The Effects of Mechanical Damage to Roof Insulation

By Jim D. Koontz and Vickie Crenshaw

Keywords

Thermal resistance, tensile strength, thickness, density, compressive strength, perpendicular tensile strength, foot traffic, dynamic impact loading, EPDM, polystyrene, polyisocyanurate, wood fiber, TPO.

Abstract

Mechanical damage to roof insulation in single-ply roof assemblies can occur as the result of multiple factors. Two of these factors include foot traffic and impact from hail. As a result of mechanical damage to roof insulation, a roof system's overall physical performance properties may be compromised. Debates continue about the extent of physical property loss.

Since the energy crisis of the early 1970s, building codes have required construction of buildings with additional insulation to provide increased thermal resistance resulting in energy savings. There is an expectation that roof insulation will retain sufficient physical and thermal properties throughout the anticipated life of a roof system to prevent damage to itself, the membrane and a loss of insulating value. The purpose of this study is to examine the effects of mechanical damage to roof insulation.

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Background

Resistance to damage from foot traffic and impact has long been recognized as a desirable attribute of roof insulation. Early researchers within the roofing industry were aware of the necessity for adequate physical properties of roof insulation. In 1966, Miles Jacoby discussed the compression of insulation when exposed to foot traffic and the result of loading "plastic" insulation beyond the strength of its cells, which resulted in permanent collapse and loss of thickness. Jacoby also discussed the effect of hail impact and a roof assembly's ability to absorb impact energy. [1]

Research performed by Richard Fricklas in 1977 recognized the critical value of adequate compressive strength to prevent mechanical breakdown of both the insulation and membrane. [2] In 1979, Donald Brotherson referred to the "toughness" of insulation to get safely through the installation operation and indicated that an insulation's resistance to impact is needed throughout a roof system's service life. [3]

Associated with polyisocyanurate insulation have been issues of facer sheet delamination. Jim Koontz observed in 1986 that fully adhered single-ply assemblies could suffer facer sheet delamination during extreme hail events. [4]

Facer sheet delamination and its relationship to compressive strength have been subjects of manufacturers' ongoing research. John Geary concluded that reducing foot traffic over fully-adhered applications during installation and subsequent to roof completion was desirable. [5]

Once insulation has been crushed by either foot traffic or hail impact, a concern is then raised as to the significance of this damage. Some slight crushing of insulation is inevitable during roof system installation and has been recognized by Thomas Lee Smith. [6] Concern with the loss of R-value in polyisocyanurate insulation has historically been compared between newly manufactured insulation vs. aged insulation. Loss of R-value associated with mechanical damage has not been assessed. In 2001, Scott Baxter questioned the loss of R-value and reduction in wind uplift properties as a result of crushed polyisocyanurate insulation bringing about facer sheet delamination. [7]

Maintenance of adequate tensile strength of a roof assembly measured perpendicular to its surface can be important to wind uplift resistance. Joseph Malpezzi stated that perpendicular tensile values of 500 pounds per square foot (lbf/ft^2) (23,940 Pa), for fully adhered systems provide adequate performance for fully adhered systems. Perpendicular tensile strength, however, is not a critical factor for mechanically attached or ballasted single-ply systems. [8]

Prior foot traffic test methods have been limited in their abilities to provide useful data. One cyclical foot traffic test used by Joseph Malpezzi utilizes a 285-pound (1267.7 N) load distributed over a 6-inch (15.24 cm) diameter or 28.27-square-inch (182.39 cm^2) plate, which contacts the top of the roof insulation. After 200 cycles, a majority of the insulation tested had minor to no damage. [8] This particular foot traffic test produces a loading of approximately 10 lbf/in^2 (68.94 kPa), which is well below the compressive strength listed in the marketing literature of most insulation manufacturers.

Factory Mutual Research Corp. (FMRC) utilizes a 9-inch (22.86 cm) square plate with a 200-pound (889.6 N) load to test roof assemblies. The roof assembly is subjected to four cycles and then examined for damage. [9]

The Polyisocyanurate Insulation Manufacturer's Association (PIMA) recognizes compressive strength as an important quality of roof insulation. In the June 2001 issue of *The Interface*, PIMA indicates polyisocyanurate products commonly have compressive strengths of 16 to 25 psi (110 to 172 kPa) when tested in accordance with ASTM C 165, "Test Method for Measuring Compressive Properties of Thermal Insulations". [10]

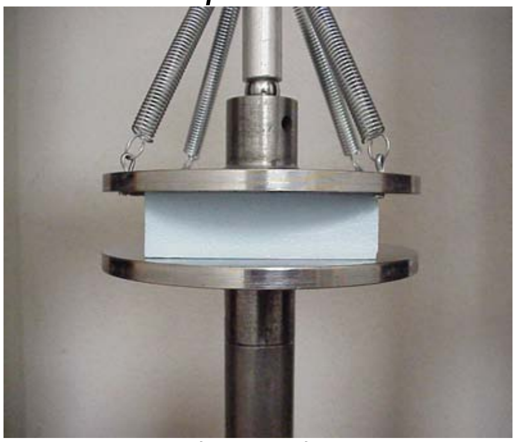
Research

Roof assemblies were constructed with three common types of roof insulation: 1-inch (2.54 cm) wood fiber, 1-inch (2.54 cm) extruded polystyrene and 1½-inch (3.81 cm) polyisocyanurate. The initial physical properties of the insulation were determined prior to incorporation into roof assemblies. These physical properties include thickness, density, compressive strength, perpendicular tensile strength and thermal resistance (TABLE A; *Photographs 1 and 2*).

TABLE A

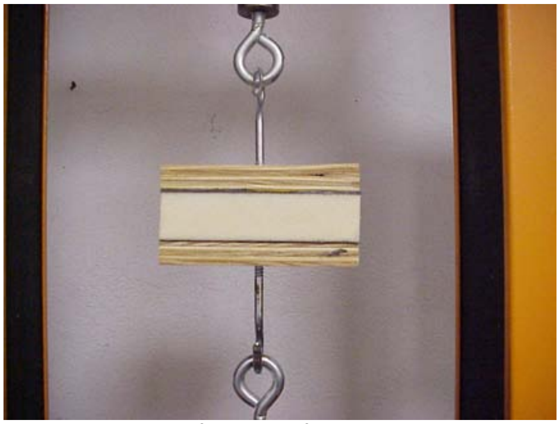
Insulation Type	**Thickness** Inches cm	**Density** lb/ft^3 kg/m^3	**Compressive Strength** lbf/in^2 kPa	**Perpendicular Tensile Strength** lbf/ft^2 Pa	**Thermal Resistance** Per 1" @ 75°F 2.54 cm @ 23.6°C
	ASTM C 303	**ASTM C 303**	**ASTM C 165**	**ASTM C 209**	**ASTM C 518**
Wood Fiber	1" 2.54 cm	16.51 lb/ft^3 264.49 kg/m^3	32.98 lbf/in^2 227.36 kPa	972 lbf/ft^2 46,539 Pa	2.5 °$Fhft^2$/Btu 0.44 m^2°K/W
Extruded Polystyrene	1" 2.54 cm	1.61 lb/ft^3 25.79 kg/m^3	29.90 lbf/in^2 206.13 kPa	---	5.2 °$Fhft^2$/Btu 0.92 m^2°K/W
Polyisocyanurate	1½" 3.81 cm	2.68 lb/ft^3 42.93 kg/m^3	25.04 lbf/in^2 172.63 kPa	1,336 lbf/ft^2 63,968 Pa	6.2 °$Fhft^2$/Btu 1.09 m^2°K/W

Compression Test



Photograph 1

Tensile Strength



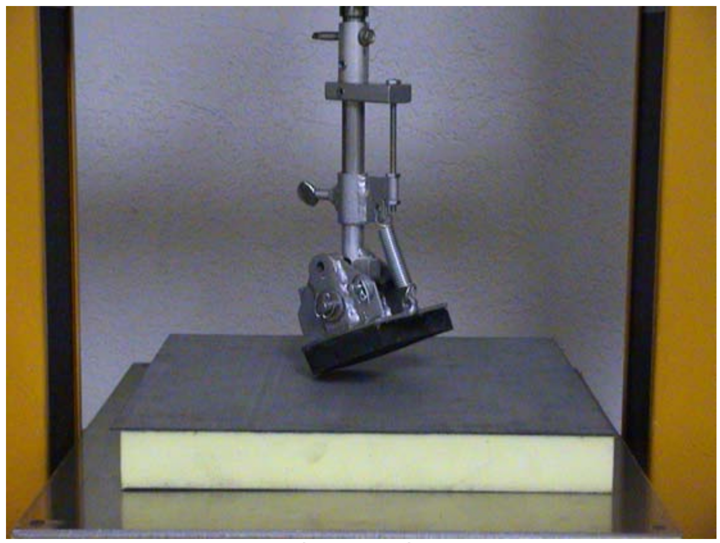
Photograph 2

Using a combination of single-ply membranes and insulations, roof assemblies were constructed utilizing fully adhered and mechanically attached configurations (TABLE B). The roof assemblies were subjected to two types of dynamic mechanical loads: simulated foot traffic and hail impact.

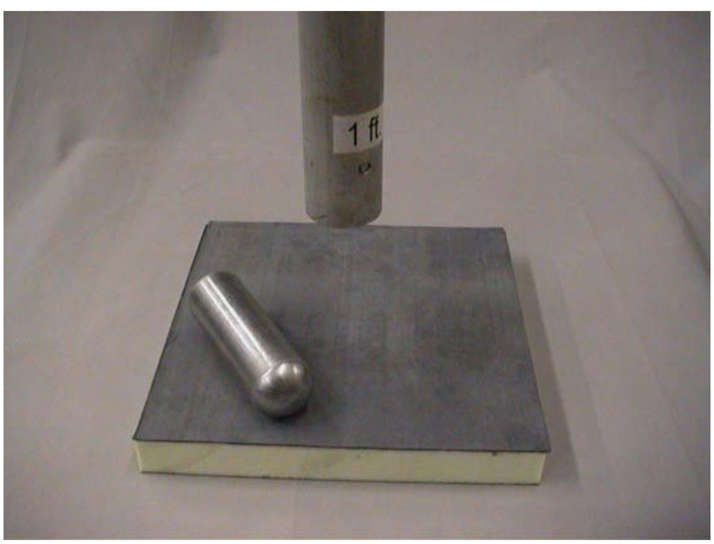
TABLE B

Membrane	Insulation	Attachment Method
Non-reinforced EPDM	Polyisocyanurate	Fully Adhered
Reinforced EPDM	Polyisocyanurate	Mechanically Attached
TPO	Polyisocyanurate	Mechanically Attached
Non-reinforced EPDM	Wood Fiber	Fully Adhered
TPO	Polystyrene	Mechanically Attached
PVC	Polystyrene	Mechanically Attached

The foot traffic procedure utilized a tensile machine fitted with a spring-loaded rotating platform. The heel of a size 10 work-boot was attached to the platform. The heel platform device was initially set at a 15-degree angle to the plane of the roof assembly (*Photograph 3*). A 25-pound (111.2 N) load was required to extend the spring and rotate the heel platform, producing an ultimate load of 200-pounds (889.6 N) applied at a rate of 40-inches (1,016.0 mm) per minute.



Photograph 3



Photograph 4

Dynamic impact loading was accomplished with a falling steel dart per ASTM D 3746, "Standard Test Method for Impact Resistance of Bituminous Roofing Systems". This test procedure involved impacting a target by dropping a 5-pound (2.27 kg), rounded, 2-inch (5.08 cm) steel dart. The dart was dropped from a height of 53 inches (135 cm), which produced impact energy of 22-foot-pounds (30 J) (*Photograph 4*). The kinetic energy generated was equivalent to impact from a 2-inch (5.08 cm) hail stone.[11]

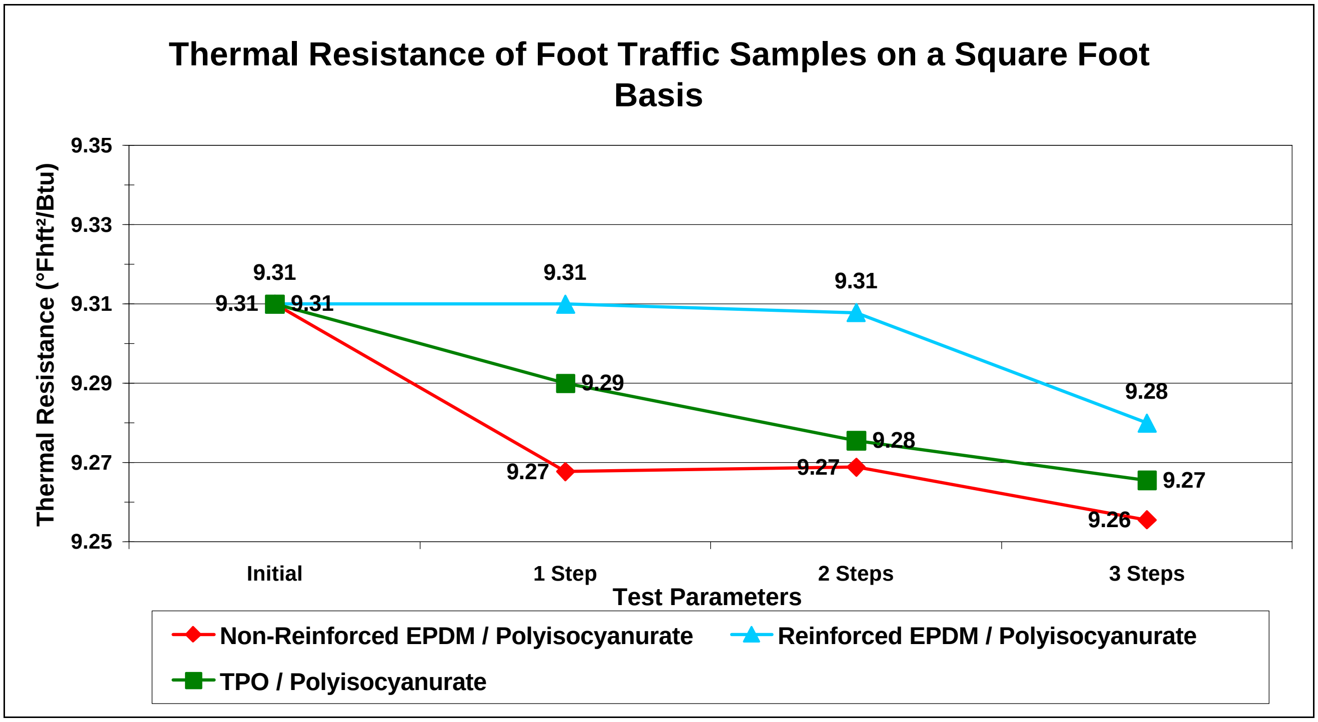
The ASTM D 3746 procedure is similar to tests used by Underwriters Laboratories Inc. and FMRC. Advantages of these procedures include relative ease of use, reproducibility and consistent impact energy. Research has indicated that similar indentations occur in insulation impacted with either a 2-inch (5.08 cm) falling steel dart or a 2-inch (5.08 cm) ice sphere fired from a hail gun.[4]

Numerous roof assemblies were prepared for dynamic load testing. Incremental measurements of the changes in the thermal and perpendicular tensile strength properties of the insulation/roof assemblies were recorded.

Foot Traffic Loading

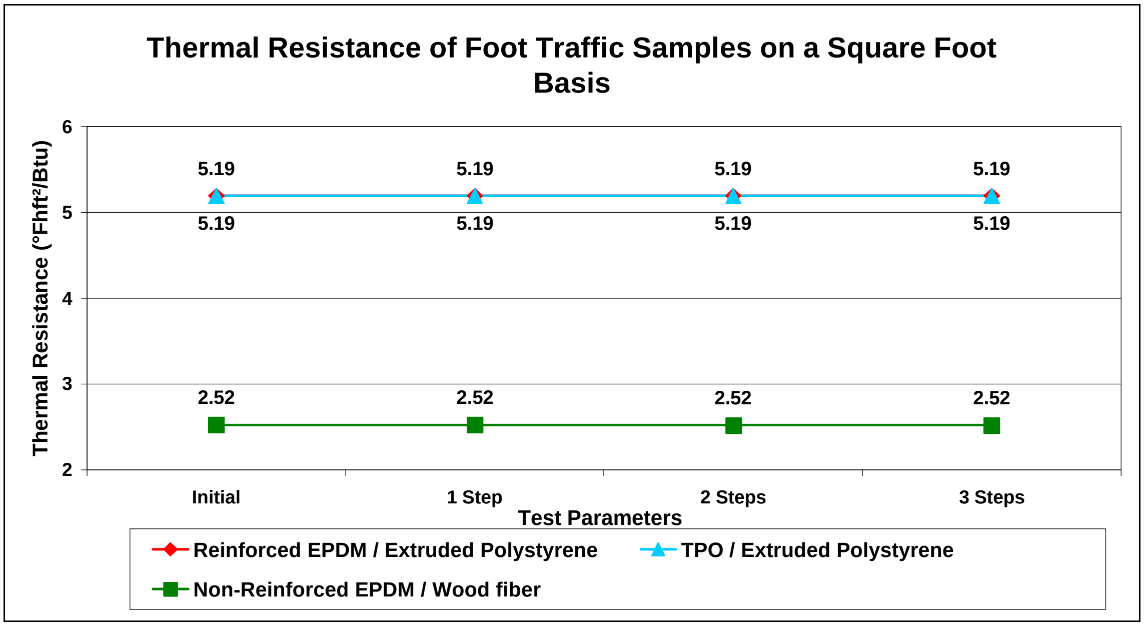
Following incremental foot traffic loading, measurements of the thermal values were taken at one, two and three steps for each of the six roof assemblies. Slight decreases in thermal values occur with polyisocyanurate insulated assemblies (TABLE C). Non-reinforced EPDM adhered over 1-1/2 in (3.81 cm) polyisocyanurate had a decrease in thermal R-value from 9.31 to 9.26°Fhft^2/Btu (1.64 to 1.63 m^2°K/W) on a per-square-foot (.093 m^2) basis. Reinforced EPDM mechanically attached over polyisocyanurate had a reduction of thermal value from 9.31 to 9.28°Fhft^2/Btu (1.64 to 1.63 m^2°K/W). Reinforced TPO over polyisocyanurate experienced a drop from 9.31 to 9.27°Fhft^2/Btu (1.64 to 1.63 m^2°K/W).

TABLE C



Assemblies constructed with polystyrene and wood fiber insulation generally retained thermal values after three cycles of foot traffic loading (TABLE D).

TABLE D



Three roof assemblies--reinforced EPDM mechanically attached over polystyrene; non-reinforced EPDM adhered to wood fiber; and reinforced EPDM mechanically attached over polyisocyanurate--were further loaded to five, ten and fifteen step increments per foot. After fifteen steps, the polyisocyanurate covered with mechanically attached, reinforced EPDM experienced a drop in thermal value from 9.31 to 9.18°Fhft^2/Btu (1.64 to 1.62 m^2°K/W) (TABLE E). The wood fiber and polystyrene insulated assemblies continued to retain thermal value (TABLE F).

TABLE E

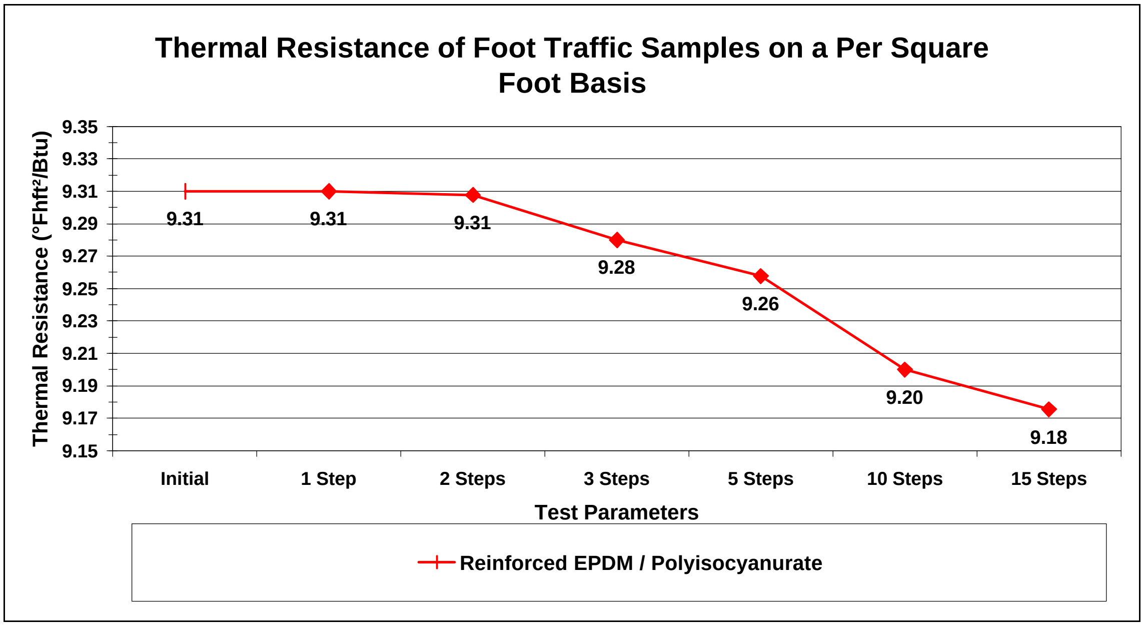
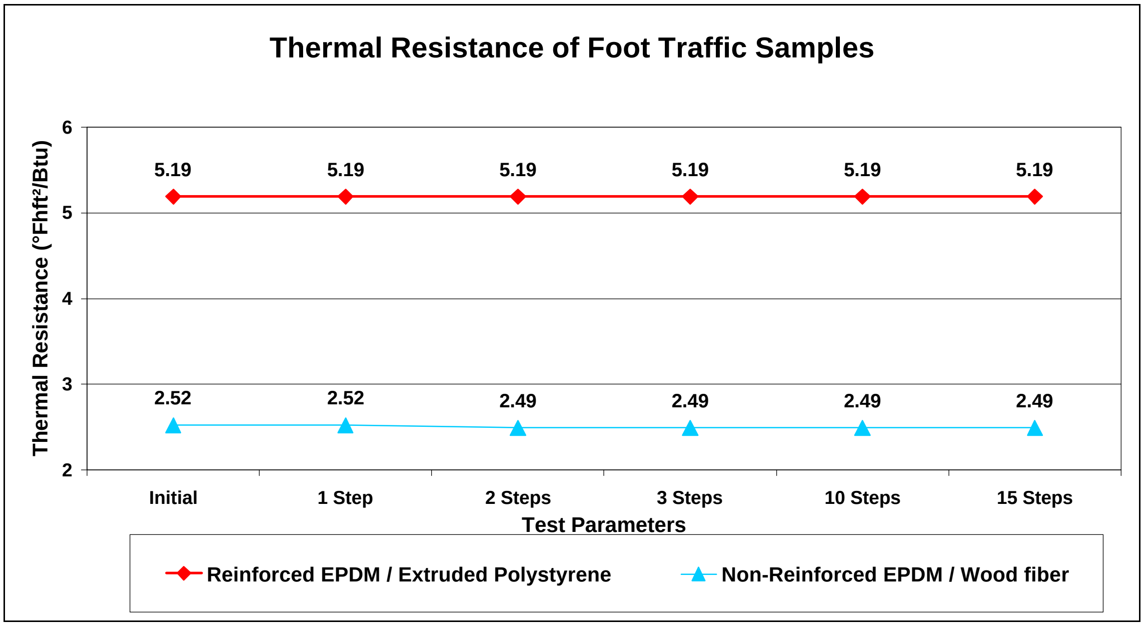
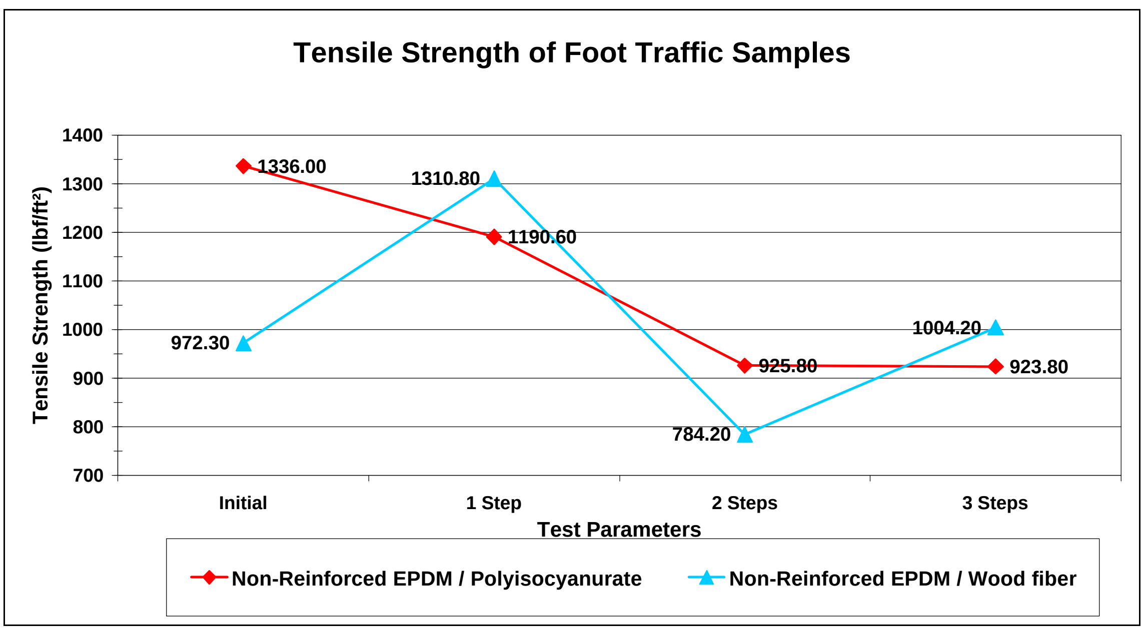


TABLE F



Two assemblies were constructed with non-reinforced EPDM adhered to wood fiber and polyisocyanurate. Following each of the three step loadings, a test for perpendicular tensile strength was performed. The polyisocyanurate systems experienced a decrease in perpendicular tensile strength from 1,336.0 lbf/ft^2 to 923.8 lbf/ft^2 (63,968 to 44,232 Pa). The results of the wood fiber assemblies were somewhat random but generally stable, possibly as a result of variations in the wood fiber product (TABLE G).

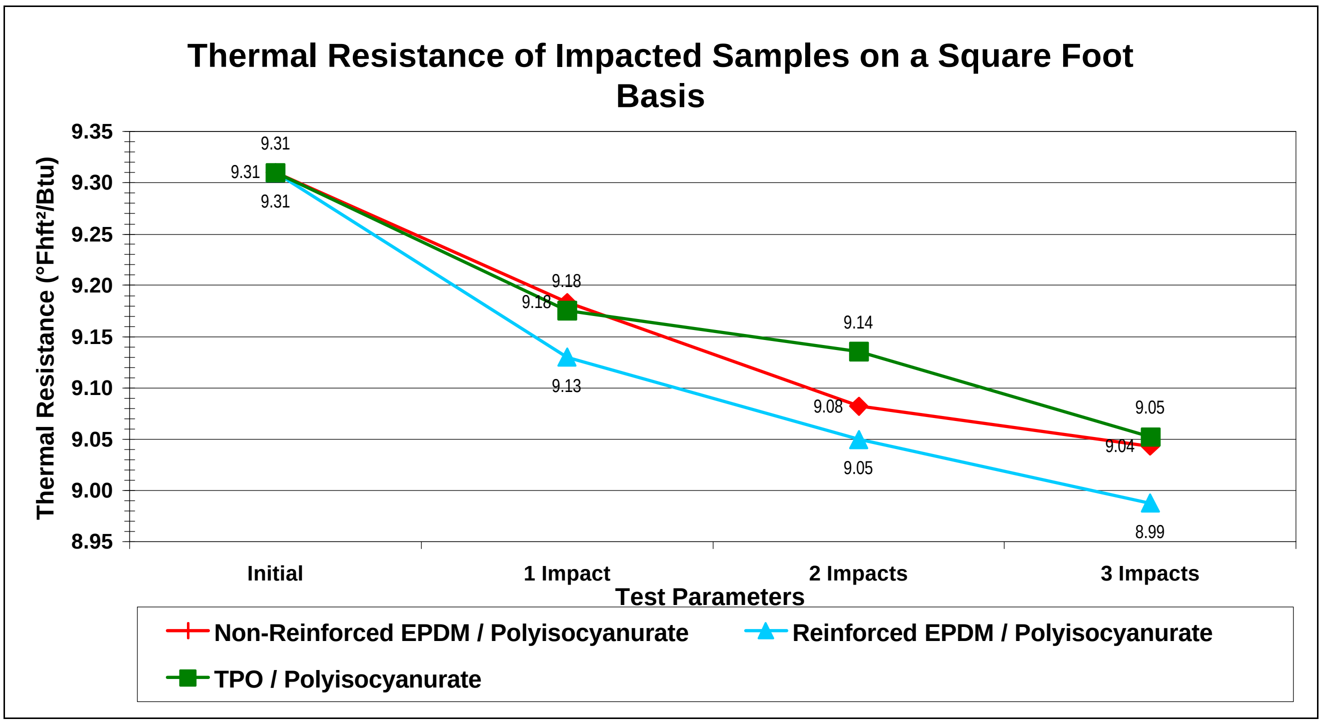
TABLE G



Impact Loading ASTM 3746

Following impact loading, incremental measurements of the thermal values were taken at one, two and three impacts for each of the six roof assemblies. Reinforced TPO over polyisocyanurate experienced a decrease in thermal value from 9.31 to 9.05°Fhft^2/Btu (1.64 to 1.59 m^2°K/W). Non-reinforced EPDM adhered over 1½inch (3.81 cm) polyisocyanurate decreased from 9.31 to 9.04°Fhft^2/Btu (1.64 to 1.59 m^2°K/W) on a per-square-foot basis. Polyisocyanurate insulation covered with a mechanically attached reinforced EPDM assembly decreased from 9.31 to 8.99°Fhft^2/Btu (1.64 to 1.58 m^2°K/W) (TABLE H).

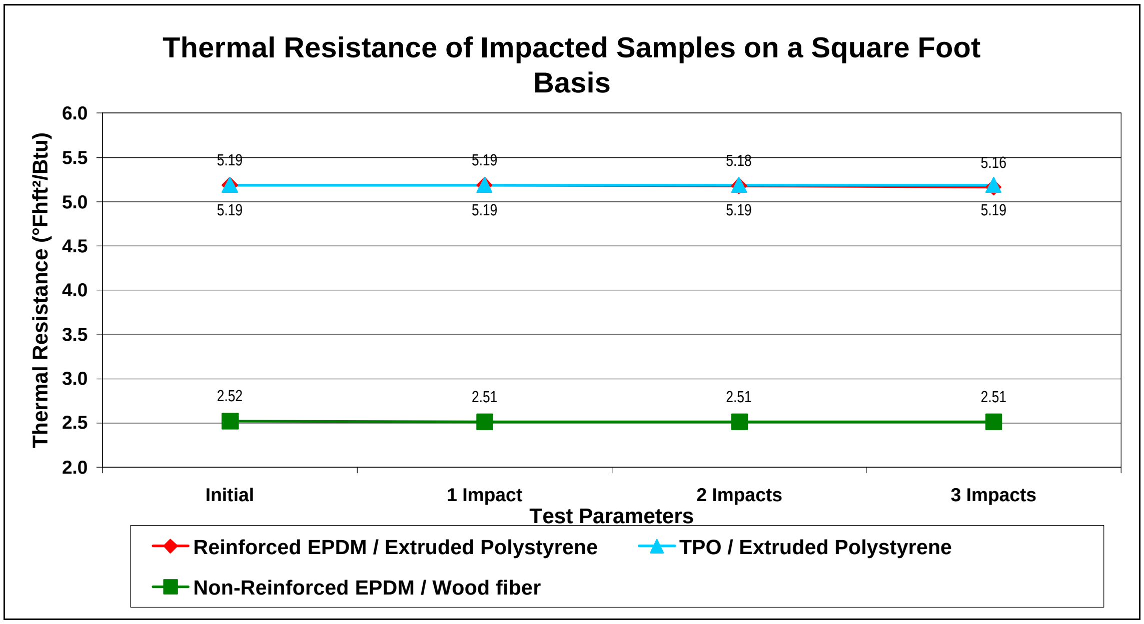
TABLE H



Assemblies constructed with wood fiber and polystyrene insulation generally maintained thermal values after three impacts (TABLE I).

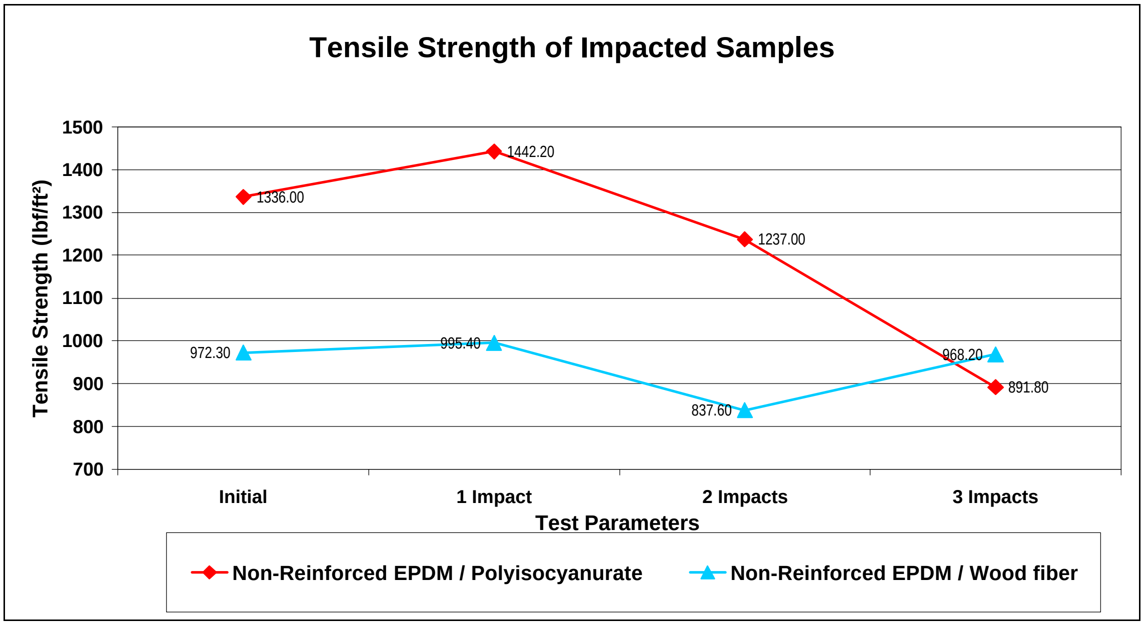
The precision and bias factors within tables listing thermal resistance are addressed within ASTM C 518 "Test Method for Steady-State Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus". Some factors affecting the results can be variations in insulation manufacturing, test apparatus, test conditions and sample preparation techniques.

TABLE I



Two assemblies were constructed with non-reinforced EPDM adhered to wood fiber and polyisocyanurate. Following each of the three impacts, perpendicular tensile strength tests were conducted. The roof assemblies with polyisocyanurate insulation experienced a decrease in perpendicular tensile strength from 1,336.0 lbf/ft^2 to 891.8 lbf/ft^2 (63,698 to 42,699 Pa). Wood fiber insulated assemblies were generally stable and retained perpendicular tensile strength (TABLE J).

TABLE J



Conclusions

- Higher compressive strength insulations provide greater resistance to mechanical loading.

- Wood fiber and polystyrene insulation can provide fairly stable physical properties following mechanical loading.

- Following mechanical loading, decreases in thermal properties and perpendicular tensile strength of polyisocyanurate insulation are greater than other types of insulation tested. Under the tests conducted, the reductions of these values are relatively minor and would not appear to affect the overall performance of a roof system. Clearly, impact loading at a greater rate and magnitude may compromise the performance of a roof system.

- Insulation resistance to mechanical damage should be considered by building code organizations. Several code bodies now include impact resistance as a part of the physical requirements of roof membranes. [12]

- Mechanical loading procedures were performed on insulation not covered with a roof membrane. The presence of a roof membrane enhances the roof insulation's resistance to mechanical damage. Foot traffic over unprotected insulation should be kept to a minimum. [13]

- The presence of reinforcement within a single-ply membrane provides some additional degree of foot traffic and impact resistance. Systems constructed with non-reinforced EPDM experienced a greater decrease in insulation thermal values than reinforced single-ply systems.

Discussions

Walkway pads can help reduce foot traffic damage; however, the reality is that workers and maintenance personnel walk randomly across roof surfaces.

All roof insulation should allow for some degree of loading from both foot traffic and hail impact. These desirable performance properties have long been recognized by researchers in the roofing industry. [14] Foot traffic loading during periodic maintenance of roof systems and mechanical units is expected. When a substantial degree of foot traffic is anticipated, architects, engineers, contractors and owners should consider the use of either walkway pads or substrates with higher density.

Within the composite of a roof assembly, portions of the insulation matrix can provide a high degree of thermal resistance. If the primary insulating element lacks sufficient compressive strength and resistance to mechanical damage, an overlay of a higher density product such as wood fiber or gypsum board, may provide a buffer from mechanical damage.

Impact loading is a performance issue. Manufacturers are beginning to provide warranties for single-ply membranes to resist some degree of impact energy. Warranty Excerpt: *"… with this special limited "Hail Damage Warranty Rider", any damage to the 100 mil. C-EPDM, from hail will be repaired free of cost……."* [15]

Retention of thermal resistance value is not covered in most roof system warranties. A few insulation manufacturers, however, are guaranteeing the retention of thermal values exclusive of mechanical damage. Warranty Excerpt: *"… warrants that for a period of fifteen years the insulation's actual thermal resistance for all the products listed below will not vary by more than ten percent from its published R-value."* [16]

In special remembrance of Hal Roberts, P.E., R-Max, researcher with PIMA.
With thanks to Gerald B. Curtis, independent roof consultant.

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