PERFORMANCE CONSIDERATIONS FOR THERMALLY EFFICIENT ROOFING SYSTEMS

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ABSTRACT: The energy shortage has produced both legal and practical reasons to increase the thermal efficiency of roofing systems. Experience, as well as some research, shows that the accepted standards of good roofing technology are even more important for systems with efficient insulation than for conventionally insulated roofs. Among these principles are the need to keeping all roof components dry, to insure complete adhesion for all components, and to use dimensionally stable insulation boards. The top layer of insulation should be rigid enough to avoid indentation. An increase in the strength of felts through addition of reinforcing components is suggested.

Concerns have been expressed that thermally efficient insulation will produce many new types of failures. Of these, the fear of greater thermal movement of the membrane is proven to be essentially unfounded. Regardless of insulation efficiency, roofs do not split from the effect of temperature changes alone, but moisture in the system can cause damage. Some questions are raised about the validity of the assumption that very rapid temperature changes cause roof splits in the absence of other causes.

KEY WORDS: Aging, Asphalt, Bond, Dimensional Stability, Energy, Indentation, Insulation, Joints, Roofing, Splitting Strain, Strength, Thermal Efficiency, Thermal Resistance, Thermal Shock.

1. Introduction

Thermally efficient roofs are here to stay. The roofing industry must deal with, and must make every effort to adjust itself to, the resultant changes. For example, the Massachusetts Building Code now requires residence roofs to have a thermal resistance of $R = 3.5\ m^2 \cdot K/W$ ($20\ h \cdot ft^2 \cdot {}^\circ F/Btu$) or more, and all other buildings an R of $2.5\ m^2 \cdot K/W$ ($14.3\ h \cdot ft^2 \cdot {}^\circ F/Btu$). At this time, insulation is a matter of first cost vs. heating expenses. Because the energy shortage is real, we must face an ever increasing cost of fuel, which automatically will raise the cost limits on insulation in construction; the economic break-even thermal resistance factor will rise faster than inflation. More important, I foresee that eventually the issue will not be the cost of paying for insulation or fuel, but will be a question of freezing or not freezing.

The purpose of this paper is to:

- persuade designers and contractors that the need for increased thermal efficiency of roofs is real and present;
- enumerate some of the potential technological problems of roofing design and construction associated with thermally efficient roofs, and the means of dealing with them; and
- examine critically some of the fears which have been expressed in the industry about the implications of increasing thermal efficiency of roofs.

2. Need for Energy Conservation

The current debate over energy is a luxury we can afford only at the expense of the last supplies of oil. We have heard, again and again, that the American people do not believe in the energy shortage, that they refuse to do anything about it, and that it is undemocratic to expect our citizens to change their way of life to save energy. The propaganda about finding new places to drill for oil is irrelevant, since it only postpones the day of reckoning for a few months or years. We must realize that the energy crunch is permanent.

In buildings, as well as other energy-consuming sectors of our economy, the issue is not the first cost of insulating a building, but of providing enough insulation to make the best use of available energy. In effect, this means that insulation must be fitted to the available heat supply. The only available choice is whether to freeze or be reasonably comfortable, not whether the cost of insulation is too much.

3. Problems of Thermally Efficient Roofs

The thermally efficient roof is not a novelty. For years, freezer buildings have been built with thermal resistance factors of $R = 3.5\ m^2 \cdot K/W$ ($20\ h \cdot ft^2 \cdot °F/Btu$) or better. From our experiences with such roofs, we have learned that virtually all of their problems derive from the violation of well known principles of proper roofing design and construction, which apply regardless of insulation efficiency. Thermally efficient roofs should be built like all other roofs, except that all the conservative old principles (keep it dry, fasten it down, mop continuously) will become much more important. The good designer and the good roofer have much less to fear from thermally efficient roofs than those who try to "just get by."

Nevertheless, we suggest attention to some potential problems which may be pertinent to highly insulated roofing systems:

- Thermally efficient insulation, as compared to less efficient contemporary standards, will require greater thickness. Table 1 gives some examples for various insulation materials for present standards, assumed to be $R = 0.7\ m \cdot K/W$ ($4\ h \cdot ft \cdot °F/Btu$); the Massachusetts Code for non-residential buildings $R = 2.5\ m \cdot K/W$ ($14.3\ h \cdot ft \cdot °F/Btu$); and for very high thermal efficiency, $R = 6.2\ m \cdot K/W$ ($35\ h \cdot ft \cdot °F/Btu$). For conversion, insulation thickness $t = k \cdot R$ (where K = thermal conductivity).
  Increased insulation thicknesses require more nailers, and more space, and intensify the focus on the more thermally efficient materials, such as plastic foams. The comparative merits of insulation materials have been discussed in other papers [Ref. 1]; unfortunately, foams still present significant problems of dimensional stability which may affect the roofing membrane unfavorably. The thermal warp theory by C. G. Cash [Ref. 2] gives additional cause for caution, because increasing the layers of insulation may lead to local areas of poor attachment. In view of the problems with warping, aging, and thermal coefficient of expansion (see table above), we consider the thermally more efficient foam insulation to be a risk, at least when directly in contact with the roofing membrane. For the top of the insulation "heap," fiberboard (organic) is more desirable, because of its stability and impact resistance. Perlite board is good, as long as wind uplift is low and the membrane is topped by gravel.
- At least two layers of insulation should always be used, to attenuate local movement of the structural roof deck, and to produce a more coherent and stable base for the membrane. With very thick foam insulation boards, there is risk of excessive joint movement, especially because of the increased temperature gradient between the top and the bottom of the board. Membranes rarely, if ever, are damaged by thermal movement in the center of the insulation boards; the usual damage is caused at the insulation joints, which (locally) act as strain multipliers.
- Inevitably, if movement and solid substrate are discussed, proposals are made to tape the insulation joints for better continuity of the support for the membrane. The case of such taping is debatable; we have seen some instances in which the tape has malfunctioned, bunching near the joint, producing some ridging in the membrane. In other cases, splits in the membrane have been observed over the edges of unbonded tapes.
- The use of more insulation requires more time for installation per unit area. Since it is vitally important to keep all roofing components dry, the exposure of the system to weather is lengthened. To reduce this risk, it will be necessary to reduce the area which can be started and completed in any single day. The quantitative effect of this restriction is uncertain, and will have to be worked out by roofing contractors on a trial-and-error basis.
- It is possible that more insulation thickness will produce increased softness in the assembly. Not all types of insulation present an equal risk of this softness, which would manifest itself primarily in punching or indentation damage in the membrane, caused by installation and maintenance traffic. We have long recommended that any glass fiber insulation be topped by a rigid board, to distribute loads over a larger area and to reduce indentation problems.
- The problem of lateral stability of thick insulation must be considered because of the potential of increased lateral (shear) deformation as thickness increases. Various insulation types have various shear moduli; while some shear deformation is helpful in attenuating deck movement, too much might be harmful, although there is no direct evidence available. There is no certain answer to this problem, except the need for a very good interlayer bond at all surfaces is obvious. A good case can be made for increased bond quality between deck and insulation. The best solution to this problem is the use of positive anchorage by mechanical means. This would not only increase the bond quality at an important interface of the roofing system, but would also be useful in positively restraining any tendency of insulation boards to move, cup, and bow. Mechanical fastening, now required by Factory Mutual for the perimeters of roofs, is increasing in popularity because of its reliability and simplicity. It is particularly useful for the plastic foams, which have high thermal efficiency per unit of thickness, but suffer from the problems of dimensional instability. Mechanical attachment, if achieved with effective fasteners, will overcome many weaknesses of the foam insulations, as

long as the foam is not used directly as the base for roofing membranes.

- None of the concerns expressed above shows that thermally efficient roofing systems are seriously disadvantaged by virtue of their greater insulation thickness or efficiency. Nevertheless, it may be useful to consider possible improvements in the membrane, to compensate for potential problems of movement. The most obvious means of improving the membrane is to increase the quality of its roofing felts, especially in respect to its minimum (i.e., transverse) tensile strength. A suggestion for more study, not a prescription, may be the idea of introducing some reinforcement into the roofing plies.
- Until a completely non-directional felt is available, membranes should always be laid at right angles to the direction of the uppermost insulation layer. Since the "through" joints are the most likely to move, such potential movement should stress the felts in their strongest (i.e., longitudinal) direction. It might be worthwhile to consider the possibility of changing the orientation of the insulation boards at every layer, since this would help in integrating the system and reducing its susceptibility to lateral movement.

4. Commonly Expressed Concerns About Thermally Efficient Roofing Systems

Since the start of the discussion on thermally efficient roofing systems, a number of concerns have been expressed about the possible difficulties which will be encountered. Typical for these worries is a NRCA release in 1974, warning that increased insulation "will dramatically shorten the life of most roofing membranes...by...thermal decomposition and mechanical failure." It continues by quoting NBS research that "the rate of oxidation of roofing asphalt....more than doubles for each 18°F rise in temperature within the membrane."

The following discussion attempts to deal with these and other concerns expressed by the roofing industry:

- Increases in the temperature within the membrane with increases in thermal efficiency are very small. A paper published in 1977 on this subject [Ref. 3] proves, by appropriate computations, that once some insulation has been introduced between the roof deck and the membrane, even a major change in the insulation value produces little change in the temperature of the membrane. For example, by raising the insulation value from R = 0.7 m • K/W (4 h • ft • °F/Btu) to R = 2.5 m • K/W (14.3 h • ft • °F/Btu), an increase of 56°C (100°F) in the ambient temperature will produce a temperature change of only 2.4°C (4.4°F) at midline of the membrane; and for an increase to R = 6.2 m • K/W (35 h • ft • °F/Btu), the membrane will undergo a temperature change of only 2.6°C (4.7°F). Only negligible temperature changes are induced into the membrane by increased insulation, and this concern can be safely laid to rest.
- Somewhat connected with this concern is the one about thermal splitting. It has been shown long ago that, in a uniform roofing system, membranes do not split themselves apart by reason of temperature changes along [Ref. 4].
- The work at the National Bureau of Standards, for laboratory prepared samples (data shown in Table 2), selected for this paper from various types of typical membranes, is shown in Table 2.

  The thermal shock factor is the amount of temperature change needed to cause tensile failure of a membrane, assuming that the temperature is dropping and that both ends of the membrane are fixed. Actually, fixity at both ends of the membrane is rare, since flashings usually allow at least some movement. It follows, then, that temperature changes will have to be extraordinarily high (at low temperatures), 50 to 360°C (90 to 640°F) to explain tensile failure in the membrane, provided that there is no stress concentration anywhere in the membrane. Our experience shows that independent of the amount of insulation and the dimension of a roof, stress concentrations occur at insulation joints, where substrate movement and/or dimensional instability of the insulation produce much higher local movement and higher deformations of the membrane. The only other phenomenon which could add sufficiently to thermal movement is moisture movement.
- The effect of moisture on roofing membranes has been discussed in some detail by Shuman [Ref. 5]. An extract from his work is shown on Table 3. Allowing for some approximations, it is clear that the strain produced by drying of a wet felt comes fairly close to he strain of the membrane at failure. These figures show that moisture can contribute a strain of the same order of magnitude as that caused by temperature changes close to the thermal shock factor.
- There is suspicion that high insulation value increases the growth of blisters. Blisters are the result of the presence of moisture; they have nothing to do with the efficiency of the insulation.
- The same applies to the aging of the membrane. Since the membrane ages primarily due to exposure, the small temperature changes, as shown earlier, have only a negligible effect on the aging.
- General membrane shrinkage has been cited as a result of efficient insulation use. This is true in all cases where moisture in the system is associated with inadequate adhesion between one or more components. For thick insulation, there is more risk of failure to bond at least one component to the other; but it appears that proper workmanship would result in about equal performance, regardless of the amount of insulation involved.

- Thermal shock is often cited as a cause of roof splitting; sudden temperature drops are blamed for tensile membrane failures. This may be so, but has never been proven. We suggest that there is at least some logic in arguing against such action. In connection with some work for ASTM Committee D8, some tests have been made to relate the tensile testing strength of a typical #15 asphalt-saturated organic felt to the speed with which it is pulled apart (strain rate) by the testing machine [Ref. 6]. The felt was air dry, with a moisture content of 3.8%. The results of testing at various speeds are given in Table 4.

  These figures show a smooth and believable pair of curves. They show that tensile strength in a roofing felt increases as the rate of deformation increases. Since temperature failure of membranes, if it occurs, is of a tensile nature for a specific strain rate, the table shows that the faster the strain (i.e., rate of straining), the higher the strength of the felt (breaking load). We do not claim that this disproves conclusively the idea that sudden temperature changes are more likely to produce felt splitting than a more gradual temperature drop; but this proposition is put forward to suggest more serious thinking and research in this important field.

5. Summary

Thermally efficient roofs will become the rule, rather than the exception, in roofing design and construction. A further increase in the thermal resistance, as required by the present standards of energy conservation, is inevitable. The roofing industry must be ready to do its part in making these changes as painless as possible.

Many of the fears about deleterious effects of highly efficient roofing insulation on the performance of roofing systems are not well founded. There is virtually no evidence to support the suspicion that heavy insulation will cause greatly accelerated deterioration of the membrane. There is no reason to believe that a roof will tear itself apart by thermal action alone. New thinking may be required about membrane failures caused by rapid drops in ambient temperatures.

The best way to deal with thermally efficient roofs is to apply to their design all the rules of roofing technology already known. However, more detailed attention to these rules is needed to avoid accumulation of design and workmanship errors, to which thermally efficient roofing systems are more vulnerable.

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TABLE 1 –
MEMBRANE TEMPERATURES AS A FUNCTION OF INSULATION EFFICIENCY

Thermal Property:	Expansion Coefficient α		Thermal Conductivity k		$R = m^2 \cdot K \cdot W^{-1} (ft^2 \cdot h \cdot {}^\circ F \cdot Btu^{-1})$					
					0.7	(4)	2.5	(14.3)	6.2	(35)
					Thickness for required resistance					
Unit	$\frac{10^{-6}}{{}^\circ C}$	$\left(\frac{10^{-6}}{{}^\circ F}\right)$	$\frac{W}{m\ K}$	$\left(\frac{Btu\ in.}{h \cdot ft^2 \cdot {}^\circ F}\right)$	mm	(in.)	mm	(in.)	mm	(in.)
Glass foam	8.3	(4.6)	0.06	(0.39)	41	(1.6)	142	(5.6)	348	(13.6)
Fiber board	5	(3)	0.05	(0,36)	36	(1.4)	130	(5.1)	320	(12.6)
Perlite board	5	(3)	0.05	(0.36)	36	(1.4)	130	(5.1)	320	(12.6)
Glass fiber board	?	(?)	0.04	(0.25)	25	(1.0)	91	(3.6)	224	(8.8)
Polystyrene foam	63	(35)	0.03	(0.20)	20	(0.8)	74	(2.9)	178	(7.0)
Polyurethane foam	63-126	(35-70)	0.02	(0.15)	15	(0.6)	53	(2.1)	135	(5.2)

TABLE 2 –
BREAKING LOADS AND THERMAL SHOCK FACTORS OF ROOFING MEMBRANES AT 0°F

Asphalt Membrane Type	Felt Direction relative to load	Breaking load at 0°F		Thermal expansion*		Thermal Shock Factor**	
		$\frac{\text{kN}}{\text{m}}$	$\frac{\text{lbf}}{\text{in. width}}$	$\frac{\cdot 10^{-6}}{°\text{C}}$	$\frac{\cdot 10^{-6}}{°\text{F}}$	°C	°F
Organic felt 4 plies	longitudinal	89	(506)	25	(14)	360	(640)
	transverse	48	(267)	67	(37)	110	(200)
Asbestos felt 4 plies	longitudinal	79	(448)	35	(20)	160	(290)
	transverse	32	(182)	68	(38)	50	(90)

*Coefficient for temperature range from 0 to −30°F

**Defined as half the failure load, divided by sample width in inches, and by the sample strain at half the failure load.

TABLE 3 –
EFFECT OF MOISTURE ON RESTRAINED ROOFING MEMBRANES

Type of Membrane	Felt Direction relative to load	% Strain under moisture change		Failure * Strain, %
		Immersion	80% Rel. Humidity	
3-ply asphalt (asbestos)	longitudinal	small	** 0.1	0.8
	transverse	0.2	0.05	0.9
3-ply coated asphalt (organic)	longitudinal	0.2	*** 0.05	0.7
	transverse	0.9	0.1	0.7
3-ply asphalt (organic)	longitudinal	0.2	0.1	1.4
	transverse	1.1	0.2	1.5

* these figures taken from Ref. (4)

** two organic felts and one asbestos felt

*** two organic felts and one coated organic felt

TABLE 4 –
TENSILE STRENGTH OF ORGANIC ROOFING FELTS AS FUNCTION OF TESTING SPEED

Machine Rate of Straining		Tensile Strength of Sample, (ASTM D 2523)			
		Longitudinal Felt Direction		Transverse Felt Direction	
mm/s	(in./min)	kN/m	(lbf/in.)	kN/m	(lbf/in.)
0.02	(0.05)	5.4	(30.6)	2.6	(14.9)
0.04	(0.10)	5.8	(33.1)	2.7	(15.4)
0.21	(0.50)	6.8	(38.9)	2.8	(15.9)
0.42	(1.00)	7.6	(43.4)	3.0	(17.1)
2.12	(5.00)	9.3	(52.9)	3.4	(19.2)
4.23	(10.00)	10.9	(62.5)	4.0	(22.8)
8.47	(20.00)	11.5	(65.7)	4.3	(24.4)