contents.

The dynamic thermal performance of wet insulation in roofs is a complex matter still under investigation. Hedlin[5] and others have shown that it takes very little moisture to cause a permeable insulation such as fibrous glass to lose much of its insulating ability when subjected to warming and cooling cycles. Most other roof insulations are less permeable and less influenced by dynamics. However, a steady-state laboratory test such as the one used in this study is limited in its ability to quantify the thermal performance of wet insulation in roofs. That limitation understood, such tests can provide useful guidance on the general behavior of wet roof insulation.

WETTING APPARATUS

The 305 X 305mm (12 X 12 in.) specimens of insulation were wetted by placing them in the cover of insulation wetting apparatuses (Figure 1) having a temperature of 29°C (85°F). The apparatuses were located in a 4°C (40°F) cold room; some were maintained at a relative humidity of 70 percent, while others were maintained at a relative humidity of 100 percent. Additional information on how the apparatuses were built, how temperatures and relative humidities were controlled and how specimens were prepared is presented in Reference 1.

For insulations with facers, our early tests were done with the facers in place. In order to isolate the effect of the facers, additional tests were conducted with the facers removed.

The edges of some specimens and the top and edges of others were sealed with a vapor barrier paint. Other specimens were not sealed. These three sealing conditions are referred to as follows:

- Top and edges sealed, TES
- Edges sealed, ES
- No seals, NS

As examples, an unsealed specimen tested with 70 percent RH below is designated as NS70 and an edge-sealed specimen with 100 percent RH below is designated as ES100.

Edge seals were primarily applied to toughen the specimens against deterioration during the many times they were removed from the apparatus for weighing and thermal testing.

Top seals were used to prevent upward drying in the same way that waterproof membranes prevent upward drying of insulation in roofs.

The sealing condition influenced the amount and distribution of moisture in most insulations and the rate at which they gained moisture. As expected, specimens that were sealed on top accumulated moisture faster than those that could dry upward into the cold room. However, the sealing condition had only a minor influence on the moisture content-insulating ability relationship for most materials. Thus, tests were combined with different sealing conditions when generating the moisture content-insulating ability graphs and equations in this paper.

THERMAL RESISTANCE MEASUREMENTS

Periodically, each specimen was removed from the wetting apparatus, and carried to a 21°C (70°F) laboratory where it was quickly surface dried with a towel. It was then wrapped in a sheet of 0.013mm (0.0005 in.) thick plasticized PVC, weighed again, and placed in the thermal conductivity instrument, which had its top plate at about 4°C (40°F) and its bottom plate at about 29°C (85°F). Thus, during the test, the specimen was subjected to the same thermal environment that it encountered in the wetting instrument.

Isolating specimen moisture from the thermal conductivity instrument was essential to avoid measurement errors caused by condensation on cold portions of the instrument. The plastic film prevented moisture from entering or leaving the specimen during the test. Thus, the moisture environment in the thermal conductivity instrument was not identical to that encountered in the wetting apparatus. This does not appear to introduce significant errors in materials such as cellular plastics which have a relatively low vapor permeability, since little moisture migrates during the test. For materials such as fibrous glass, with a relatively high vapor permeability, some moisture migration occurs during the test. This causes test stabilization time to increase beyond 30 minutes and, we expect, decreases the accuracy of the final measurement.

After the 1- to 2½ hour thermal test was completed, the specimen was weighed, the wrap was removed, the specimen was weighed again, and then it was returned to the wetting apparatus.

A Dynatech Rapid-K thermal conductivity instrument was used to make the thermal measurements in accordance with ASTM Standard C518-76 "Test for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter."[6] The requirements of this test were met except that (1) specimens contained moisture since that was the purpose of this study, (2) six successive readings did not always yield thermal resistance values agreeing within 1 percent and (3) the 25C° (45F°) temperature difference across a few specimens thicker than 25mm (1 in.) was somewhat less than recommended.

Each day of testing, the instrument was calibrated by first determining the thermal resistance of a 305 X 305 X 22mm (12 X 12 X 1 in.) thick specimen of oven-dried fibrous glass insulation having a known thermal resistance.

MATERIALS TESTED

Table 1 lists the 15 different materials tested, the number of tests performed on each, and the average air-dry density and the average air-dry apparent thermal resistivity (R-value) before wetting.

Instead of presenting plots that relate the thermal resistivity of each material to its moisture content or its time under test, we have normalized thermal resistivity by dividing it by the specimen's air-dry thermal resistivity. This ratio (i.e., wet R-value/air-dry R-value), expressed as a percent, is called the thermal resistance ratio (TRR). A dry specimen has a TRR of 100 percent. As moisture accumulates in an insulation its TRR decreases.

AIR-DRY VS. OVEN-DRY

The specimens were conditioned at room temperature and about 40 percent RH for more than a week before they were placed in the wetting test. They were not oven-dried before testing and thus they contained a small amount of "equilibrium moisture." Such moisture is described by Cash.[7]

When samples of insulation are taken from a roof and oven-dried to determine their moisture content, most of the "equilibrium moisture" is removed. The small error introduced by changing the moisture datum was neglected for all insulations except phenolic.

The presence of somewhat more moisture in off-the-shelf "dry" phenolic insulation created problems. After removing the facers from phenolic specimens and allowing them to condition at room temperature and about 40 percent RH for several days, "air-dry" thermal resistivities were about 70 K•m/W (10 ft.^{2}•hr•°F/BTU•in.). The advertised and measured thermal resistivity of phenolic insulation with its facers intact is about 57 K•m/W (8.3 ft.^{2}•hr•°F/BTU•in.). Additional tests determined that the moisture content of phenolic insulation drops 5 percent to 8 percent a few days after the skins are removed. Although the phenolic wetting tests began at this lower moisture content and higher thermal resistivity, a "dry" thermal resistivity of 57 K•m/W (8.3 ft.^{2}•hr•°F/BTU•in.) was used when calculating TRR. This effectively corrected the phenolic results for the moisture content difference between as-supplied "dry" material and "air-dry" material. This correction was necessary because of the large (20 percent) difference in thermal resistivity between these two conditions for phenolic insulation. This difference in thermal resistivity was much less for all other insulations tested, so they were not corrected in this manner.

FACERS

In order to determine the TRR vs. moisture content relationship for urethane, isocyanurate and fibrous glass insulations without facers, specimens tested with facers were separated at the end of the test and the moisture contents of the facers and the core were determined separately. The proportion of moisture in the facers to that in the core was assumed to have remained constant throughout the test. By measuring the dry weight and thickness of the facers, the dry weight and dry density of the core could be calculated and compared to measurements made on the dried core. The facers contribute little to the thermal resistance of the specimen, and thus the TRR values for specimens with facers were assumed to be valid for specimens without facers.

Because of the assumptions necessary to apply test results with facers to the behavior of specimens without facers, several additional specimens were tested without facers. Time did not permit these tests to be run longer than a few months. Nevertheless, they verified that the procedure used to account for the facers was appropriate.

Other investigators have measured long-term thermal drift in some cellular plastic insulations. Since our specimens were without facers, were several months old before being tested, and were not subjected to high temperatures, it was assumed that little thermal drift occurred during our tests. Thermal resistivity measurements made of dried material after testing indicated that thermal drift could be ignored.

RATE OF WETTING

Figures 2 and 3 show the decrease in thermal resistance ratio (TRR) for 25mm (1 in.) thick top and edge-sealed (TES) specimens with 100 percent RH conditions below. Cork is shown as dashed since no 25mm (1 in.) thick, TES specimens were tested; the "cork" curve is for a 25mm (1 in.) thick specimen with no seals (NS100). Since a TES100 specimen should wet even faster, it is clear that cork wets rather fast. The cellular glass curve is also shown dashed since it is a 38mm (1½ in.) thick ES100 specimen, not a TES100 specimen. A TES100 specimen should have accumulated somewhat more moisture. However, we expect it also would have remained nearly dry, since a 25mm (1 in.) thick TES70 cellular glass specimen had no measurable loss in its insulating ability after 315 days of testing.

Since the primary focus of these tests was to study the behavior of insulations in membrane roofing systems, TES specimens with top seals were of primary interest. However, it should be realized that vapor drives across real roofs can be more or less (often less) than the values imposed on these specimens. Also, during warm weather, the direction of vapor drive in roofs often reverses, which tends to promote downward drying.

Essentially all insulations can get wet when they are subjected to thermally induced vapor pressure gradients such as are present in roofs. Under conditions that cause a permeable material such as fibrous glass to become quite wet in a few days, an extruded polystyrene or cellular glass insulation could survive for years without gaining much moisture. The rate of wetting for other roof insulations lies between these extremes.

Tests underway at CRREL indicate that cellular glass insulation can be destroyed by freeze-thaw action when moisture is present.

The rate of wetting for most insulations is great enough that they need to be protected from indoor moisture if they are subjected to high vapor pressure gradients for long periods. Reference 8 provides recommendations for when and where vapor retarders should be used in membrane roofing systems to provide such protection.

TRR-MOISTURE CONTENT RELATIONSHIPS

Graphs that relate the thermal resistance ratio (TRR) to moisture content by dry weight for the 15 materials tested are presented in Figures 4-9.

To find the volumetric moisture content of each material from these figures, multiply the material's dry-weight-based moisture content by its density in kg/m^3 (which is given in Table 1) and then divide by 1000 kg/m,^{3} the density of water. When the density is given in pounds per cubic foot, multiply by the density in pcf and divide by 62.4 pcf. For example, a 16 kg/m^3 (1 pcf) expanded polystyrene insulation with a moisture content of 3000 percent (dry weight basis) has a volumetric moisture content of 3000 X 16 kg/m^3/1000 kg/m^3 = 48 percent or 3000 X 1.0 pcf/62.4 pcf = 48 percent.

The graphs in Figures 4-9 were developed by fitting curves to each data set. An attempt was made to use the same form of curve for all materials ($y = ae^{bx} + c$) but the fit of another form ($y = ax^b + c$) was significantly better for the fiberboard, perlite, and phenolic data and thus was used. None of the curves was forced to go through the origin, which in this case was y (i.e., TRR) = 100, and x (i.e., moisture content) = 0. This introduces a little discrepancy near the origin. To resolve this, each curve can be ended where y = 90 percent and from that point to y = 100, a linear relationship can be assumed to exist. By doing this, the TRR of each air-dry material calculates to 100.

The two equations for each material are presented in Table 2 along with the x-value (i.e., moisture content) below which the linear relationship applies. The coefficient of determination (R^2) and the sample standard deviation (s) of each nonlinear equation are presented in Table 3.

PASS-FAIL MOISTURE CONTENTS

For about a decade now, we and others have used a TRR of 80 percent as the lowest acceptable value for any roof insulation. Insulation with a TRR below 80 percent is considered "wet" and unacceptable due to its loss of insulating ability.

For some insulations, less moisture than that required to reduce the TRR below 80 percent can be detrimental for other reasons (e.g., delamination, rot and corrosion of fasteners).[9] It is not yet known what those moisture "limit states" should be. Until it is known, the moisture content at which TRR equals 80 percent is proving to be a reasonable pass-fail criterion for judging when insulation is "wet" and unacceptable.

Cash[10] characterizes any material with much more than its equilibrium moisture content as "wet" and unacceptable. Table 4 compares Cash's equilibrium moisture contents[7] and our 80 percent TRR values. We agree that when constructing roofs, equilibrium moisture content is an appropriate pass-fail criterion for the new materials to be installed. For existing roofs, we feel that 80 percent TRR values, which are generally much greater than equilibrium moisture contents, are a more realistic pass-fail criteria. We are monitoring many roofs that are giving good service even though their insulation contains much more than its equilibrium moisture content.

CONCLUSION

Essentially all insulations can get wet when they are subjected to the thermally induced vapor pressure gradients that are present in roofs. The rate of wetting varies greatly among insulation types as Figures 2 and 3 show.

Moisture reduces the insulating ability of insulations. The reduced thermal value is termed thermal resistance ratio (TRR). It is related to moisture content for the 15 roof insulations in Figures 4 through 9 and Table 2. Those relationships are for the insulation itself without any facers that might be furnished with it. By taking core samples of the insulation itself and determining its moisture content, these relationships can provide an indication of the present insulating ability of roofs containing moisture.

Table 5 lists the moisture content at which the thermal resistance ratio of these insulations equals 80 percent. We have found that this is a convenient and useful pass-fail criterion for existing roofing systems. At higher moisture contents the insulation is considered 'wet' and unacceptable.

The TRR-moisture content relationships in this paper are being used in "ROOFER," the roof maintenance management system developed by the U.S. Army Corps of Engineers.[11] As additional information on other moisture "limit states" becomes available, it is expected that maximum acceptable moisture contents for some materials will decrease below the 80 percent TRR values.

REFERENCES

[1] Tobiasson, W. and J. Ricard, "Moisture Gain and its Thermal Consequence for Common Roof Insulations," Proceedings, 5th Conference on Roofing Technology, National Roofing Contractors Association (NRCA), Rosemont, Ill., April 1979. Also available as CRREL Misc. Paper MP 1361, Hanover, N.H.

[2] Kaplar, C.W., "Moisture and Freeze-Thaw Effects on Rigid Thermal Insulations," U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Technical Report 249, Hanover, N.H., 1974.

[3] Hedlin, C.P., "Moisture Gains by Foam Plastic Roof Insulations Under Controlled Temperature Gradients," *Journal of Cellular Plastics*, September/October 1977.

[4] Tobiasson, W. and Korhonen, C., "Roof Moisture Surveys: Yesterday, Today and Tomorrow," Proceedings Second International Conference on Roofing Technology, NRCA, Rosemont, Ill., September 1985. Also available as CRREL Misc. Paper MP 2040, Hanover, N.H.

[5] Hedlin, C.P., "Heat Flow Through a Roof Insulation Having Moisture Contents Between 0 and 1 Percent by Volume in Summer," American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), Transactions Part 2, pp. 1579-1594, 1988.

[6] ASTM "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter," ANSI/ASTM C518-76, Annual Book of ASTM Standards, Part 18, American Society for Testing and Materials, Philadelphia, Pa., 1977.

[7] Cash, C.G., "Moisture and Built-Up Roofing," Proceedings, Second International Symposium on Roofing Technology, NRCA, Rosemont, Ill., September 1985.

[8] Tobiasson, W., "Vapor Retarders for Membrane Roofing Systems," Proceedings, 9th Conference on Roofing Technology, NRCA, Rosemont, Ill., May 1989. Also available as CRREL Misc. paper MP-2489, Hanover, N.H.

[9] Tobiasson, W., "Condensation Control in Low-Slope Roofs," Proceedings of Workshop on Moisture Control in Buildings, Building Thermal Envelope Coordinating Council (BTECC), Washington, D.C., September 1984. Also available as CRREL Misc. paper 2039, Hanover, N.H.

[10] Cash, C. G., Personal Communication, Simpson Gumpertz and Heger, Cambridge, Mass., 1988.

[11] Bailey, D.M., Brotherson, D.E., Tobiasson, W. and Knehans, A., "ROOFER: An Engineered Management System (EMS) for Bituminous Built-Up Roofs," United States Army Construction Engineering Research Laboratory (USACERL) Technical Report M90/04, Champaign, Ill., 1989.

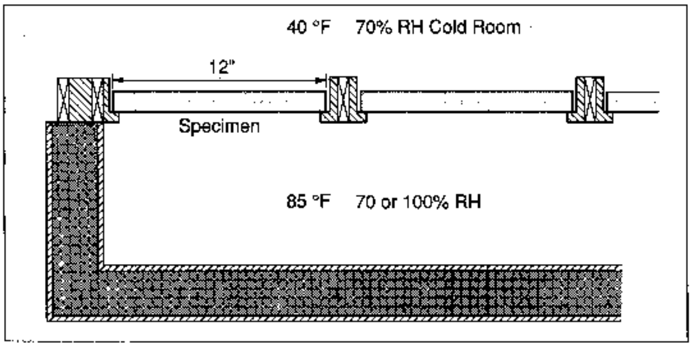

Figure 1 Sketch of specimens in wetting apparatus.

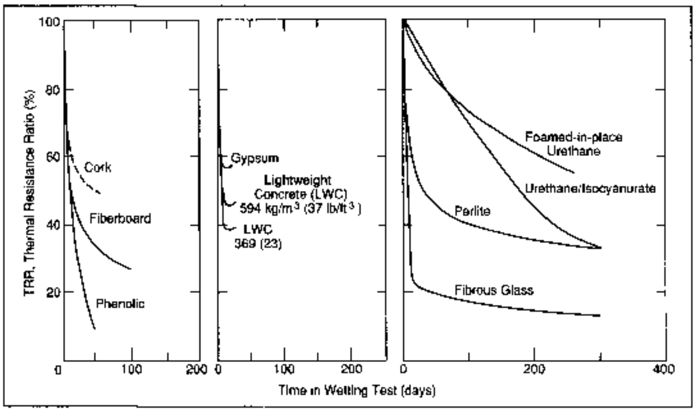

Figure 2 *Decay of TRR with time under test for specimens of cork, fiberboard, phenolic, gypsum, lightweight concrete, foamed-in-place urethane, urethane/isocyanurate, perlite and fibrous glass.*

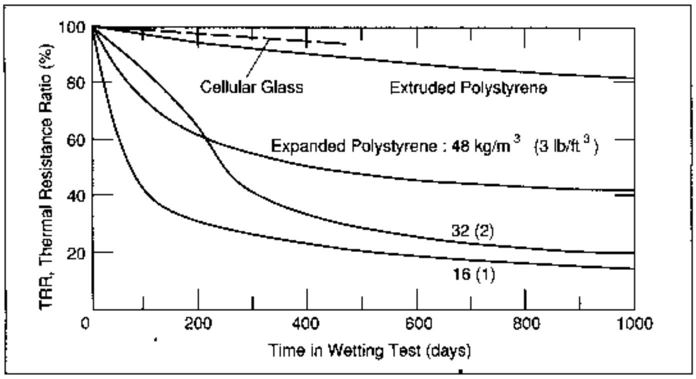

Figure 3 *Decay of TRR with time under test for specimens of cellular glass, extruded polystyrene and expanded polystyrene.*

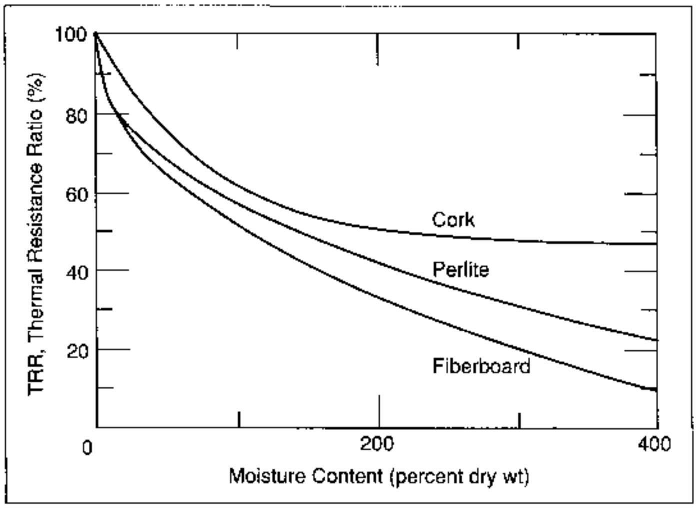

Figure 4 *TRR vs. moisture content relationships for cork, fiberboard and perlite.*

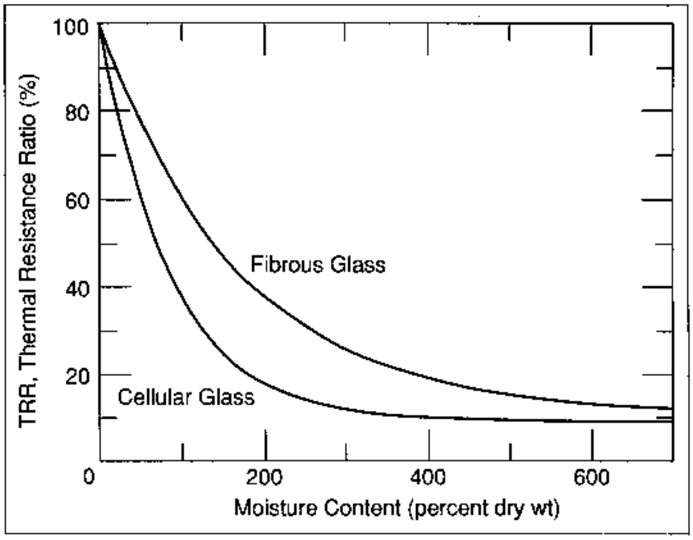

Figure 5 *TRR vs. moisture content relationships for fibrous glass and cellular glass.*

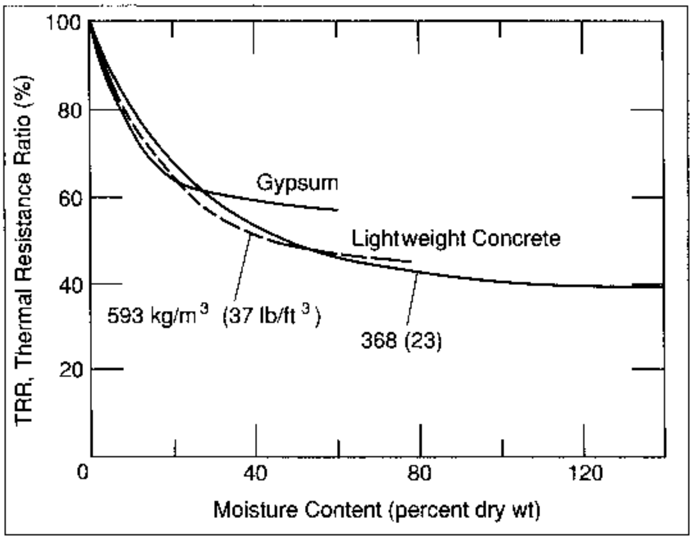

Figure 6 *TRR vs. moisture content relationships for gypsum and 369 and 594 kg/m (23 and 37 pcf) lightweight concrete.*

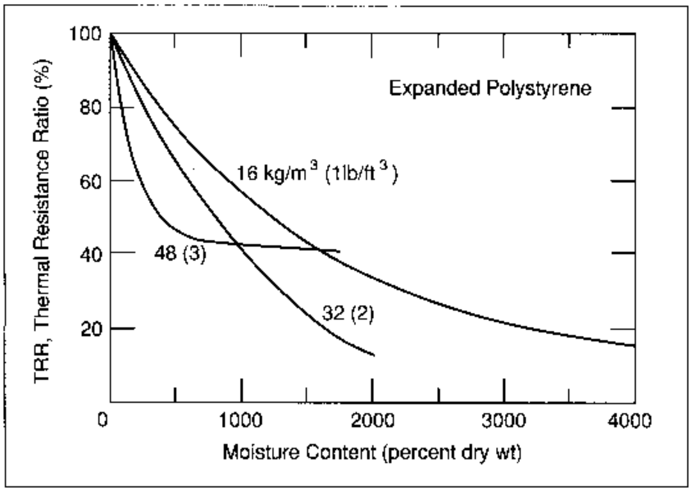

Figure 7 *TRR vs. moisture content relationships for 16, 32 and 48 kg/m (1, 2 and 3 pcf) expanded polystyrene.*

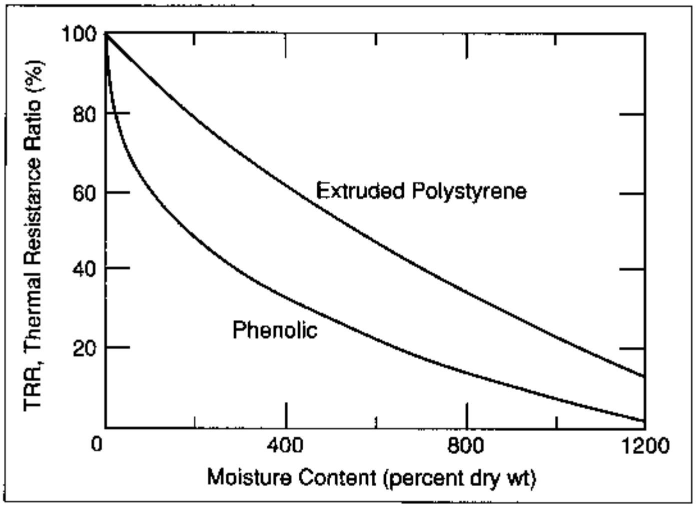

Figure 8 TRR vs. moisture content relationships for extruded polystyrene, and phenolic.

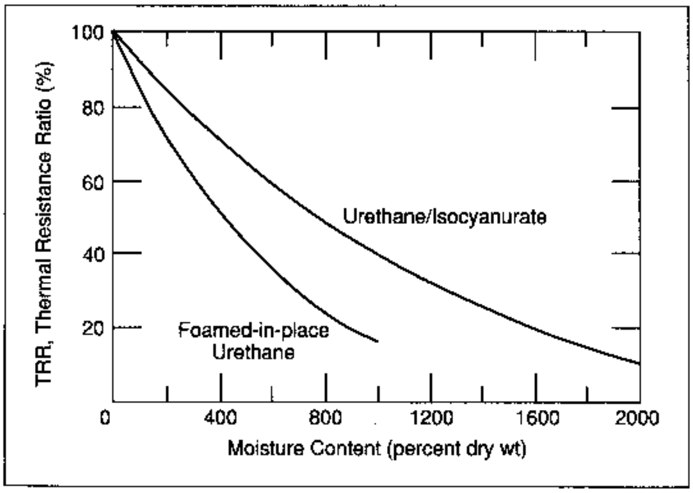

Figure 9 TRR vs. moisture content relationships for urethane/isocyanurate and foamed-in-place urethane.

Type	Number	Density (kg/m^3/pcf)	Air-dried R-value*	Variations from normal (TES100) wetting condition
Cork	1	256/16.0	17.8/2.57	1 @ NS100
Fiberboard	6	295/18.4	17.6/2.54	2 @ ES100
Perlite	5	163/10.2	17.6/2.60	1 @ ES70, 1 @ NS100, 1 @ ES100
Fibrous glass	5	147/9.2	25.9/3.73	2 @ ES100
Cellular glass	6	134/8.4	28.5/4.11	2 @ ES70, 1 @ TES70, 2 @ NS100, 1 @ ES100
Gypsum	2	921/57.5	3.7/0.54	
Lightweight concrete 369 kg/m^3 (23 pcf)	2	367/22.9	10.1/1.46	
Lightweight concrete 594 kg/m^3 (37 pcf)	2	599/37.4	7.4/1.06	
Expanded polystyrene 16 kg/m^3 (1 pcf)	2	16/1.0	25.5/3.68	
Expanded polystyrene 32 kg/m^3 (2 pcf)	2	29/1.8	29.7/4.29	1 @ TES70
Expanded polystyrene 48 kg.m^3 (3 pcf)	1	53/3.3	31.5/4.54	
Extruded polystyrene	4	32/2.0	35.7/5.15	
Urethane/isocyanurate	3	34/2.1	36.7/5.30	
Foamed-in-place urethane	2	50/3.1	41.3/5.96	
Phenolic	6	42/2.6	69.7/10.05	

* Apparent thermal resistivity (R-value) units are K•m/W and ft.^{2}•hr•°F/BTU•in.

Table 1 Background information on the 15 materials tested.

Cork:	if $x > 19\%$ use $y = 56.54\,e^{-0.0135x} + 46.47$ if $x \leq 19\%$ use $y = 100 - 0.52\,(x)$
Fiberboard:	if $x > 4\%$ use $y = -7.294\,x^{0.4260} + 103.12$ if $x \leq 4\%$ use $y = 100 - 2.5\,x$
Perlite:	if $x > 3.3\%$ use $y = -5.983\,x^{0.4285} + 100.0$ if $x \leq 3.3\%$ use $y = 100 - 3.0\,x$
Fibrous glass	if $x > 20\%$ use $y = 90.53\,e^{-0.006148x} + 10.07$ if $x \leq 20\%$ use $y = 100 - 0.5\,x$
Cellular glass	if $x > 12.5\%$ use $y = 94.315\,e^{-0.0122x} + 8.993$ if $x \leq 12.5\%$ use $y = 100 - 0.80\,x$
Gypsum:	if $x > 3\%$ use $y = 43.11\,e^{-0.0720x} + 55.04$ if $x \leq 3\%$ use $y = 100 - 3.4\,x$
Lightweight concrete 369 kg/m^3 (23 pcf)	if $x > 3.8\%$ use $y = 59.02\,e^{-0.0342x} + 38.23$ if $x \leq 3.8\%$ use $y = 100 - 2.6\,x$
Lightweight concrete 594 kg/m^3 (37 pcf)	if $x > 4\%$ use $y = 56.67\,e^{-0.0510x} + 43.74$ if $x \leq 4\%$ use $y = 100 - 2.5\,x$
Expanded polystyrene 16 kg/m^3 (1 pcf)	if $x > 181\%$ use $y = 91.40\,e^{-0.000649x} + 8.744$ if $x \leq 181\%$ use $y = 100 - 0.055\,x$
Expanded polystyrene 32 kg/m^3 (2 pcf)	if $x > 109\%$ use $y = 117.65\,e^{-0.000655x} - 19.55$ if $x \leq 109\%$ use $y = 100 - 0.09\,x$
Expanded polystyrene 48 kg/m^3 (3 pcf)	if $x > 33\%$ use $y = 55.96\,e^{-0.00480x} + 42.25$ if $x \leq 33\%$ use $y = 100 - 0.30\,x$
Extruded polystyrene	if $x > 84\%$ use $y = 137.37\,e^{-0.00080x} - 39.47$ if $x \leq 84\%$ use $y = 100 - 0.12\,x$
Urethane/isocyanurate	if $x > 129\%$ use $y = 117.75\,e^{-0.000734x} - 17.12$ if $x \leq 129\%$ use $y = 100 - 0.078\,x$
Foamed-in-place urethane	if $x > 56\%$ use $y = 107.09\,e^{-0.00144x} - 8.78$ if $x \leq 56\%$ use $y = 100 - 0.18\,x$
Phenolic	if $x > 9.7\%$ use $y = -19.067\,x^{0.263} + 124.62$ if $x \leq 9.7\%$ use $y = 100 - 1.03\,x$

Table 2 *Equations that relate TRR (y) and moisture content in percentage of dry weight (x) for common roof insulations.*

Material	**Coefficient of Determination R^2**	**Sample Standard Deviation s (%)**
Cork	0.953	4.0
Fiberboard	0.979	3.3
Perlite	0.978	3.6
Fibrous glass	0.937	6.3
Cellular glass	0.926	2.9
Gypsum	0.989	1.8
Lightweight concrete 369 kg/m^3 (23 pcf)	0.973	3.7
Lightweight concrete 594 kg/m^3 (37 pcf)	0.990	2.2
Expanded polystyrene 16 kg/m^3 (1 pcf)	0.996	1.9
Expanded polystyrene 32 kg/m^3 (2 pcf)	0.983	4.3
Expanded polystyrene 48 kg/m^3 (3 pcf)	0.976	2.7
Extruded polystyrene	0.938	3.7
Urethane/isocyanurate	0.991	2.8
Foamed-in-place urethane	0.990	1.8
Phenolic	0.951	6.6

Table 3 *Statistical values for the nonlinear TRR vs. moisture content equations.*

Insulation	Equilibrium Moisture Content (% of dry weight) from Ref. 7		Moisture Content (% of dry weight) at 80% TRR
	@ 45% RH	@ 90% RH	
Cellular glass	0.1	0.2	23
Expanded polystyrene 16 kg/m^3 (1 pcf)	1.9	2.0	383
Extruded polystyrene	0.5	0.8	185
Fibrous glass	0.6	1.1	42
Isocyanurate	1.4	3.0	262
Perlite	1.7	5.0	17
Phenolic	6.4	23.4	25
Urethane	2.0	6.0	262

Table 4 *Comparison of equilibrium moisture contents and those at 80 percent TRR for insulations without facers.*

Material	Moisture Content	
	% of dry weight	% of volume*
Cork	39	9.9
Fiberboard	15	4.4
Perlite	17	2.7
Fibrous glass	42	6.2
Cellular glass	23	3.1
Gypsum	8	7.0
Lightweight concrete 369 kg/m^3 (23 pcf)	10	3.7
Lightweight concrete 594 kg/m^3 (37 (pcf)	9	5.3
Expanded polystyrene 16 kg/m^3 (1 pcf)	383	6.1
Expanded polystyrene 32 kg/m^3 (2 pcf)	248	7.2
Expanded polystyrene 48 kg/m^3 (3 pcf)	82	4.3
Extruded polystyrene	185	5.9
Urethane/isocyanurate	262	8.8
Foamed-in-place urethane	130	6.5
Phenolic	25	1.0

* Using densities in Table 1.

Table 5 *Moisture contents at which TRR equals 80 percent.*