FREEZE-THAW DURABILITY OF COMMON ROOF INSULATIONS

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Specimens of extruded and expanded polystyrene, polyurethane, polyisocyanurate, sprayed polyurethane, phenolic, fibrous glass, cellular glass, lightweight concrete, fiberboard, perlite, and cork insulation were frozen in air and thawed in water up to 948 times. Their moisture contents were determined periodically, and relationships developed previously at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) were used to determine the effect of that moisture on their insulating ability.

Most insulations became quite wet, which caused them to lose much of their insulating ability. After 400 freeze-thaw cycles, phenolic, cellular glass, fibrous glass, and fiberboard lost more than three-quarters of their insulating ability. Lightweight concrete and perlite lost about two-thirds, cork and gypsum lost about half, and expanded bead polystyrene lost about one-third. Sprayed polyurethane, polyurethane, polyisocyanurate, and extruded polystyrene foam lost only 6 to 16 percent of their insulating ability after 400 cycles. Cellular glass is quite resistant to moisture, but when water in cut cells at its edges froze and expanded, it was progressively broken down into a black powder. After 25 freeze-thaw cycles, it had less than 20 percent of its original insulating ability.

KEYWORDS

Degradation, freeze-thaw, insulation, moisture, protected membranes, thermal resistance.

INTRODUCTION

The effect of moisture on the insulating ability of common roof insulations and the relative rates of wetting of these materials has been quantified.[1] In those CRREL tests, the wet thermal resistance of a material was divided by its air-dry thermal resistance to normalize thermal findings. This ratio, expressed as a percent, was called the thermal resistance ratio (TRR) of that material at that moisture content. Graphs were presented that relate TRR to moisture content for 15 common roof insulations. Figure 1 presents those findings for extruded polystyrene, cellular glass, and polyisocyanurate insulation.[1]

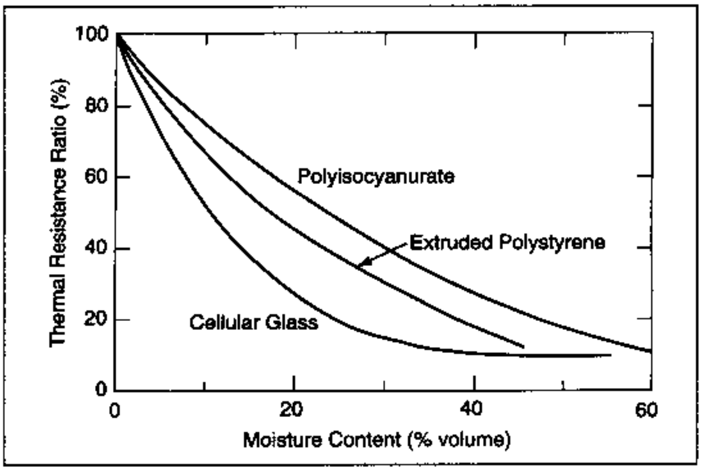

Figure 1. Thermal resistance ratio (TRR)—moisture content relationships for extruded polystyrene, cellular glass, and polyisocyanurate insulation.[1]

Those tests subjected the 12- by 12-inch (300- by 300-mm) specimens, which were about 1 inch (25 mm) thick, to a sustained one-way vapor drive with their tops sealed and their bottoms open. The top seal represented the essentially impermeable condition created on a roof by the waterproofing membrane. The unsealed bottom represented the condition created when no deliberate or inadvertent vapor retarding layer was present below the insulation in a roof or when, because of membrane or flashing flaws, water had gotten into a roofing system with a vapor retarder and was subjected to upward vapor drive (usually in cold weather).

In those tests, the temperature above the specimens was 4°C (40°F) and the relative humidity was about 50 percent. Below the specimens, the temperature was 29°C (85°F) and the relative humidity was 70 percent for some tests and 100 percent for others.

Periodically, the moisture content and the thermal resistance of each specimen were determined by weighing it, then wrapping it in a plastic film and testing it in a thermal conductivity apparatus with its top at 4°C (40°F) and its bottom at 29°C (85°F). Thermal testing was done according to ASTM Standard C 518-91 Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter.[2] However, not all requirements of that standard could be met because the samples were not dry.

Some insulations rapidly became quite wet and thermally inefficient. Table 1 presents the time it took the various insulations to lose 20 percent of their insulating ability (i.e., the time it took the TRR of each to reach 80 percent). Note that the TRRs of cellular glass and extruded polystyrene did not drop to 80 percent even after more than 1,000 days (about three years) of testing while the 80 percent value was reached by all other insulations in less than 125 days and, for all but the cellular plastic insulations, in less than five days. These tests were all done at above-freezing temperatures.

Extruded polystyrene insulation is used *above* the waterproofing membrane in protected membrane (upside down) roof systems (Figure 2). It needs ballast to keep it in place and to protect it from UV degradation, but it can survive for years in that sometimes wet, sometimes freezing, environment. The authors and others have disassembled old pro-

Material	Time (days)
Phenolic	< 1
Wood fiber	1
Perlite	1
Gypsum	1
Lightweight concrete, (369 kg/m^3 [23 pcf])	1
Lightweight concrete, (594 kg/m^3 [37 pcf])	1
Fibrous glass	3
Cork	4
Sprayed polyurethane	66
Polyurethane-polyisocyanurate	66
Expanded bead polystyrene, (16 kg/m^3 [1 pcf])	22
Expanded bead polystyrene, (32 kg/m^3 [2 pcf])	124
Expanded bead polystyrene, (48 kg/m^3 [3 pcf])	70
Extruded polystyrene	about 1,000*
Cellular glass	about 1,600†

* still 92% TRR after a year and 81% TRR after 1000 days.
† still 96% TRR after a year: 1600 is based on linear extrapolation of this rate

Table 1. Time to reach 80 percent TRR in CRREL wetting tests.[1]

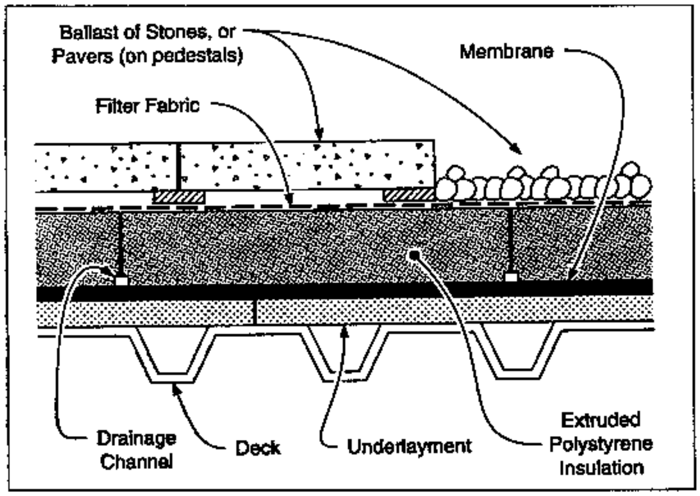

Figure 2. Cross section of a protected membrane roof system.

tected membrane roofs to verify the long-term durability of extruded polystyrene insulation in the harsh environment above a protected membrane.[3, 4, 5] However, some wet extruded polystyrene insulation has been found in such roofs,[6, 7, 8] suggesting that some action (perhaps freeze-thaw) or some variability in its manufacture can allow it to become wet under some circumstances.

The authors have also determined in the laboratory, in exposure studies, and on roofs that expanded bead polystyrene insulation, even at a density as high as 48 kg/m^3 (3 lb/ft^3), should not be used above a protected membrane.[1, 3]

Cellular glass is advertised as being moisture-resistant. Table 1 supports that claim. However, cellular glass insulation is not used above waterproofing in protected membrane roofs. The authors and others have cut into conventional roofs containing cellular glass insulation where that material was falling apart and full of water. The authors speculate that although cellular glass is resistant to moisture, it is damaged when moisture enters the cells cut at the surfaces of each piece and freezes.

These findings and speculations prompted the authors to study the effect of freeze-thaw on the moisture resistance of cellular glass, extruded polystyrene, expanded bead polystyrene, and other common roof insulations.

FREEZE-THAW CYCLES

Meteorological data have been used in various ways to establish the annual number of freeze-thaw cycles expected in various places. If a freeze is assumed to occur when the air temperature drops from 1.1° to -2.2°C (34° to 28°F) and a thaw is assumed to occur when the air temperature rises from -2.2° to 1.1°C (28° to 34°F),[9] the freeze-thaw cycles expected per year are as shown in Table 2.

Very cold and very warm places have fewer freeze-thaw cycles than places with intermediate climates. For many places in North America, several hundred freeze-thaw cycles are to be expected over a 10- or 20-year period. The number of freeze-thaw cycles experienced by a component of the roof of a heated building is also influenced by the temperature of the building; where the component is located within the building envelope; the orientation of the roof relative to the sun; and the absence or presence of snow on the roof.

If an insulation is dry, freezing it has little or no deleterious effect. Thus, the freeze-thaw resistance of an insulation that is kept dry is of no consequence. However, when moisture gains access to roof insulation because of entrapment before or during construction, waterproofing flaws, inadequate condensation control, or deliberate use of the material in a wet environment such as in a protected membrane roof (Figure 2), its freeze-thaw resistance is a very important issue.

Freeze-thaw tests provide useful information on the durability of insulations that freeze and thaw in the presence of moisture.

Location	Cycles per year
San Francisco, CA	0
Portland, OR	15
Macon, GA	15
Baker Lake, NWT	28
Boston, MA	42
Winnipeg, Manitoba	46
Juneau, AK	52
Yarmouth, Nova Scotia	52
Akron, OH	63
Millinocket, ME	71
Elkins, WV	85
Garden City, KS	96
Elko, NV	137

Table 2. Average annual freeze-thaw cycles for various North American locations.[9]

FREEZE-THAW TEST PROCEDURE

ASTM Standard C 666-84 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing[10] was used as a guide for the freeze-thaw tests. However, because it is for concrete, not a wide range of insulations, some wet and others dry, not all test requirements could be met. Procedure A calls for freezing and thawing in water. Procedure B calls for freezing in air and thawing in water. To achieve Procedure A, prismatic concrete specimens are placed in open-topped, water-filled stainless steel containers slightly larger than themselves. When the water below and around each concrete specimen freezes, the walls of its container bulge. The standard warns of the damage this can cause to the containers and to the specimens and indicates that such tests should be interpreted with caution. Roof insulations are much weaker than concrete and, the authors reasoned, would be even more adversely affected by freezing within a confined space. Thus, Procedure B was chosen, freezing in air and thawing in water, for freeze-thaw testing of roof insulations.

Considerable effort was directed to ensure that complete freezing and complete thawing of every specimen occurred on every cycle. Before actual testing, wet and dry specimens of various insulations were frozen and then thawed to determine how long each cycle had to be to achieve complete freezing and complete thawing. Those tests were used to determine which specimens would take the longest to freeze and thaw. A 30-gauge copper-constantan thermocouple was placed at the center of those specimens expected to freeze and thaw the slowest. Those thermocouples were monitored throughout the 948 freeze-thaw cycles of testing to verify that each cycle was long enough to achieve complete freezing and thawing.

The temperature at the center of a specimen of wet expanded bead polystyrene insulation during one cycle is shown in Figure 3. Table 3 presents the initial computerized control sequence used to freeze and thaw the specimens. As freeze-thaw cycles accumulated and specimens became wetter, the reference thermocouples indicated that it was taking them longer to completely freeze and completely thaw. The authors increased the cycle time as testing proceeded in order to ensure complete freezing and complete thawing. By the end of testing at cycle 948, the cycle time had increased from three and one-half hours to six and one-half hours. Wet 2-inch- (51-mm-) thick expanded bead polystyrene took the longest to freeze and thaw.

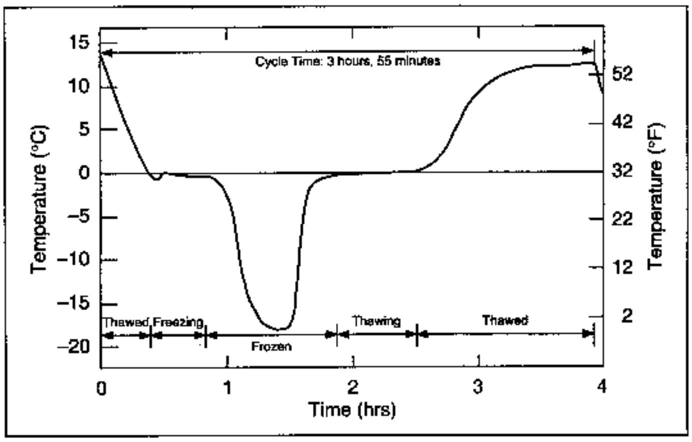

Figure 3. Temperature at the center of a wet expanded bead polystyrene specimen during a freeze-thaw cycle.

Figure 4 shows the freeze-thaw apparatus used for these tests. Table 4 lists background information on the materials tested. Most of the 12- by 12-inch (300- by 300-mm) specimens were about 1 inch (25 mm) thick. However, extruded and expanded bead polystyrenes about 2 inches (51 mm) thick were also tested. Each specimen was placed in a bag of fine fabric (i.e., no-see-um) screening of the type used in tents (Figure 5). This was done to prevent pump damage from any pieces that might break off and circulate with the water pumped into and out of the chamber to thaw the specimens. Spacers were used to keep the specimens at least 0.5 inch (13 mm) apart so that they would not insulate each other from freezing and thawing. Stainless steel wire cages (Figure 6) held arrays of the specimens in the tank where they were frozen in air and thawed in water.

The samples were removed from the freeze-thaw apparatus for weighing after 25 cycles and after 50 cycles, then about every 50 cycles until the end of the 948-cycle test. Once out of the apparatus for weighing, they were removed from their

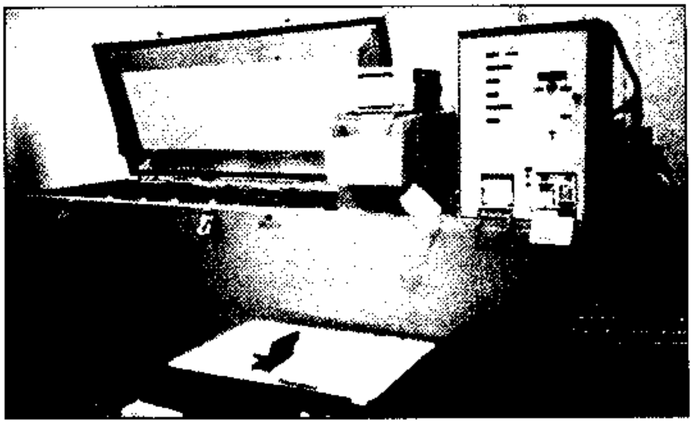

Figure 4. Freeze-thaw apparatus.

STEP	STEP TIME	TOTAL TIME	OPERATION
	(HR - MIN)	(HR - MIN)	
1.	1 - 10	1 - 10	Specimens submerged in circulating water maintained at 16°C (60°F).
2.	0 - 17	1 - 27	Water pumped from test chamber. All specimens now thawed.
3.	0 - 30	1 - 57	Freezer on with fan circulating cold air around test chamber. Chamber temperature ramped down to -23°C (-10°F).
4.	1 - 25	3 - 22	Freezer and fan on with chamber temperature ramped up to -18°C (0°F). All specimens frozen.
5.	0 - 10	3 - 32	Water at about 16°C (60°F) pumped into test chamber.

Table 3. Initial freeze-thaw control sequence (one cycle).

Insulation	Thickness mm (inches)	Density kg/m³ (lb/ft³)	Air-dried R-value*
Cork	25 (1.0)	256 (16.0)	18 (2.6)
Fiberboard	25 (1.0)	296 (18.5)	17 (2.5)
Perlite	21 (0.8)	189 (11.8)	18 (2.6)
Fibrous glass	28 (1.1)	143 (9.0)	26 (3.7)
Cellular glass	27 (1.1)	137 (8.6)	20 (2.9)
Gypsum	25 (1.0)	878 (54.8)	3.5 (0.5)
Lightweight concrete	26 (1.0)	391 (24.4)	10 (1.5)
Expanded bead polystyrene:			
A	24 (0.9)	14 (0.9)	25 (3.6)†
B	49 (1.9)	15 (1.0)	25 (3.6)†
C	24 (1.0)	18 (1.1)	26 (3.8)†
D	51 (2.0)	18 (1.1)	26 (3.8)†
E	50 (20)	20 (1.3)	27 (3.9)†
Extruded polystyrene:			
A	25 (1.0)	33 (2.1)	36 (5.2)‡
B§	26 (1.0)	33 (2.0)	36 (5.2)‡
C	26 (1.0)	36 (2.2)	36 (5.2)‡
D§	26 (1.0)	30 (1.8)	36 (5.2)‡
E	53 (2.1)	30 (1.9)	36 (5.2)‡
Polyurethane	23 (0.9)	30 (1.9)	37 (5.3)
Polyisocyanurate	29 (1.2)	30 (1.9)	37 (5.3)
Sprayed polyurethane	24 (0.9)	54 (3.4)	42 (6.0)
Phenolic	30 (1.2)	40 (2.5)	58 (8.3)

* From tests of the same materials reported by Tobiasson, Greatorex and Van Pelt (1991).[1] The values for cellular glass and phenolic were wrong in this reference. Their correct values are presented in this table. Units are km/W (ft² · hr · °F/BTU · in.).

† Estimated from tests of 1 lb/ft³ (16 kg/m³) and 1.8 lb/ft³ (29 kg/m³) expanded bead polystyrene in above reference assuming linear relationship between R-value and density.

‡ Used value for 2 lb/ft³ (32 kg/m³) extruded polystyrene in above reference.

§ With surface skins cut away.

Table 4. *Background information on the materials tested.*

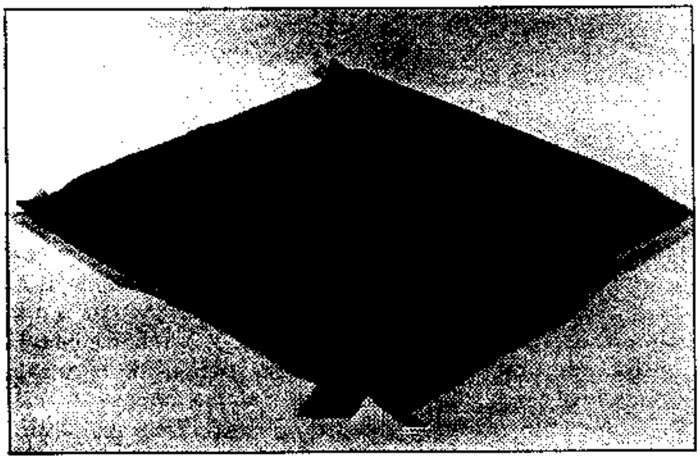

Figure 5. *A specimen in its no-see-um mesh bag.*

mesh bags, surface dried with towels and weighed. Any pieces and particles that remained within a bag were collected and oven dried. Their dry weight was subtracted from the initial dry weight of that specimen when determining its moisture content at that freeze-thaw cycle. The specimens were returned to the chamber for further testing as long as a reasonable sample remained. Freeze-thaw action broke apart the cellular glass, gypsum, and lightweight concrete specimens as cycles increased. At some point, they were not returned to the apparatus for further testing. Figure 7 shows the condition of these specimens after a few hundred freeze-thaw cycles. Other materials warped and lost a corner here and there as they were handled, but they were not broken down by freeze-thaw in the way that cellular glass, gypsum, and lightweight concrete were.

TEST RESULTS

Figure 8 shows the increase in moisture content with increase in freeze-thaw cycles for four specimens that represent the range of behavior experienced. Points are shown to illustrate

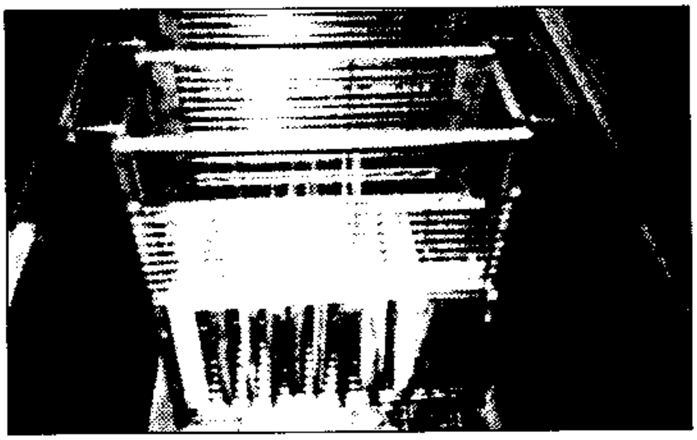

Figure 6. *Specimens in lower level of wire cage that held them in the tank where they were frozen in air and thawed in water.*

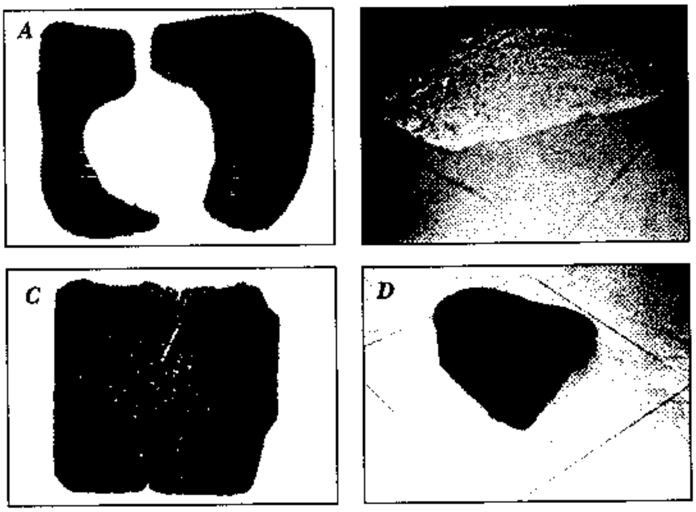

Figure 7. *Some specimens were broken apart by freeze-thaw action.* ***A.*** *Much of the lightweight concrete had disappeared by 327 freeze-thaw cycles.* ***B.*** *The gypsum specimen was quite thin at 500 cycles.* ***C.*** *One cellular glass specimen was broken but most of it remained at 300 cycles.* ***D.*** *Most of another cellular glass specimen was gone at 327 cycles.*

the limited amount of data scatter. The moisture content of the fiberboard increased rapidly, followed by that of the cellular glass. Other studies indicate that had the cellular glass just been immersed in water without being subjected to freeze-thaw cycles, it would have had a moisture content of less than 2 percent at the end of this test.[11] Thus, essentially all of the cellular glass wetting was the result of freeze-thaw deterioration. Fiberboard, on the other hand, would have rapidly become quite wet if only immersed in water. It does not need freeze-thaw action to get wet.

Both extruded and expanded polystyrenes wet much more slowly than the cellular glass and fiberboard when subjected to freeze-thaw. Neither polystyrene picks up much moisture when immersed.

Figure 9 shows the TRR vs. freeze-thaw cycle relationship for these four materials. Freeze-thaw action affects extruded polystyrene, but even after nine hundred cycles, it had lost only about 21 percent of its insulating ability (i.e., its 948-cycle TRR was 79 percent). During the same number of cycles, expanded bead polystyrene lost more than 60 percent of its insulating ability (i.e., its 948-cycle TRR was 37 percent). Those losses were gradual. Fiberboard and cellular glass lost most of their insulating ability after a few freeze-thaw cycles. To survive for long in most roofs, they must be kept dry.

The information in Figures 8 and 9 is from specimens about 25 mm (1 inch) thick. A specimen of extruded polystyrene 53 mm (2.1 inches) thick was even more resistant to freeze-thaw. It still had 90 percent of its thermal resistance after 948 freeze-thaw cycles while the 25-mm- (1-inch-) thick specimen of that material had a 948-day TRR of 79 percent. A similar reduction in rate of wetting with thickness was observed for that material when subjected to a sustained one-way vapor drive.[1] Thus, to reduce the rate of wetting of extruded polystyrene insulation in protected membrane roofs, thick layers of that material should be used instead of several thinner layers.

The density of the expanded bead polystyrene specimen shown in Figures 8 and 9 was only 14 kg/m^3 (0.9 lb/ft^3) while the density of the extruded polystyrene shown there was 36 kg/m^3 (2.2 lb/ft^3). Two 50-mm- (2-inch-) thick specimens of expanded bead polystyrene, one also having a density of 15 kg/m^3 (1.0 lb/ft^3) and the other having a density of 20 kg/m^3 (1.3 lb/ft^3) had 948 cycle TRRs of 31 percent and 51 percent, respectively. This indicates that increasing the density of expanded bead polystyrene reduces its rate of wetting during freeze-thaw. If we had subjected a sample of 35-kg/m^3 (2.2-lb/ft^3) expanded bead polystyrene to freeze-thaw, we would be able to directly compare expanded bead and extruded polystyrenes of the same density. Unfortunately, we do not have this answer. However, we have weighed expanded bead polystyrene with a density of 30 kg/m^3 (1.9 lb/ft^3) that has become very wet (i.e., moisture contents in excess of 20 percent by volume and TRRs less than 50 percent) from a few-years-old protected membrane roof in Alaska. Although increasing the density of expanded bead polystyrene reduces its wetting rate, our collective experience indicates that it will become wet much faster than extruded polystyrene of about the same density.

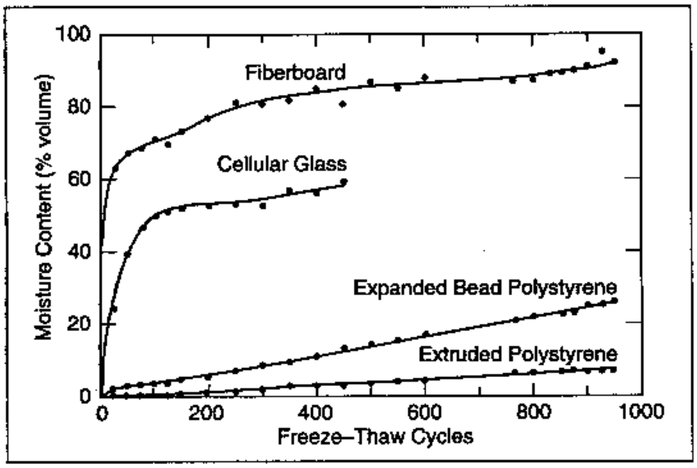

Figure 8. Moisture content-freeze-thaw cycle relationships for fiberboard, cellular glass, expanded bead polystyrene, and extruded polystyrene insulations.

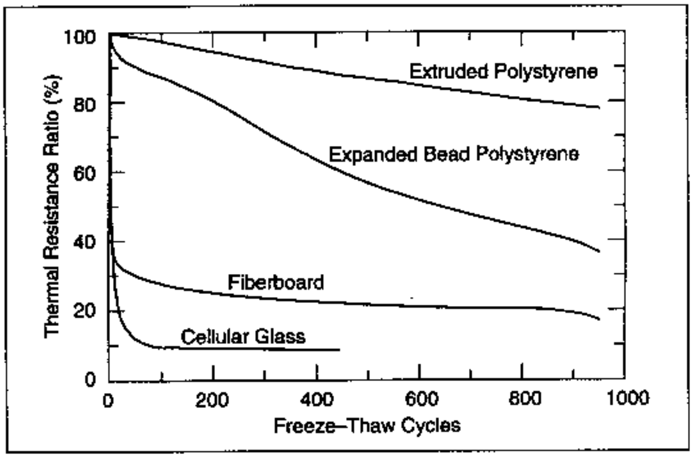

Figure 9. Thermal resistance ratio (TRR)-freeze-thaw cycle relationships for the four insulations shown in Figure 8.

Comparing the two previously mentioned 14-15 kg/m^3 (0.9-1.0 lb/ft^3) specimens of expanded bead polystyrene, one of which was 25 mm (1 inch) thick and the other 51 mm (2 inches) thick, the thicker specimen had a lower 948-cycle TRR than the thinner one (31 percent vs. 37 percent). The reverse was to be expected (i.e., thicker should wet slower). The expanded bead polystyrene specimens came from different manufacturers, and the authors expect that variations in cell structure (e.g., open cell content) among manufacturers also influences the wetting rate of this type of insulation, resulting in this unexpected comparison.

All expanded bead polystyrenes that the authors have studied in the field[3] and in the laboratory[1,3] are more rapidly wet by vapor drive and freeze-thaw action than extruded polystyrenes.

The authors do not consider expanded bead polystyrenes suitable for use in protected membrane roofs where vapor drive and freeze-thaw cycles occur in an often wet environment. Both expanded bead and extruded polystyrenes can be used in conventional roofs where the design intent is to keep moisture from them. Expanded bead polystyrene is particularly attractive for such uses because it is relatively inexpensive per unit of insulating ability delivered. However, compressive strength, dimensional stability, chemical resistance, heat distortion temperature, and other properties limit the window of applicability of polystyrene insulations in conventional roofs.

Figure 10 relates moisture content to freeze-thaw cycles for fibrous glass, perlite, lightweight concrete, polyurethane, and sprayed polyurethane insulations. Data points are shown only for fibrous glass, which displays a lot of scatter. Data points for all other materials have a scatter similar to that shown in Figure 8. The two polyurethanes (i.e., sprayed material and boards) wet slowly. Less control of the foaming process in-place compared to in a factory probably explains why the sprayed polyurethane wets somewhat faster, even though its density is almost double that of boards made in a factory. Freeze-thaw cycling seems less damaging to these insulations than sustained one-way vapor drive.

Fibrous glass and lightweight concrete insulation become quite wet after only a few freeze-thaw cycles. Both also wet rapidly when subjected to sustained one-way vapor drive.[1] Fibrous glass wets rapidly when submerged.[11] Freeze-thaw cycling appears to increase this rate.

Perlite becomes quite wet during freeze-thaw cycling but it wets more gradually than fibrous glass or lightweight concrete. It displayed similar behavior in submersion[11] and vapor-drive[1] tests. Freeze-thaw cycling appears to accelerate the rate of wetting of perlite.

Figure 11 relates TRR to freeze-thaw cycles for the materials shown in Figure 10. The two polyurethanes retain most of their insulating ability even after several hundred freeze-thaw cycles. Most of the insulating ability of wet fibrous glass and lightweight concrete insulation is lost after less than 25 freeze-thaw cycles. It takes more freeze-thaw cycles to reduce the thermal efficiency of perlite, but after only a hundred cycles, it had only about 40 percent of its initial insulating ability.

Figure 12 relates moisture content to freeze-thaw cycles for polyisocyanurate, phenolic, cork, and gypsum. Data points for all but gypsum have a scatter similar to that shown in Figure 8. As shown in Figure 7B, much of the gypsum sample eroded during the test. Our method of tracking this weight loss was inaccurate, so the only accurate dry weight was that measured by oven drying the sample at the end of the test. That value is shown as a black dot at the end of the gypsum curve. The other black dot is after 25 cycles, and it uses the initial dry weight. Because some gypsum was probably lost during the first 25 cycles, the actual moisture content is probably somewhat higher than is shown. Nonetheless, it is clear that gypsum gains considerable moisture after just a few freeze-thaw cycles. Cork and phenolic insulations also wet rapidly. Polyisocyanurate wets slowly like its polyurethane cousins.

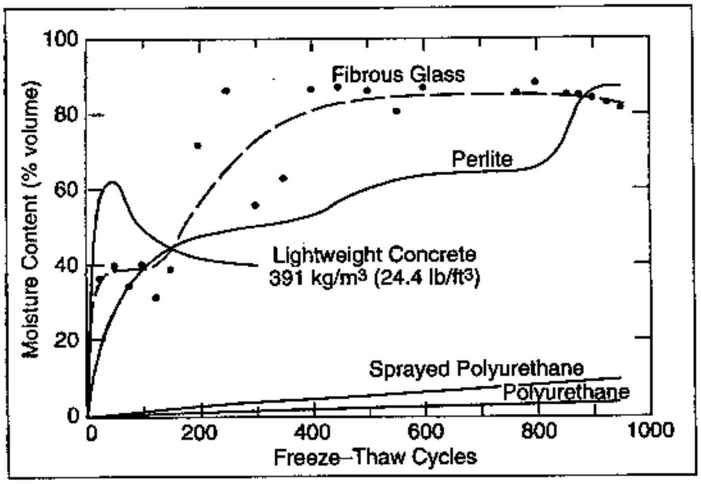

Figure 10. Moisture content-freeze-thaw cycle relationships for fibrous glass, perlite, lightweight concrete, sprayed polyurethane, and polyurethane insulations.

Cork, phenolic, and gypsum also wet rapidly when subjected to one-way vapor drive.[1]

Figure 13 relates TRR to freeze-thaw cycles for the four materials shown in Figure 12. The polyisocyanurate retained most of its insulating ability even after several hundred freeze-thaw cycles. Gypsum and cork quickly lost more than 40 percent of their insulating ability, but their TRRs stabilized between 50 and 57 percent. Phenolic insulation rapidly lost almost all of its insulating ability. It had less than 10 percent of its thermal resistance after only 50 freeze-thaw cycles.

SUPPLEMENTAL TESTS OF CELLULAR GLASS

Cellular glass insulation, which is otherwise moisture-resistant, can be quickly destroyed by freeze-thaw action. Because the TRR of that material had dropped to 20 percent at the first measurement (i.e., after 25 freeze-thaw cycles), the authors decided to run supplemental freeze-thaw tests on that material to determine what happens during the first few freeze-thaw cycles. The supplemental tests were run on 25-mm-(1-inch-) thick specimens, but because the freeze-thaw appa-

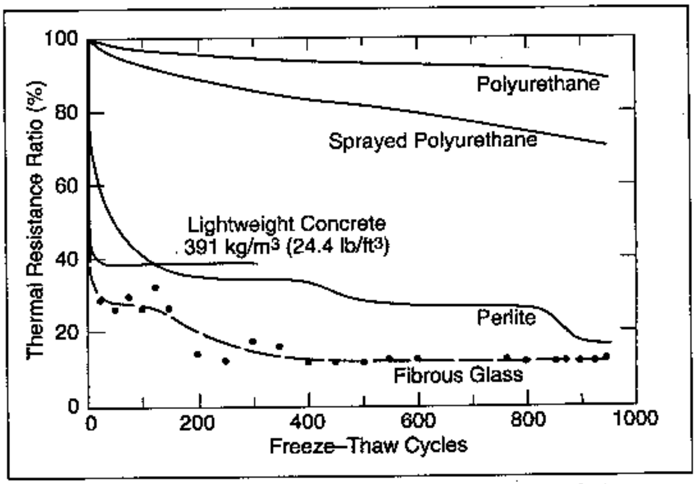

Figure 11. TRR-freeze-thaw cycle relationships for the five insulations shown in Figure 10.

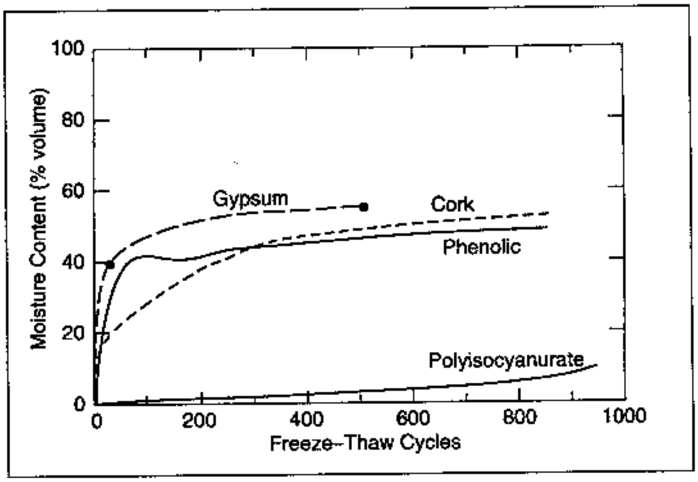

Figure 12. Moisture content-freeze-thaw cycle relationships for polyisocyanurate, phenolic, cork, and gypsum.

ratus (Figure 4) was not then available, the specimens were simply moved into and out of a cold room kept at about -18°C (0°F). They remained in the cold room for at least 5 hours per cycle, often longer. They were thawed in warm water for at least 5 hours per cycle, often longer. Unlike all other specimens that were frozen and thawed in a vertical position, as shown in Figure 6, these were kept horizontal with padded bricks used to hold them underwater during the thawing portion of each cycle. This water was removed prior to freezing.

Moisture contents were determined by oven drying successive specimens after one, five, 10, 20, 25, and 38 freeze-thaw cycles. Results are shown in Figure 14. These cellular glass specimens became wet faster than those discussed previously. Their 80 percent TRR moisture content of 3 percent by volume was reached after only 5 freeze-thaw cycles. After 25 cycles, their moisture content and TRR were 67 percent by volume and 9 percent, respectively. Similar values for the previously discussed cellular glass specimens after 25 cycles were 24 percent by volume and 20 percent, respectively. A photograph of one of the supplemental cellular glass specimens after only 38 freeze-thaw cycles is shown in Figure 15.

These supplemental tests showed that after a few freeze-thaw cycles, cellular glass insulation loses a significant amount of its insulating ability and is deteriorated. A control specimen of cellular glass kept submerged all during these supplemental tests had a moisture content of only 2.4 percent by volume after more than 90 days of soaking in room temperature water.

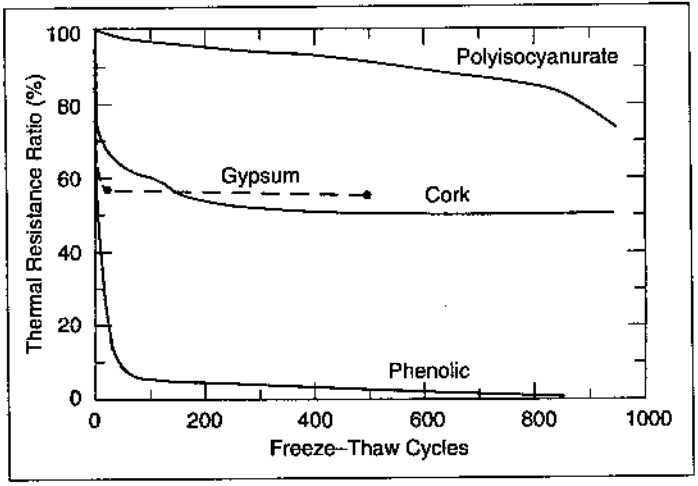

Figure 13. TRR-freeze-thaw cycle relationships for the four insulations shown in Figure 12.

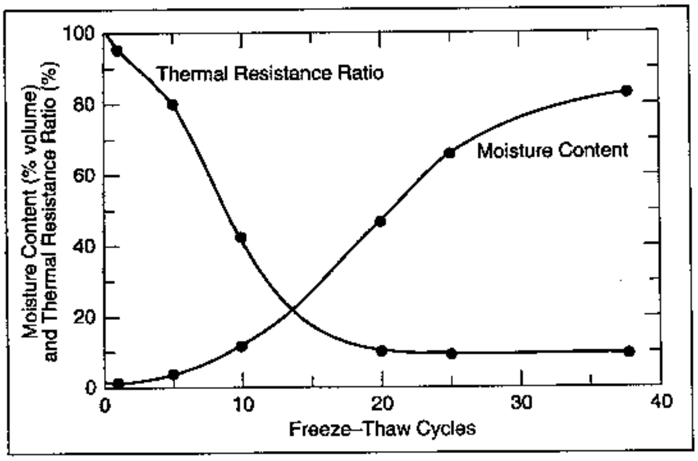

Figure 14. Supplemental results for cellular glass.

CONCLUSIONS

Table 5 summarizes test results similar to the way Table 1 summarizes the results of prior CRREL tests that subjected most of these materials to a sustained one-way vapor drive. The TRR of the first eight materials listed in Table 5 dropped to 80 percent in less than 25 cycles. The curves in Figures 9, 11, and 13 suggest that in almost all cases, their 80 percent TRR was reached in less than five cycles, but because the authors took their first measurement at 25 cycles, this number is shown in Table 5. Cellular glass is in this group.

It takes many more freeze-thaw cycles to wet expanded bead polystyrene, but freeze-thaw cycling does deteriorate that material.

Polyurethane, sprayed polyurethane, polyisocyanurate, and extruded polystyrene are even more resistant to freeze-thaw deterioration. As shown in Table 5, their TRRs remained above 80 percent even after 400 freeze-thaw cycles.

When subjected to freeze-thaw cycles in the presence of moisture, most insulations become quite wet, which causes them to lose much of their insulating ability. After a few hundred freeze-thaw cycles, phenolic, cellular glass, fibrous glass, and fiberboard lost more than three-quarters of their insulating ability. Lightweight concrete and perlite lost about two-thirds, cork and gypsum lost about one-half, and expanded bead polystyrene lost about one-third. Polyurethane, polyisocyanurate, sprayed polyurethane, and extruded polystyrene were quite resistant to freeze-thaw deterioration, losing only 6 to 18 percent of their insulating ability after 400 cycles.

With one exception, specimens that were slow to wet when subjected to sustained one-way vapor drive were also slow to wet when subjected to freeze-thaw cycles in the presence of moisture. The exception was cellular glass. It is quite resistant to wetting until moisture on and in it freezes. Then it breaks down rapidly.

Only extruded polystyrene insulation is considered suitable for use above protected membranes where vapor drive and freeze-thaw cycles occur in an often wet environment. Because moisture resistance also increases as the thickness of an insulation increases, insulation used in a potentially wet environment should be as thick as possible.

Figure 15. Supplemental cellular glass specimen that broke apart at 38 freeze-thaw cycles. The coin is a dime.

Insulation	Cycles to 80% TRR	400-cycle TRR (%)
Phenolic	<25	4
Cellular glass	<25	9
Fibrous glass	<25	13
Fiberboard	<25	22
Perlite	<25	33
Lightweight concrete	<25	39
Cork	<25	52
Gypsum	<25	55
†Expanded bead polystyrene:		
A	200	65
B*	175	63
C	180	60
D*	220	66
E*	320	76
Sprayed polyurethane	600	85
Polyisocyanurate	890	94
Polyurethane	>948	94
†Extruded polystyrene:		
A	500	84
B‡	>948	92
C	850	89
D‡	630	87
D*	>948	94

*These specimens were about 51 mm (2 inches) thick. All others were about 25 mm (1 inch) thick. See Table 4 for actual thicknesses.

†The density of the expanded and extruded polystyrenes varied from 14 kg/m³ (0.9 lb/ft³) to 36 kg/m³ (2.2 lb/ft³). See Table 4.

‡With surface skins cut away.

Table 5. Freeze-thaw cycles to reach 80 percent TRR and TRR after 400 cycles.

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