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Damage to Thermal Insulation Foams in Low-Slope Roof Systems Caused by Simulated Foot Traffic

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ABSTRACT: The results indicated that commonly used foam plastic roof insulations will be damaged if exposed to foot traffic, and that their protection with fibrous overlay boards as recommended by roofing contractor associations [1,2] continues to be good roofing practice. The results also indicated that finished roof surfaces will be damaged if exposed to frequent roof traffic and that surface protection of the membrane is good roofing practice.

1. INTRODUCTION

PLASTIC FOAM INSULATIONS are widely used to thermally insulate low- slope roofs in North America. To be thermally efficient, plastic foam insulations are necessarily low density materials, typically less than 50 kg/m^3. Without adequate mechanical protection, these low density plastic foam insulations can be damaged during and after low-slope roof construction. This study quantifies the depth of permanent indentation that might be expected to occur with plastic foam insulations when they are exposed to repeated foot traffic on roofs.

This study assessed the damage caused to plastic foam insulation by simulating repeated foot traffic over specimens of low-slope roof assemblies. A 45.4 kg load was applied to the heel of a work boot positioned at different angles (15° and 30°) at a frequency of 1 Hz. Three different plastic foam insulation

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materials (polyisocyanurate, phenolic and expanded polystyrene) were tested. This study included unprotected insulation and insulation protected with a reinforced PVC membrane, with a modified bituminous membrane, and with a reinforced PVC membrane on top of wood fibreboard.

The depth of indentation (mm) and rate of indentation (mm/s) varied as a function of the material, the angle of the heel, the number of cycles of compression, and the presence and type of protection over the insulation.

Inspection of tested specimens showed that much of the insulation surface damage is not visible when a roof membrane is in place. There was a difference in performance of the protective cover. Insulation specimens underneath all roof membranes were damaged, except for those under the PVC-fibreboard combination (only the membrane and fibreboard were indented). Wood fibreboard or a similar protective board can be placed immediately after the insulation is laid, and will protect roof insulations from damage by foot traffic.

2. EXPERIMENTAL METHODS

2.1 Specimens and Materials

Three types of commercially available plastic foam insulation boards were tested: polyisocyanurate, phenolic and expanded polystyrene. The polyisocyanurate was 76.2 mm thick and had an apparent density of 33.2 kg/m^3 including fibrous felt facers (about 1 mm thick). The phenolic insulation sample was 76.2 mm thick and had an apparent density of 44.3 kg/m^3 including thin glass fibre mat facers (less than 0.1 mm thick). The expanded polystyrene sample was 50.8 mm thick and had a density of 23.0 kg/m^3. All insulation boards were cut into 305 mm $\times$ 305 mm square specimens.

Squares (305 mm $\times$ 305 mm) of polyester-reinforced PVC membrane (1.2 mm thick), two-ply modified bitumen membrane, and 12.5 mm thick wood fibreboard were used to protect the insulation. The PVC membrane and wood fibreboard-PVC assembly were taped to the edges of insulation specimens to allow movement similar to that in a mechanically attached PVC roof. The modified bitumen was torched onto the insulation to resemble a fully adhered roof system.

2.2 Static Testing

The heel of a work boot was adhered to an angle adapter (a wooden prism) with hot melt polypropylene adhesive. The adapter was adhered to an upper metal plate that was then attached to the load cell of a universal testing machine (Instron model 4502). Insulation specimens were fixed onto a lower metal plate, which was connected to the lower grip of the machine (Figure

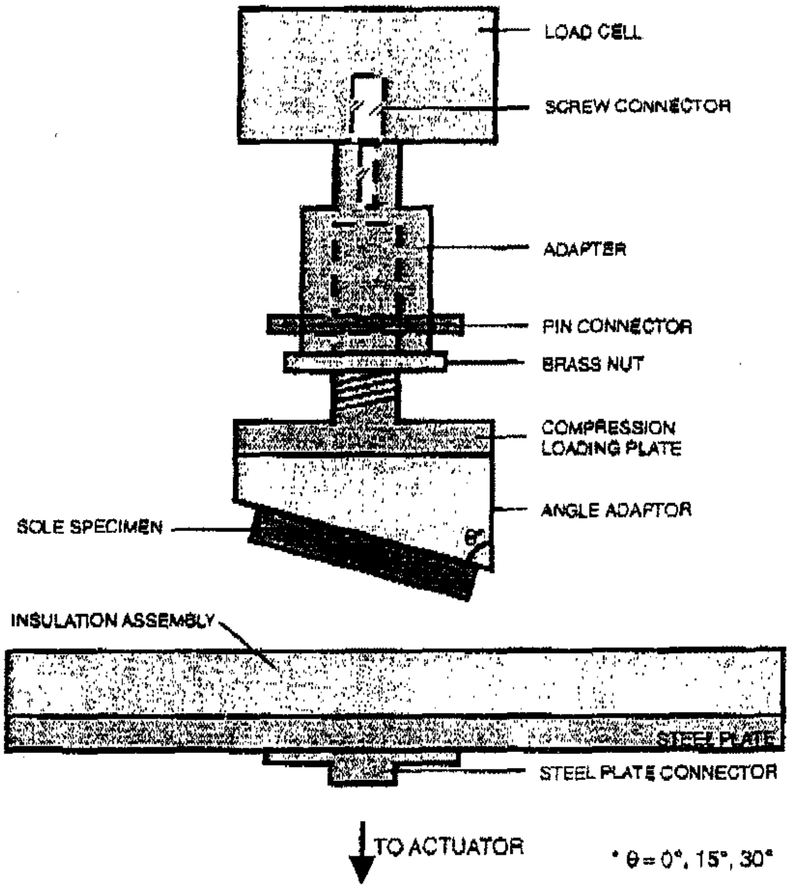

FIGURE 1. Experimental setup for simulation of foot traffic on roof assemblies.

1). The insulation specimens were compressed at a constant crosshead speed of 10 mm/min. The force and displacement as a function of time were recorded.

2.3 Dynamic Testing

The experimental set up was the same as that described in Section 2.2 except that a universal testing machine capable of high frequency cyclic loading was used (MTS model 810). A haver-sine (half of a full sine function) compression loading function with a magnitude of 45.4 kg was applied at a frequency of 1 Hz; i.e., the specimen was subjected to a cyclic compression loading between 0 and 45.4 kg every second. The load of 45.4 kg, which represents half the weight of a 90.8 kg (200 lb) person, was chosen to approximate the average force acting on one foot when he walks. Since the time between two steps is about 1.5 s during a casual walk, the frequency of 1 Hz was selected for convenience in this simulation.

Displacements of the crosshead at the peak of each loading and unloading cycle were measured. When the load reached 45.4 kg, the displacement corresponded to the instantaneous indentation of the specimen, d_i. At the end of each unloading cycle, the load was 0 kg and the displacement of the crosshead represented the permanent indentation of the specimen, d_p. The difference $(d_i - d_p)$ represents the relaxation of the specimen in each half cycle or 0.5 s.

Permanent indentations were measured on the tested specimens (insulation with or without protective coverings). When protective coverings were used, some of the permanent indentation occurred in the covering.

3. RESULTS

3.1 Static Tests

The force-displacement curves of the insulation samples under compression by the heel positioned at different angles are shown in Figures 2, 3, and 4. For the polyisocyanurate specimens, the force increased almost linearly with displacement until a sudden drop in load occurred, which corresponded to the fracture of the facer (Figure 2). Facer fracture occurred when the permanent indentation reached approximately 12 mm regardless of the force applied. The glass mat faced phenolic specimens had the highest resistance to compression; these specimens were brittle as indicated by the numerous load drops on the force-displacement curves (Figure 3). The unfaced expanded polystyrene specimens displayed the most linear force-displacement curve at all loading angles (Figure 4).

3.2 Dynamic Tests

The results of the cyclic compression tests are summarized in Tables 1–5 and Figures 5–8. The curves generally consisted of two parts representing two different rates of indentation. At the beginning of the test (e.g., less than 1,000 cycles), the rate of indentation was higher. It slowed down and approached a limiting value toward the end of the test (e.g., more than 2,000 cycles).

The permanent indentation and rate of indentation varied as a function of the material, the angle of the heel, the number of cycles of compression and the presence and type of protection over the insulation.

The amounts and rates of permanent indentations expressed in mm and mm/s were generally similar for all three insulations, but varied when expressed as a percent of material thickness; e.g., when tested with the heel positioned at 15° to the unprotected specimen, the polyisocyanurate insulation reached an indentation of 10% (7.6 mm) of its thickness after 900

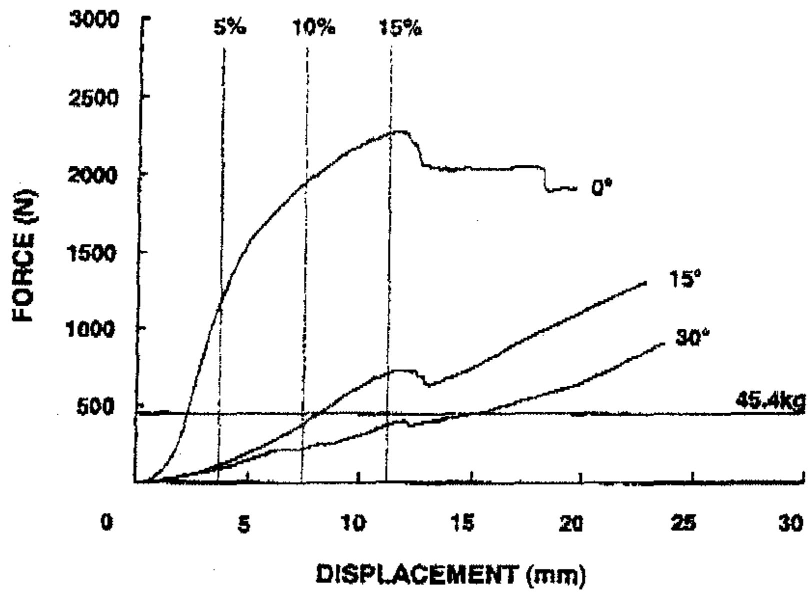

FIGURE 2. Force-displacement curves for static compression test of polyisocyanurate insulation with loading head positioned at different angles.

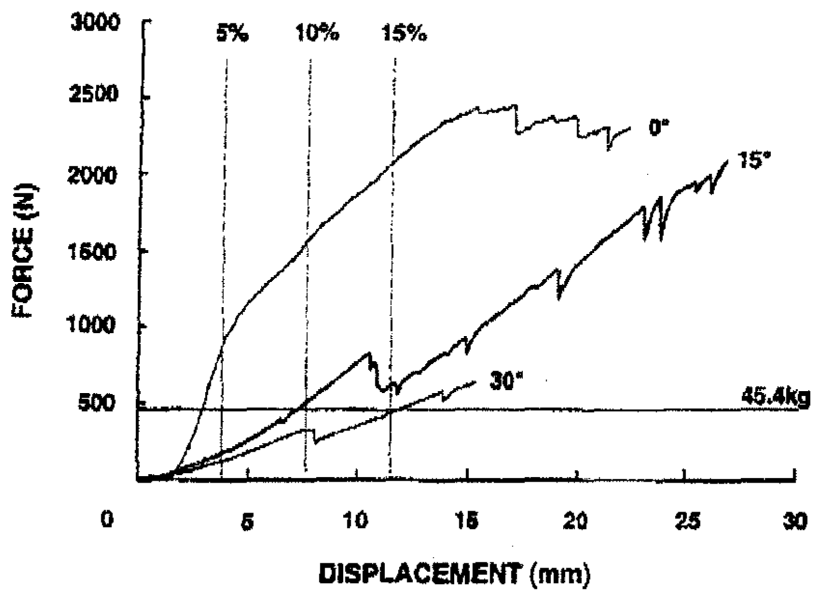

FIGURE 3. Force-displacement curves for static compression test of phenolic insulation with loading head positioned at different angles.

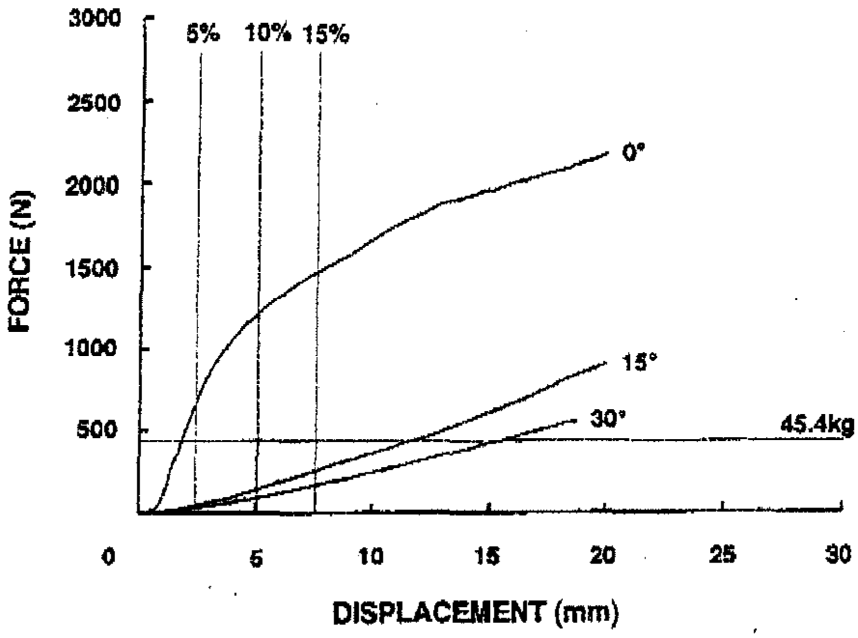

FIGURE 4. Force-displacement curves for static compression test of expanded polystyrene insulation with loading head positioned at different angles

cycles and the phenolic insulation was indented 10% (7.6 mm) after 140 cycles. The expanded polystyrene insulation was indented 10% (5.1 mm) in the first cycle, however, it reached an indentation of 7.6 mm (15%) after 540 cycles.

Both the permanent indentation and rate of indentation were reduced with protection (Table 1).

The effect of fibreboard overlay alone, without the PVC membrane on top, was found to be only slightly different than the fibreboard-PVC combination. At a 30° loading angle and phenolic insulation, the indentation after 2,000 cy-

Table 1. Permanent indentations in protected and unprotected plastic foam insulations.

Insulation	Heel Angle (%)	Permanent Indentation of Specimens after 2,000 Loading Cycles (mm)			
		Unprotected	PVC	Mod. Bit.	Fibreboard-PVC
Polyisocyanurate	15	10.01	5.03	2.16	2.80
	30	14.62	9.89	5.11	3.94
Phenolic	15	9.71	6.45	4.03	2.72
	30	13.81	9.54	4.24	4.18
Expanded polystyrene	15	9.40	7.87	4.26	3.72
	30	15.71	10.70	4.68	4.03

Table 2. Cyclic compression test results on (unprotected) plastic foam insulations.

Sample	Angle (%)	Total No. of Cycles	Number of Cycles Required to Reach a Permanent Indentation of: 4 mm	8 mm	12 mm	16 mm	Permanent Indentation at N = 200 (mm)	(%)
Polyisocyanurate	15	4000	<100	1060	>4000		10.01	13.1
Phenolic	15	4000	<100	250	>4000		9.71	12.7
Expanded polystyrene	15	7680	<60	820	>7680		9.40	18.5
Polyisocyanurate	30	2200		<50	120	>2200	14.62	19.2
Phenolic	30	2200		<50	130	<2200	13.81	18.1
Expanded polystyrene	30	9000		<50	430	3150	15.71	30.9

Table 3. Cyclic compression test results on plastic foam insulations underneath a PVC roofing membrane..

Sample	Angle (%)	Total No. of Cycles	Number of Cycles Required to Reach a Permanent Indentation of: 4 mm	8 mm	12 mm	16 mm	Permanent Indentation at N = 200 (mm)	(%)
Polyisocyanurate	15	6200	<50	>6200			5.03	6.6
Phenolic	15	7000	<50	>7000			6.45	8.5
Expanded polystyrene	15	5000	<100	2380	>5000		7.87	15.5
Polyisocyanurate	30	9480	<60	360	>9480		9.89	13.0
Phenolic	30	6360	<90	240	>6360		9.54	12.5
Expanded polystyrene	30	7200	<60	380	>7200		10.70	21.1

Table 4. Cyclic compression test results on plastic foam insulations underneath a two-ply modified bitumen roofing membrane.

Sample	Angle (%)	Total No. of Cycles	Number of Cycles Required to Reach a Permanent Indentation of:				Permanent Indentation at $N = 200$	
			4 mm	8 mm	12 mm	16 mm	(mm)	(%)
Polyisocyanurate	15	8940	>8940				2.16	2.8
Phenolic	15	10020	1740	>10020			4.03	5.3
Expanded polystyrene	15	9000	920	>9000			4.26	8.4
Polyisocyanurate	30	8700	80	>8700			5.11	6.7
Phenolic	30	9000	1000	>9000			4.24	5.6
Expanded polystyrene	30	9180	430	>9180			4.68	9.2

Table 5. Cyclic compression test results on plastic foam insulations underneath a 12.5 mm wood fibreboard and a PVC roofing membrane.

Sample	Angle (%)	Total No. of Cycles	Number of Cycles Required to Reach a Permanent Indentation of:				Permanent Indentation at $N = 200$	
			4 mm	8 mm	12 mm	16 mm	(mm)	(%)
Polyisocyanurate	15	9300	>9300				2.80	3.7
Phenolic	15	8940	>8940				2.72	3.6
Expanded polystyrene	15	7200	4960	>7200			3.72	7.3
Polyisocyanurate	30	7200	>7200				3.94	5.2
Phenolic	30	7200	690	>7200			4.18	5.5
Expanded polystyrene	30	6300	1860	>6300			4.03	7.9

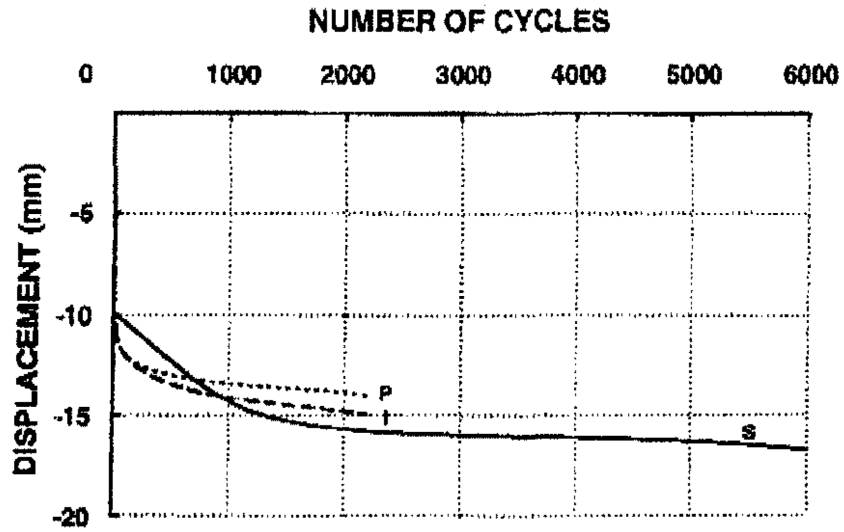

FIGURE 5. Permanent indentations of polyisocyanurate (I), phenolic (P) and expanded polystyrene insulation (S) specimens subjected to cyclic compression testing at 30°.

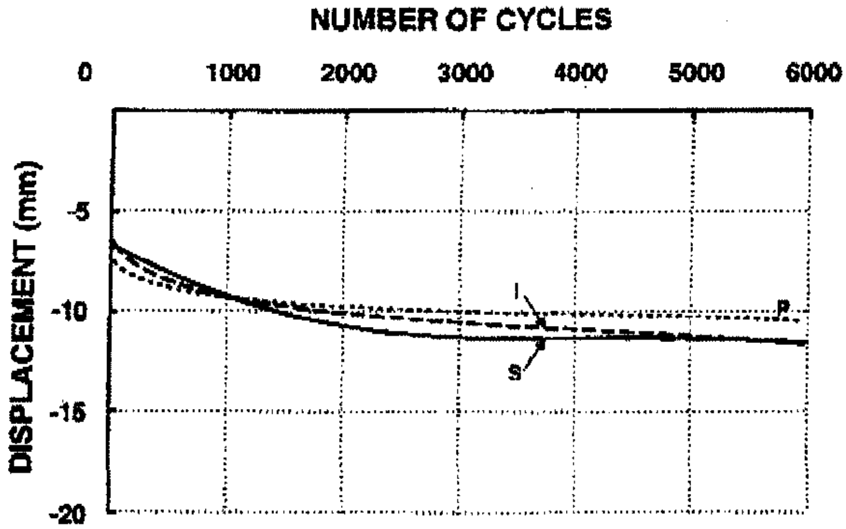

FIGURE 6. Permanent indentations of polyisocyanurate (I), phenolic (P) and expanded polystyrene insulation (S) specimens covered with a PVC membrane and subjected to cyclic compression testing at 30°.

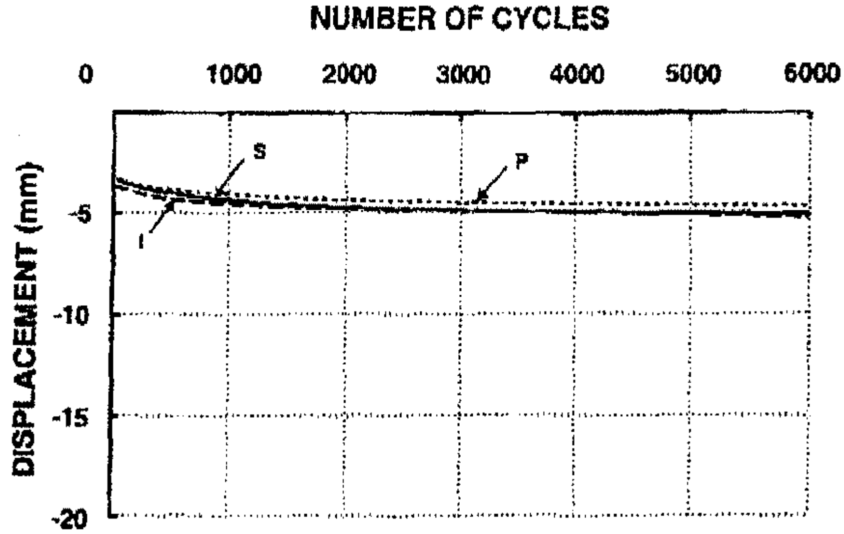

FIGURE 7. Permanent indentations of polyisocyanurate (I), phenolic (P) and expanded polystyrene insulation (S) specimens covered with a modified bituminous membrane and subjected to cyclic compression testing at 30°.

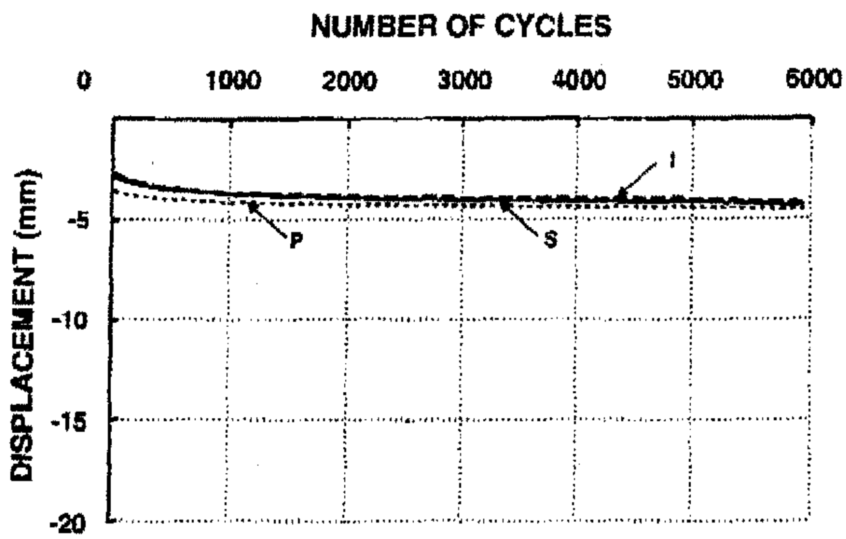

FIGURE 8. Permanent indentations of polyisocyanurate (I), phenolic (P) and expanded polystyrene insulation (S) specimens covered with 12.5 mm thick wood fibreboard plus a PVC membrane and subjected to cyclic compression testing at 30°.

cles was 4.62 mm with fibreboard and it was 4.18 mm with fibreboard plus the PVC membrane.

4. DISCUSSION

Photographs of workmen walking over roofs indicate that a 30° angle between a boot and the roof surface is typical. All test specimens (insulation with or without coverings) were permanently indented in the first cycle of 45.4 kg loading on a work boot at a 30° angle.

The pressure on a surface (load per area) rather than the load per se appears to be the key factor in insulation damage. This was exemplified by lower indentations when the work boot heel angle was lowered, thereby spreading the load over a larger surface, and also by the lower indentations in insulations protected by "load spreading" overlays.

Although not fully evaluated, it appears that indentations and compression as a percentage of thickness can be misleading if insulations of different thicknesses are compared. Linear dimensions (mm) might be more appropriate when comparing indentations of insulations with different thickness.

No attempt was made to investigate the effect of facers or foam density on indentation. The commercial products available to us did not allow for this, and laboratory prepared foam materials may not resemble commercial foam products.

Other studies suggest that foam density, facer type, and facer adhesion are factors that affect roof traffic damage [3,4].

The results indicate that commonly used foam plastic roof insulations will be damaged if exposed to foot traffic, and that their protection with fibrous overlay boards as recommended by roofing contractors associations [1,2] continues to be good roofing practice.

The results indicated that finished roof surfaces that are exposed to foot traffic will be damaged, and that surface protection of finished roof membranes is good roofing practice.

The load dispersion offered by thin overlays on plastic foam insulation on roofs appears to be significantly greater than that suggested for bridge overlays [5].

5. CONCLUSIONS

1. All unprotected insulations were permanently damaged during the first loading cycle (simulated step). These results indicate that plastic foam insulations are susceptible to damage when they are walked over.

2. The amount of indentation increased with repeated loading until approximately 2,000 cycles, after which the increase in indentation was small.
3. Protection of insulation specimens by roof membranes resulted in reduced indentations.
4. Protection of insulation specimens by wood fibreboard resulted in reduced indentations in the system and no indentation of the foam insulation. During roof applications, fibreboard overlays can be immediately laid over foam insulations, thereby providing early and substantial damage protection.

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