USE OF PHENOLIC FOAM IN LOW-SLOPE ROOFING

MICHAEL J. DVORCHAK

Koppers Co., Inc.
Monroeville, Pa.

Phenolic foam insulation is used with both built-up and single-ply roofing systems. This paper addresses some of the basic performance properties of phenolic foam insulation.

Phenolic foam is a thermoset polymer. It solidifies irreversibly when reacted. Leo Hendrick Baekeland (1863-1944), a Belgian-American chemist, initiated the study of thermoset polymers in 1907. He discovered the first thermoset polymer when heating a phenol with a formaldehyde. The resulting phenol-formaldehyde polymer (PFP) was not readily dissolved by solvents and easily could be molded into complex shapes. The PFP also exhibited very low flammability and outstanding electrical insulation properties. This thermoset polymer was later trademarked "Bakelite" and has had many applications such as high temperature electrical circuits and telephones.[1]

MANUFACTURING PROCESS

Phenolic foam is produced by catalytic curing of a phenol-formaldehyde resin incorporating a fluorocarbon blowing agent. The phenolic foam core is laminated between facer materials to form a rigid insulation board. Generally the insulation board is produced by a continuous laminating process. Premixed resin is dispensed onto a carrier sheet (facer). The expanding foam then is laminated to the top facer as it moves through the manufacturing line. A series of slats confine the foam and control its thickness. The composite insulation board then is cut to proper size at the end of the manufacturing line.

Phenolic foam currently is available in two distinct forms, open cell and closed cell. Open celled phenolic foams first were manufactured in the United States in 1937.[2] However, closed-cell phenolic foam insulation was not introduced to the low slope roofing industry in the United States until 1982. Phenolic foam is commercially produced in the United States, Canada, Europe and the U.S.S.R. The Soviets estimate that phenolic foam is nearly 25 per cent of their total foam production.[3]

Other applications for phenolic insulation include home building, the space program, cryogenics, refrigeration, shipbuilding, nuclear technology, electronics and the food industry.[4,5,6]

ADVANTAGES OF CLOSED CELL PHENOLIC FOAM

Closed-cell phenolic foam represents a recent technological advance in the United States with patents being issued on the process[7]. The closed-cell product provides superior thermal insulation relative to that of open-cell phenolic and most other available roofing insulations. Also, the closed-cell product exhibits a stable, long-term "k" factor. Testing reports[8] on some of the new closed-cell phenolic foams have indicated little or no loss in thermal insulating efficiency after aging for 360 days at 140F. The data was developed using ASTM C518-76 "Steady-State Thermal Transmission Properties by Means of a Heat Flow Meter" and are presented in Table 1.

REASONS FOR "K" FACTOR STABILITY

Most closed-cell foams use a fluorocarbon or pentane blowing agent in their manufacturing process. (The thermal conductivity of the foam depends on the molecular weight of the entrapped gas.) The higher the molecular weight the lower the "k" factor. Since fluorocarbons have a higher molecular weight than air or pentane, the cells need to retain the fluorocarbon blowing agent and prevent air infiltration. Three parameters influence the loss of the fluorocarbon or pentane from cellular foams:

Polymer Blowing Agent Retention: The permeation of the blowing agents from foams made of polymers such as urethane, isocynaurate and polystyrene will occur over time. Permeability is a function of the chemical affinity between the foam polymer and the entrapped gas. The effect temperature has on permeability rates using Government Spec H-H-I-1972 has been studied. This heat aging at 140F versus the standard 73F aging accelerated the fluorocarbons diffusion rate three to six times in the foam insulations studied.[10]

Cell Size: The size of the foam cell apparently has an effect on the permeability rate. The smaller the cell size, the larger the number of barrier walls which will retard the gas interchange. The typical cells of insulation foams made from various polymers are shown in Figure 1. The cell size ranges are shown in Figures 1 and 2.

Cell Wall Perforations: The extent to which cell wall cracks, ruptures or holes occur, determines whether a foam is classified as open or closed cell. An analogy to this is the higher thermal efficiency of a triple-pane window over a single-pane window. However, if one of the triple panes is broken, efficiency is greatly reduced. During production, small holes in the cell walls can occur that may cause loss of entrapped blowing agent. The cell wall holes are visible only with a scanning electron microscope. Some foams classified as closed cell may actually have some cell wall holes. An example of this is found in Figure 1 where a "wormlike" hole is shown in a closed cell phenolic foam from manufacturer "A". The hole is revealed only at 1,000X magnification. The closed cell phenolic foam from manufacturer "B" reveals no holes that would allow the escape of the fluorocarbon and the entrance of air into the cell.

The closed cell phenolic foam demonstrates a stable "k" factor through a combination of low polymer fluorocarbon solubility, limited cell wall perforations and a relatively small cell size.

PHENOLIC FOAM IN A ROOF SYSTEM

Phenolic foam insulation in a roof system may be loose-laid, mechanically fastened or adhered with asphalt to the substrate. With a built-up roofing membrane, phenolic foam may be either mechanically fastened or adhered with asphalt to the roof deck. As with other roofing insulation boards, the type of deck dictates the acceptable attachment technique. Some manufacturers of loose-laid, single-ply ballasted membrane systems will allow the phenolic foam insulation to be loose-laid on the substrate.

A gravel surfaced built-up membrane may be attached directly to the top of a phenolic insulation board. A ½- to ¾-inch wood fiber or perlite overlayment generally is used with smooth surfaced built-up membranes and adhered single plies. Loose-laid, ballasted single-ply membrane systems may be placed directly on phenolic insulation board.

EFFECT OF FACERS

Facer materials play a large role in the performance of phenolic foam insulations. Initially they permit manufacture of the boards in a continuous process rather than in block form, which would require cutting and laminating the facers. The facers form a composite with the phenolic foam core which allows the insulation board to be handled, installed and perform in a manner typical of other insulations used in low sloped roofing.

The unfaced phenolic foam is relatively brittle compared to most other insulations. The facers improve the flexural properties and stiffness of the phenolic insulation panel. Proper flexural strength is required of the insulation board for handling, installing and spanning substrate irregularities or deck flutes. The facers also help the product resist dimensional change under different roof system temperature and moisture conditions.

FIRE PERFORMANCE

Many current insulation (i.e., perlite) foams require some type of underlayment protection to achieve a Factory Mutual Class 1 rating. But we can save material and labor costs when we eliminate the underlayment board. Phenolic insulation has attained the FM Class 1 rating on the FM calorimeter without the aid of underlayment protection between the deck and the insulation. The reason is the ability of phenolic foam to form a stable char which isolates the roof membrane from the heat of the calorimeter. Phenolic foam has met the FM Class 1 rating with a thickness range of 1.2 to 3.6 inches.

Controversy surrounds the toxicity of foam plastics in building construction. Experts cannot agree on the test method or the way in which tests should be interpreted. However, recent test results, conducted according to the National Bureau of Standards (NBS)[11] protocol, showed that phenolic foam generated products of combustion that were no more toxic than those found in wood.

COMPARATIVE PHYSICAL PROPERTIES

I conducted comparative testing to study the differences between phenolic foam and various other commercially available and typically used roofing insulations. The testing was conducted to provide a direct comparision of the insulation boards using identical test methods. All of the boards were purchased from roofing insulation distributors. The following insulation boards were tested:

Insulation Type	Core Density
Isocyanurate	1.89 pcf
Fiberglass	7.10 pcf
Expanded polystyrene (EPS)	0.94 pcf
Urethane	1.61 pcf
High-density wood fiberboard	19.15 pcf
Closed cell phenolic foam	2.96 pcf

Figure 3 compares core densities graphically.

Some of the physical properties important to low sloped roofing systems determined in this testing effort were:

- "k" factor (as purchased),
- compressive strength and modulus,
- dimensional stability,
- flexural strength and modulus,
- FM fastener pull-through.

I conducted all tests on the insulation board as purchased from the distributor. (The test results are summarized in Table 2.)

The closed cell phenolic foam was found to have the lowest "k" factor of the insulations tested (*Figure 4*). Isocyanurate and urethane apparently had experienced some of the expected drift in initial "k" value due to diffusion of the blowing agent out of the foam. Fiberglass, expanded polystyrene (EPS) and wood fiberboard attained "k" factors typical of insulations which use entrapped air rather than fluorocarbon as the cell-forming medium.

Compressive strength and modulus of elasticity gives an indication of the ability of the insulation board to carry roof traffic. The compressive strength of wood fiberboard was the highest of the insulations tested and exceeded the capacity of the test apparatus (*Figure 5*). Phenolic foam, isocyanurate and urethane produced comparable compressive strengths, but the phenolic foam had a significantly higher elastic modulus (*Figure 6*). EPS and fiberglass showed the lowest compressive strengths.

Dimensional stability of insulation boards is also important to the performance of adhered membrane roofing systems. Dimensional stability testing was conducted according to ASTM D2126 "Response of Rigid Cellular Plastics to Thermal and Humid Aging" Procedure C. Please note that at this temperature and humidity, the weight and dimensional changes did not necessarily exhibit a direct correlation for all of the insulations tested. Under the conditions of 158F ±4F and 97±3 percent relative humidity the phenolic foam was the most dimensionally stable of the insulation boards tested (*Figures 7* and *8*).

All of the insulation boards tested exhibited adequate flexural strength for typical roofing applications. Urethane produced the highest strength and modulus. Phenolic foam's flexural strength and modulus values were relatively low in the machine direction of the board but high in the transverse (cross-machine) direction (*Figures 9, 10* and *12*).

Wind uplift screening tests to evaluated the insulation board's ability to withstand pull-through of the mechanical fasteners. Values of 165 pounds or greater normally are within the tolerance of Factory Mutual's I-60 requirements. Phenolic foam produced the highest fastener pull-through resistance of the insulation boards tested (*Figure 13*).

CORROSION OF FOAMS

There is concern about corrosion of metallic decks and fasteners in contact with insulation materials. ASTM[12] and other organizations are addressing this issue. Reports[13] of corrosion related to freon-blown polyurethane foams are available. The addition of fire retardants containing chlorine or bromine reportedly increases the corrosiveness of insulating foam systems. Phenolics do not use halogenated additives for fire retardance.

Some reports also have been made about phenolic foam's corrosiveness, especially when inorganic mineral acids such as hydrochloric, sulfuric and phosphoric are used as catalysts. However, the corrosiveness of the foam greatly diminishes with the use of organic catalysts [7,14] such as oxalic, adipic, benzenesulfonic, p-toluenesulfonic, phenosulforic and petro-based sulfonic and catalysts. Some technical references[15] actually indicate the use of phenolic polymer in corrosion-resistant applications.

Further testing of all insulation materials is needed to more thoroughly evaluate corrosion potential and to determine whether corrosion represents a serious problem.

CONCLUSIONS

1. A properly manufactured closed-cell phenolic insulation board will produce a relatively low and extremely stable "k" factor.
2. Phenolic foam insulation meets the Factory Mutual Class 1 fire rating without the use of a protective underlayment board.
3. Facer materials play a large role in the performance of phenolic insulation boards.
4. The basic physical properties of phenolic foam allow it to be installed in conventional low sloped roofing systems.
5. Potential corrosion of mechanical fasteners is of concern to roofing insulation manufacturers. Corrosion is not fully understood, but it is an area that should be studied further.

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Sample No.	Test Thickness mm	inches	Test Density kgm³	lbs ft.³	Apparent Thermal Conductivity "k"@* 90 days	180 days	360 days
A	44.4	1.75	55.9	3.49	0.109	0.109	0.121
B	50.9	2.00	52.7	3.29	0.110	0.110	0.116
C	65.3	2.57	51.6	3.22	0.117	0.117	0.118
D	76.4	3.01	51.0	3.18	0.116	0.116	0.114

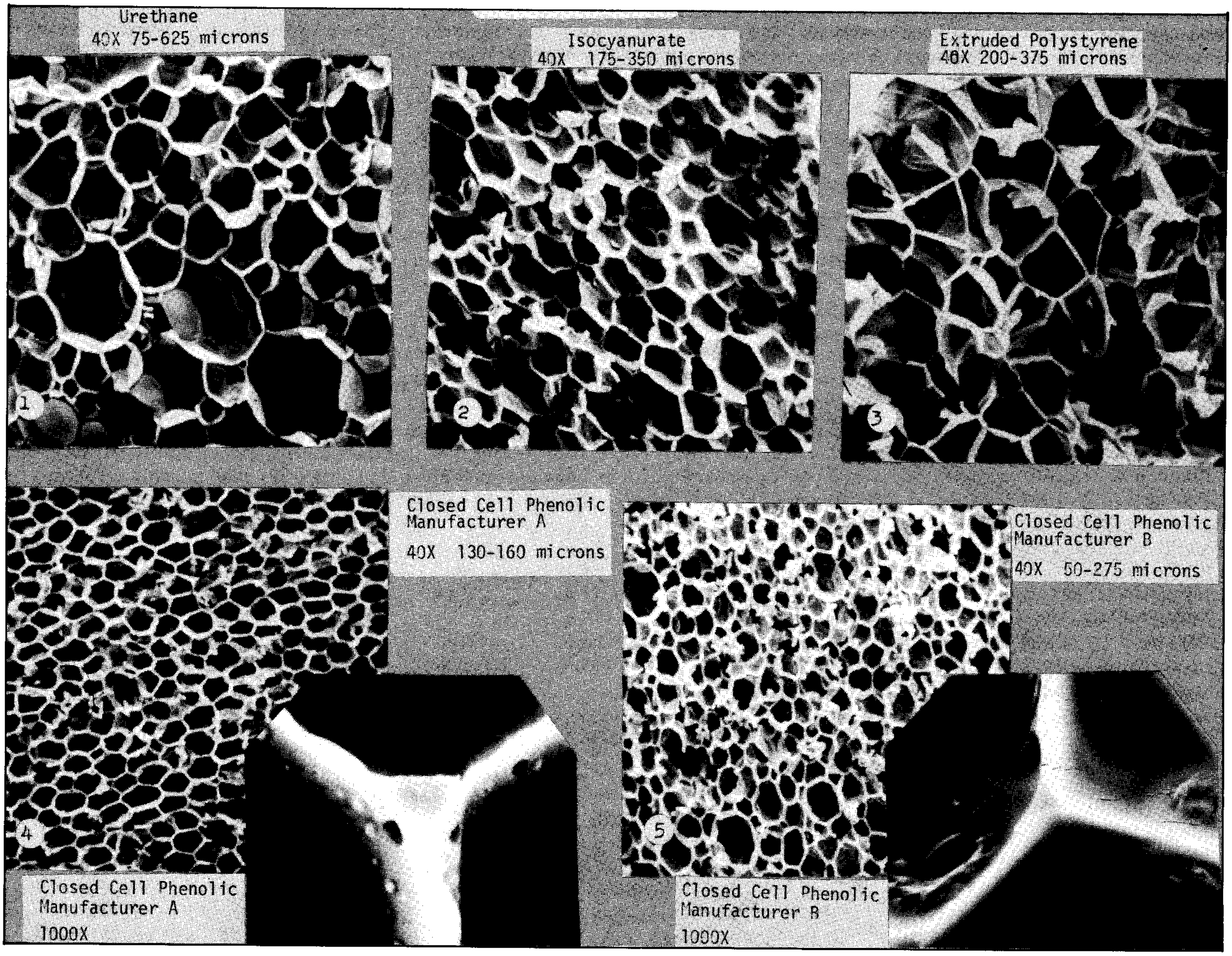
*"K" Factor (BTU in HR^{-1} FT^{-2} °F^{-1}) can vary per this test method (ASTM C-518) by ±5 percent.

Table I Apparent thermal conductivity of a closed celled phenolic foam insulation after conditioning at 140F (60C) for 90, 180 and 360 days

Insulation Type Facer	Isocyanurate Glass	Fiberglass Asphalt Sat. Felt	EPS N/A	Urethane Glass	Wood Fiber Board N/A	Phenolic Foam Corr/Felt
Thickness, inches	2.0	15/16	2.0	2.0	1/2	2.0
k-Factor (ASTM C518)	.167	.257	.256	.168	.210	.110
Comp. Strength, psi 10% consolidation (ASTM D 1621)	24.49	5.61	11.32	20.50	*(2)	28.53
Elasticity of Comp., psi	380	*(1)	303	523	*(2)	1,277
Core density, pcf (ASTM D 1622)	1.89	7.31	0.94	1.61	19.15	2.96
Water Absorption—24 hr., g/cc (ASTM C272)	.020	.131	.018	.026	.176	.062
Dimensional Stability, % change (158-4F & 97 ± 3%) (ASTM D2126, Procedure C)						
Weight	−1.02	+0.15	−0.66	−6.44	+3.94	−4.53
Length	+0.62	−0.34	−1.38	+1.04	−1.17	+0.41
Width	+0.92	−0.58	−1.52	+0.84	−1.23	+0.36
Thickness	−0.20	+0.37	0.00	−1.01	+3.15	+0.26
Tensile strength, psi (ASTM D1623)						
Minimum	2.0	0.7	1.5	41.6	4.0	8.43
Maximum	7.0	1.4	11.3	38.6	9.7	12.06
Average (4 specimens)	3.6	1.0	8.4	37.1	7.0	10.26
Failure point	Facer/Foam Interface	Fiberglass Failure	EPS Failure	Foam Failure	Wood Fiber Facer Layer	Corr. Facer/Foam Interface
Flexural Strength Machine Direction						
Modulus, psi	3040.3	1294.6	5316.5	14,841.0	5,696.3	1,254.30
Strength, psi	56.36	27.99	82.99	174.78	50.91	45.88
Strain,	2.76	3.20	2.78	4.25	1.09	5.35
Transverse Direction						
Modulus, psi	2530.0	1209.0	7046.6	15,964.0	7,347.0	4,895.20
Strength, psi	42.81	31.14	93.91	177.73	46.37	110.80
Strain, %	2.12	2.69	2.77	4.05	0.74	5.41
Fastener Pull-through, lbs. Steel Tru-Fast plates (4 specimens)						
Mean	197.21	162.86	108.20	247.88	105.04	303.76
Minimum	190.40	150.70	99.20	231.38	101.55	285.21
Maximum	203.15	178.39	126.19	260.12	111.28	348.40

*(1) Modulus of elasticity is too low to calculate from graph
*(2) Compressive strength exceeds the Instron's 60 psi capacity

***Table 2** Physical properties comparisons of typical roof board products*



Urethane
40X 75-625 microns
Isocyanurate
40X 175-350 microns
Extruded Polystyrene
40X 200-375 microns
1
2
3
Closed Cell Phenolic
Manufacturer A
40X 130-160 microns
Closed Cell Phenolic
Manufacturer B
40X 50-275 microns
4
5
Closed Cell Phenolic
Manufacturer A
1000X
Closed Cell Phenolic
Manufacturer B
1000X

Figure 1

roof deck for one part of the test. Four mechanical fasteners were used to attach the EPS insulation board to the substrate for another test series. Mechanical fastener tension force was allowed to relax for 24 hours at 70F and another 24 hours at 150F prior to testing. Surface temperature of the 0.7 pcf EPS insulation board sample was decreased from 70F to −30F. A decrease from 150F to −30F was used for the 1.25 pcf EPS insulation sample.

The effect of attachment on the dimensional stability and stiffness of 1.25 pcf EPS is shown in Figures 2 and 3, respectively. Figure 2 plots the dimensional change of the top surface of the insulation board caused by a temperature decrease. Figure 3 plots the temperature induced load as a function of contraction. The apparent coefficient of expansion and modulus of elasticity of the top surface of both 0.7 pcf and 1.25 pcf EPS insulation boards were calculater as:

EPS Insulation Density	Substrate attachment	Coefficient of expansion (in/in/°F)	Modulus of elasticity (lb/in)
0.7 pcf EPS	Loose Laid	19.4×10^{-6}	1300
0.7 pcf EPS	Mechanically Fastened	16.2×10^{-6}	1600
0.7 pcf EPS	Adhered with Asphalt	6.8×10^{-6}	4600
1.25 pcf EPS	Loose Laid	19.3×10^{-6}	1900
1.25 pcf EPS	Mechanically Fastened	14.4×10^{-6}	3000
1.25 pcf EPS	Adhered with Asphalt	8.4×10^{-6}	6200

Adhering an EPS insulation board to the substrate with asphalt significantly reduced the apparent coefficient of expansion and increased the stiffness of the board over that of a mechanically fastened or loose-laid board. This results from using the board's shear stiffness. Because EPS insulation is relatively flexible, increased stiffness is desirable if a membrane is to be adhered directly to the top surface. However, shear deflection is directly proportional to the thickness of the insulation board. Therefore, insulation thickness is a consideration when a membrane is directly attached to EPS insulation.

Mechanical fastening of an EPS insulation board produced the least change in the apparent coefficient expansion and stiffness. The mechanical fastener develops only a small portion of the potential shear stiffness and probably provides only uplift resistance for the EPS insulation board.

PHYSICAL PROPERTIES OF EPS INSULATION SYSTEMS WITH A BUILT-UP ROOFING MEMBRANE

Much past testing studied the tensile strength of built-up (BUR) membranes. However, membrane strength is only part of the information required to assemble a successful roof system. The more difficult question is: What strength is required? The insulation system and substrate attachment technique greatly affect the membrane strength required.

In an ideal roof system, the dimensional changes and forces generated in a roof membrane are symmetrical about the centerline of the roof. The center of the roof can be considered a fixed point. The greatest horizontal membrane deflection occurs at the edges of the roof. The test set-up for this part of the research program was designed to model the membrane/insulation system at the center of the roof. Figure 4 diagrams this location in an ideal roof system.

The horizontal load frame and environmental chamber used for this testing are shown on Figure 5. Testing was accomplished by attaching one end of the 4 feet long by 2 feet wide built-up membrane to one end of the load frame to simulate the fixed point at the center of the roof. The other end of the BUR membrane was attached to a freely moving sled. The test procedure was the same as for determining the physical properties of individual system components. The apparent coefficient of expansion and modulus of elasticity were determined for the total roofing systems.

Built-Up Roofing Membrane Directly Attached to EPS Insulation

A series of temperature induced contraction and load tests were conducted on a BUR membrane/EPS insulation system. The system consisted of:

1) the same three-ply glass BUR membrane used in the determination of individual physical properties.
2) 2-inch-thick 1.0 pcf EPS insulation board.
3) intermediate ribbed steel roof deck.

The BUR membrane was mopped with hot asphalt and flopped on the EPS insulation board. The system was tested loose-laid, mechanically fastened and asphalt-adhered. The same membrane and insulation board was used for each test.

A summary of the results for the BUR membrane/EPS insulation system follows:

Sample type	Substrate attachment	Coefficient of expansion @ 0°F (in/in/°F)	Modulus of elasticity (lb/in)
BUR Membrane	Loose-Laid	26.3×10^{-6}	19,300
BUR Membrane/ EPS Insulation	Loose-Laid	27.3×10^{-6}	20,700
BUR Membrane/ EPS Insulation	Mechanically Fastened	24.6×10^{-6}	20,000
BUR Membrane/ EPS Insulation	Adhered with Asphalt	27.0×10^{-6}	22,600

The test results of the BUR membrane/EPS insulation system produced relatively small differences in physical properties when compared to those of the individual BUR membrane. The EPS insulation board did not significantly change the behavior of the BUR membrane over the 4-foot length of the sample. A small increase in BUR membrane/EPS insulation system stiffness was observed when the EPS insulation board was adhered to the substrate with asphalt. This system was observed to be performing satisfactorily in the field. The EPS insulation board apparently provides gradual restraint to expansion and contraction of the BUR membrane. An EPS insulation board adhered with asphalt to a rigid substrate is stiff enough to adequately restrain membrane dimensional changes.

BUR Membrane/Composite Insulation System

The physical properties of a BUR membrane attached to a composite insulation system were also studied. The composite system consisted of:

1) the same three-ply glass BUR membrane previously used.
2) ½-inch-thick wood fiberboard overlayment.
3) 2-inch-thick 1.0 pcf EPS insulation board.

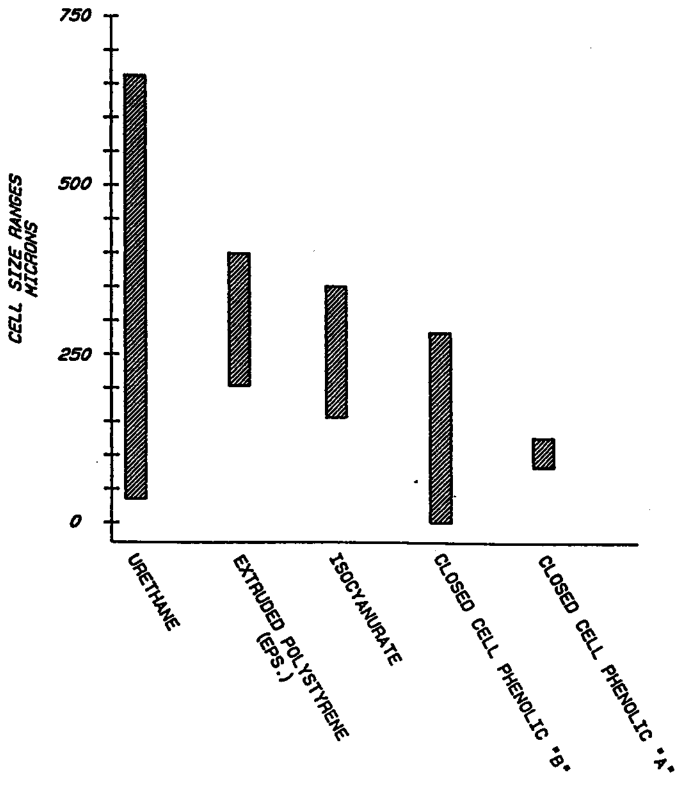


Figure 2 *Roof board cell size comparison*

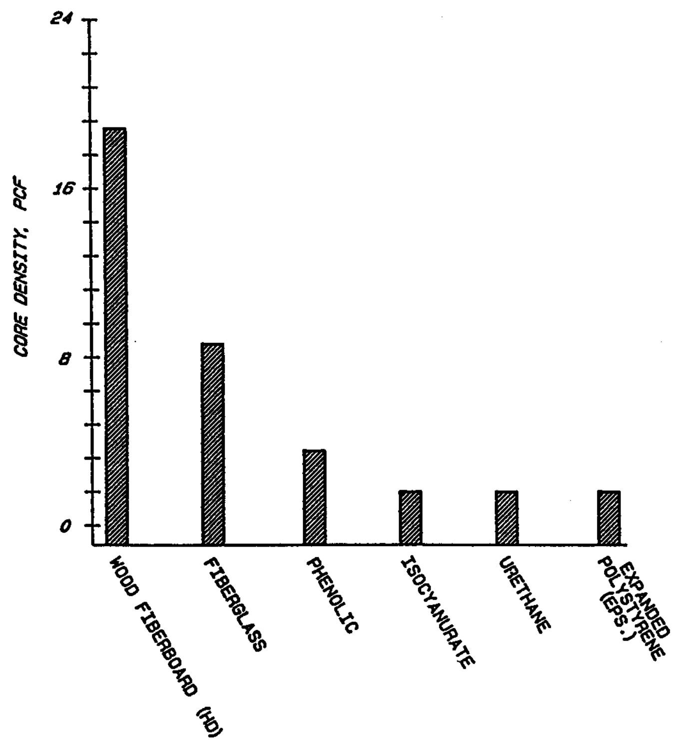


Figure 3 *Roof board core density comparison per ASTM D 1622*

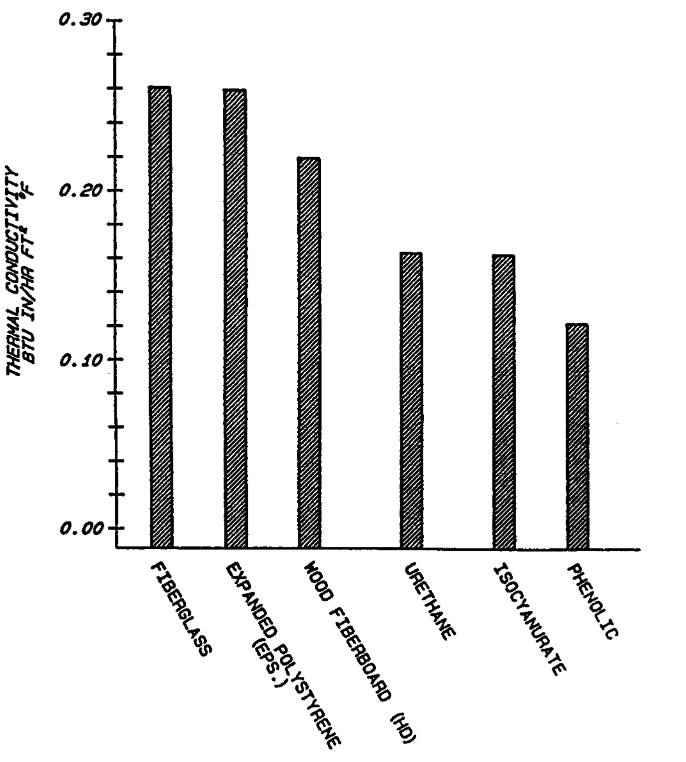


Figure 4 *Roof board thermal conductivity comparison per ASTM C 518*

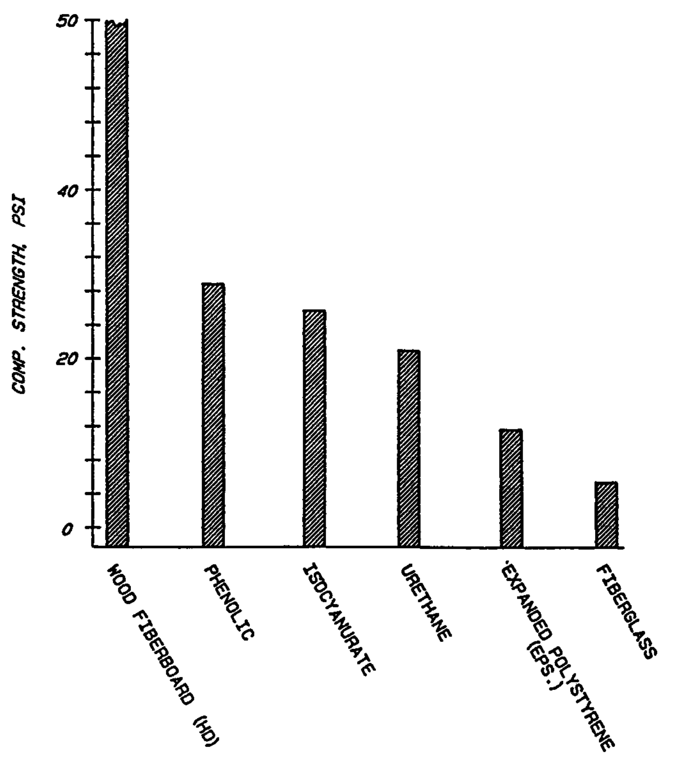


Figure 5 *Roof board compressive strength comparison per ASTM D 1621*

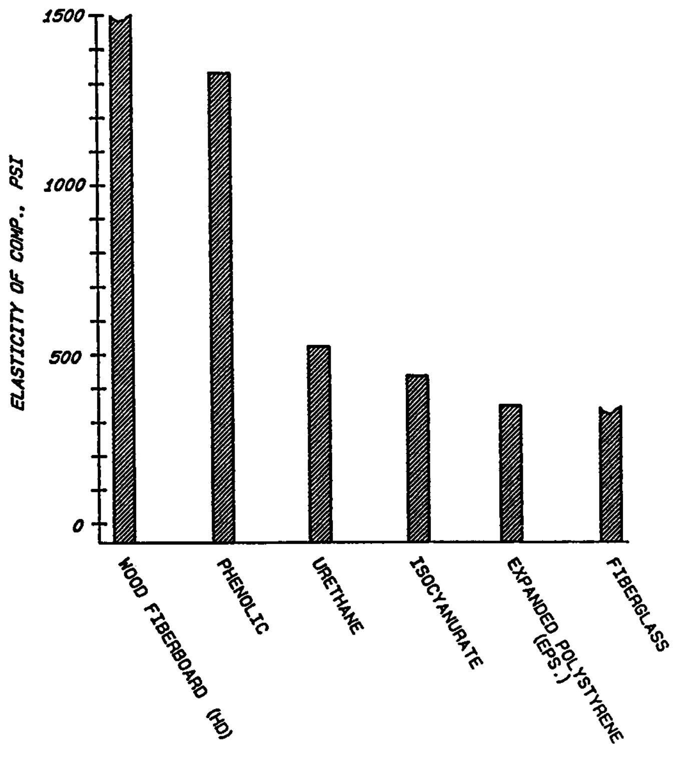


Figure 6 *Roof board elasticity of compression comparison per ASTM D 1621*

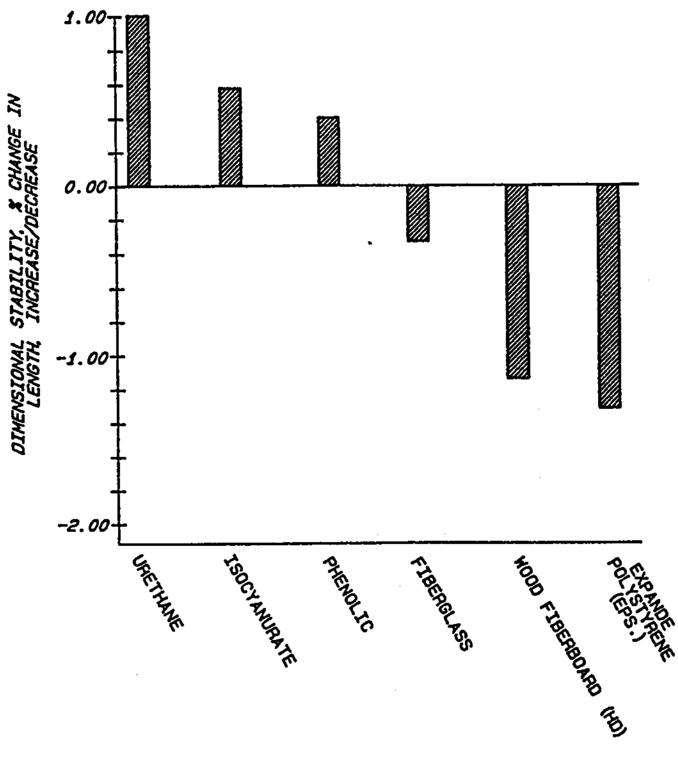


Figure 7 *Roof board percent length increase/decrease comparison per ASTM D 2126*

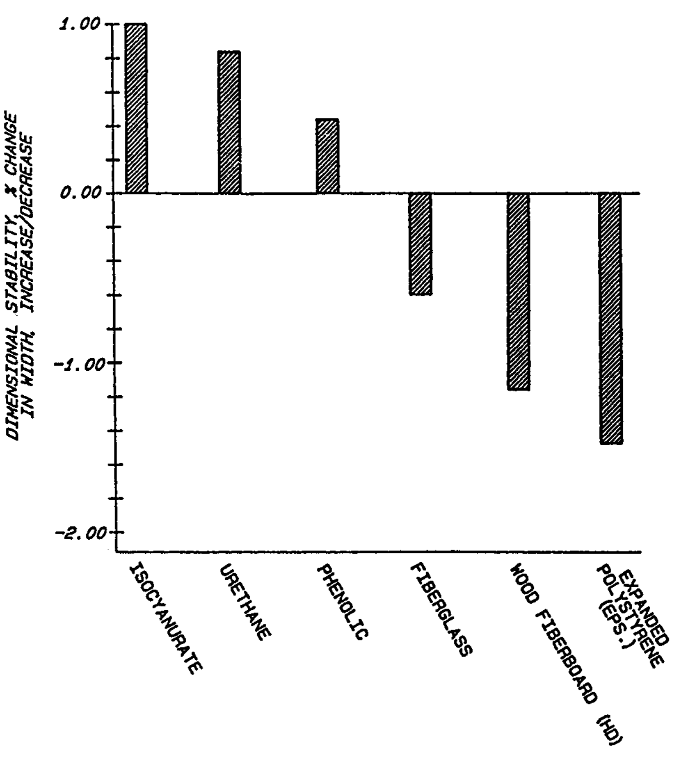


Figure 8 *Roof board width increase/decrease comparison per ASTM D 2126*

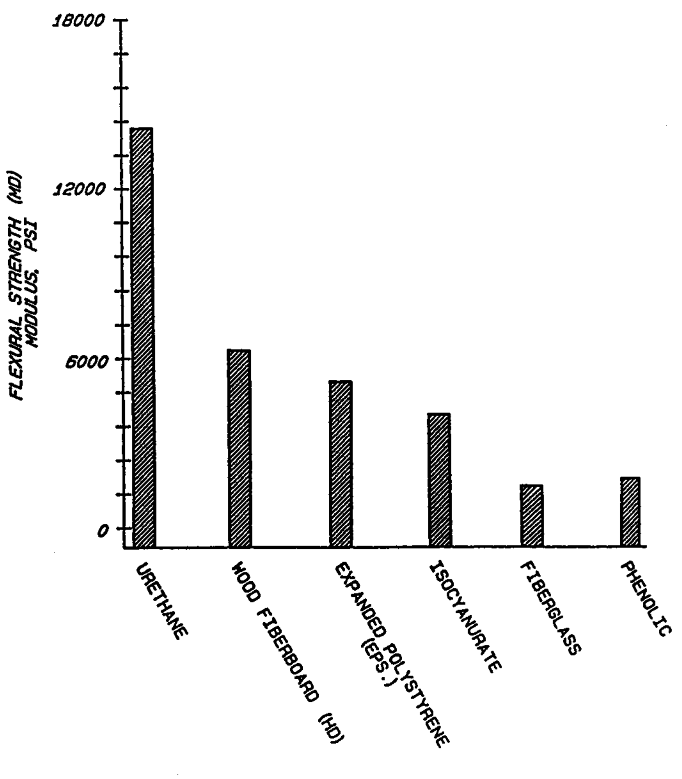


Figure 9 *Roof board modulus (MD) comparison per ASTM D 1623*

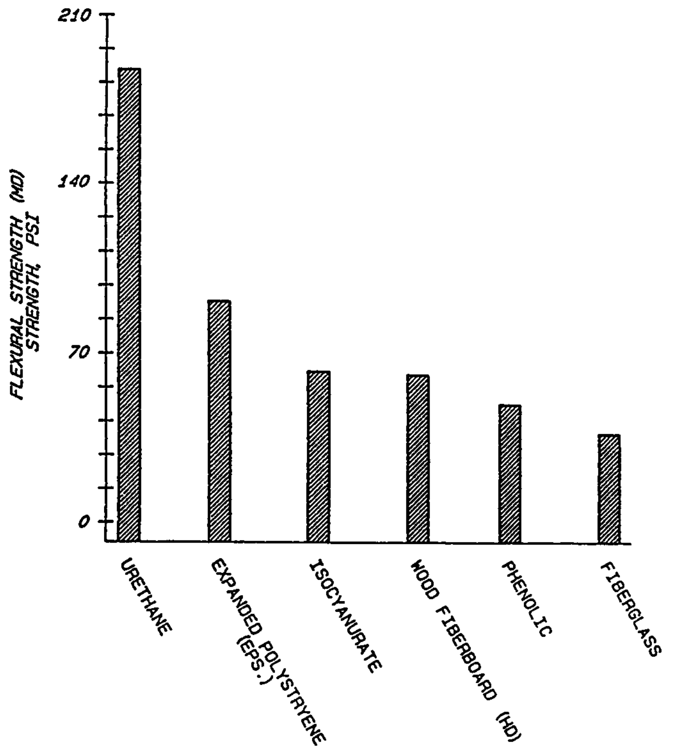


Figure 10 Roof board strength (MD) comparison per ASTM D 1623

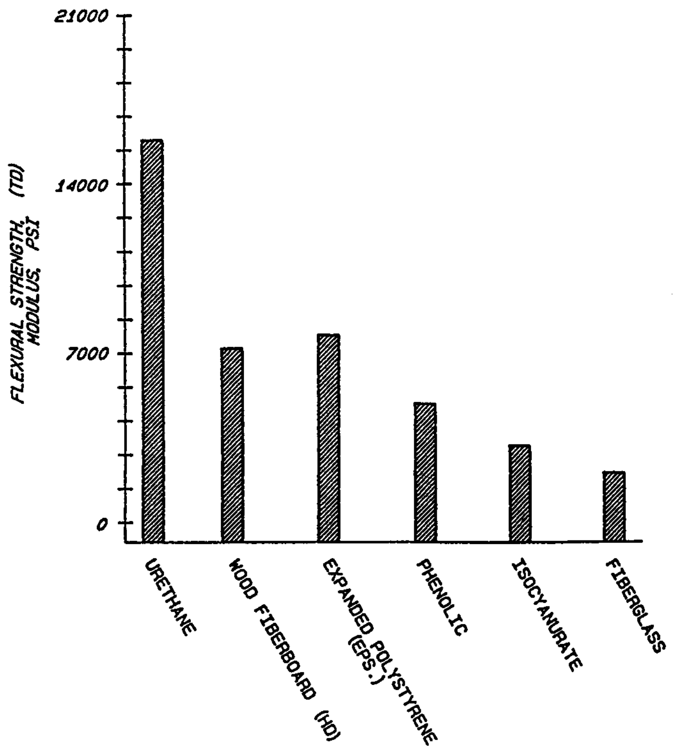


Figure 11 Roof board modulus (TD) comparison per ASTM D 1623

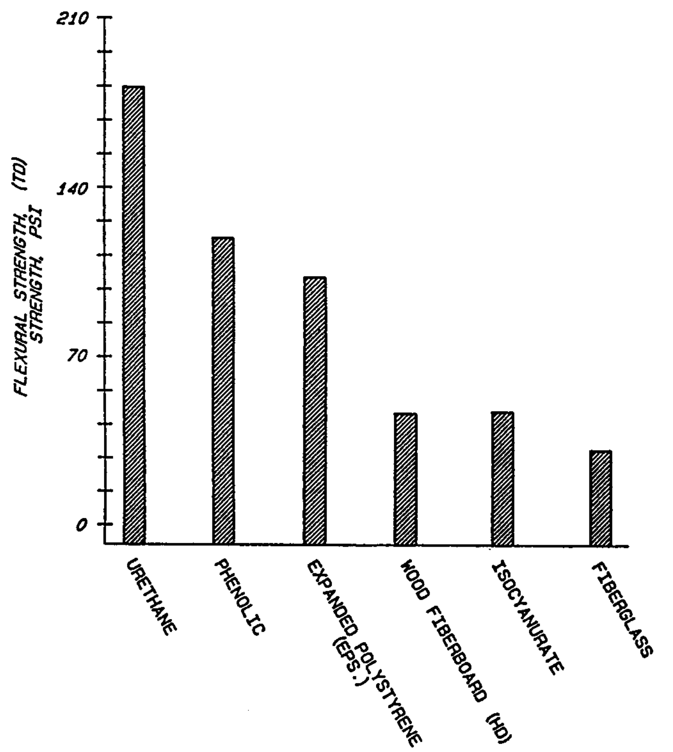


Figure 12 Roof board strength comparison (TD) per ASTM D 1623

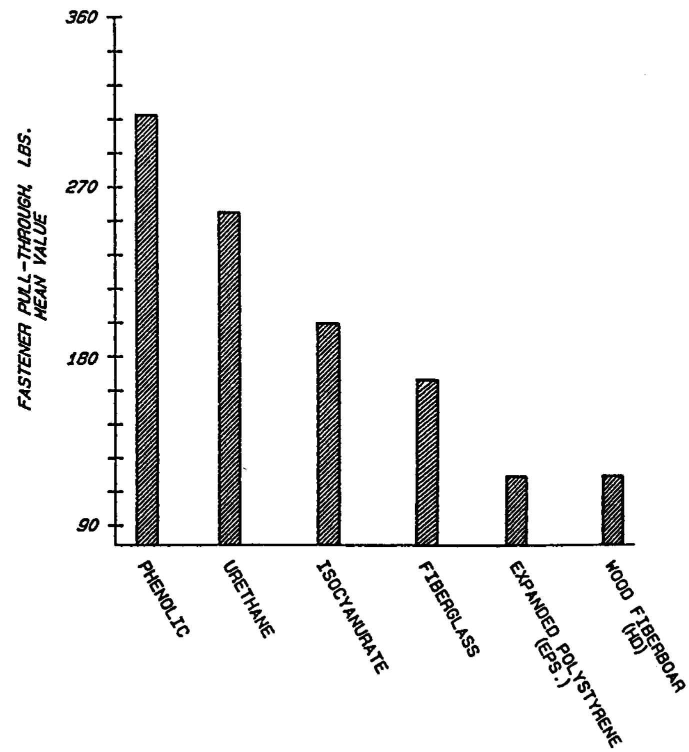


Figure 13 Roof board fastener pull-through comparison