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As the outer component of the roofing system, a built-up roofing (BUR) membrane is subjected to all the elements of the outside environment, with only partial protection provided by the top cover of gravel or other coating. Its performance will thus depend on its response to this environment which can best be explained by considering its physical properties in relation to the environmental factors to which it is exposed.

The principal environmental factors likely to affect membrane performance are moisture, air temperature and solar radiation. Bitumens are relatively unaffected by moisture due partly to the non-wetting character of their surface, but more particularly because of their non-porous structure. Solar radiation and cyclical temperatures, however, can result in a hardening of the surface and thermal contraction leading to microcracking of the exposed surface.

Shielding the surface from solar radiation with gravel or with other surface coatings provides some radiation protection and the "self healing" characteristic of bitumen may act to maintain its initial waterproofing qualities. This accepted "self healing" feature of bitumen recognizes that the material cracks at times and then reseals due to plastic flow at higher temperatures. This characteristic is indicative of the change in the physical properties of bitumen with temperature.

PROPERTIES OF BUR MEMBRANES

Only at very low temperatures or under a small, rapidly applied load do bitumens exhibit the properties of an elastic solid that deforms under load but returns to its original dimensions when the load is released (represented by line "A" in Figure 1). At temperatures such as those experienced in practice, or with a slower rate of application, the same load will result in a greater deformation (as in curve "B"). If the load is released quickly the bitumen will partially return to its original dimension (as in curve "C"), but if the load simply maintains a fixed deformation or strain, plastic flow or creep will allow the material to adjust to its new dimension as the load gradually decreases to zero (as in line "D"). This last-mentioned situation is representative of the loading induced in a membrane in practice by thermal expansion and contraction: the membrane is restrained to a fixed dimension and the load results from its tendency to expand or contract.

Some of the properties of bitumens are imparted to the felts used in built-up roofing through the factory saturation and coating process as well as in the field application of the composite membrane. Both wood fibre and asbestos felts are made by a manufacturing process which produces a fibre orientation in the long dimension of the sheet and results in a directional variation in properties. These directional properties are further exaggerated in the process of applying the felts. The fibre reinforcement is essentially unbroken in the felt direction but across the felt direction, the 36-in.-wide felts are simply overlapped and the fibres are discontinuous. Any lateral forces applied outside the dimensional limits of 36 in. are thus resisted by the bonding bitumen between the felts in shear.

Although slight variations exist between different felt-bitumen combinations, three general characteristics are most likely to influence their performance in practice:

1. Membranes tend to change in dimension with changes in temperature, the change being greater across the felt direction.
2. Except at very low temperatures or under rapid loading, bituminous membranes do not behave elastically but tend to creep or flow, resulting in a permanent deformation with time.
3. Membranes incorporating moisture-sensitive felts tend to expand and contract with increases or decreases in moisture content, the changes being greater across the felt direction.

ENVIRONMENTAL CONDITIONS

In practice the membrane in a conventional roofing system is exposed almost directly to the outside air temperature. The membrane surface temperature tends to follow this air temperature variation, but will also be significantly affected by the solar radiation conditions that occur on a daily basis, as indicated in Figure 2.

Under sunny conditions the surface temperature of a roof membrane rises to a peak well above air temperature. During the night, surface temperatures will drop to air temperature or lower because of radiation to the clear night sky. More rapid changes in temperature occur when solar radiation is intercepted by passing clouds, such effects being indicated by the fluctuations in the high portion of the curve (Figure 2).

Although the maximum range of temperature that the membrane experiences will be that between the coldest clear night in winter and the sunniest day in summer, it will undergo a significant and more rapid change in temperature on a repetitive, daily basis, particularly in summer. In view of its sensitivity to temperature its possible response to these changes should be examined.

MEMBRANE MOVEMENT - RIDGING AND SHRINKAGE

If the membrane is restrained to a fixed dimension and subjected to the daily temperature cycle it tends to expand on heating and compressive stresses will develop. Plastic flow or creep will also begin to occur at a rate that will increase with increasing temperature. Because of this characteristic property, all the stresses in the membrane can relax in time. When the membrane begins cooling, due to a reduction in solar radiation and air temperature, it tends to shrink and tensile stress will develop because it is restrained. In time, plastic flow or creep in the membrane could again allow the stresses to relax.

A bituminous roofing membrane will thus experience both compressive stresses and tensile stresses under a typical daily temperature cycle. Increasing temperatures will generally induce compressive stress; decreasing temperatures will induce tensile stress. There will also be periods during which time and temperature will permit plastic flow to occur and relax the stresses (the rate of and tendency for plastic flow being greater at higher temperatures).

There are several ways in which stresses in membranes might be relaxed. When under compression, plastic flow could allow the membrane to increase in thickness. Plastic flow in shear between the layers could allow membrane movement and if the membrane is not held down at a particular location, buckling could occur. When the membrane is subsequently placed in tension, plastic flow in the bitumen layer between the membrane and insulation may allow the buckle or ridge to flatten. If ridges had not formed, tensile forces could cause the membrane to decrease in thickness or could result in slippage between the plies, at the membrane insulation interface or between the insulation and the deck.

The resistance offered by the bitumen layers in shear will be less at higher than at lower temperatures. When subjected to a daily cycle, slippage of one felt over another is more likely to take place on heating than when the membrane goes into tension on cooling. Thus, if the membrane is not secured at its perimeter, such cyclical heating and cooling could result in an incremental, progressive shrinkage away from the edges of the roof until the net result becomes obvious. Such over-all shrinkage will be greater across the felts since the coefficient of thermal expansion is greater and in this direction nonreversible slippage between overlapping plies could occur by shear in the bitumen layers. In the felt direction the stresses will be more uniformly distributed because of the action of the continuous fibres.

EFFECT OF NONUNIFORM HEATING AND COOLING

Temperatures are not likely to be uniform on an actual roof. Shaded areas tend to cool to air temperature, there will be differences in surface colour and heat absorption, and the air flow pattern over the roof will usually be such as to dissipate heat more rapidly in some areas than in others.

In Figure 3, for example, hot air rising above the roof surface will draw in air from around the perimeter and set up convection currents causing the central area to heat up faster than the surrounding area. As the central area heats up it will expand and go into compression; this expansion will be resisted by the surrounding area as it gradually increases in temperature and goes into compression. Eventually the whole membrane will be in compression but the central area will be at a higher temperature and creep or plastic flow will allow the stresses to relax.

If the stresses in the central area are relaxed while the surroundings are still in compression, there will be a tendency for the surrounding felts to push inward towards the central area. These inward forces may promote slippage of one felt over another, a localized increase of the thickness of felt, or they could result in buckling at a point where the membrane has the least adhesion to the substrate. As the temperature of the whole membrane continues to rise, or if sufficient time elapses, plastic flow or creep could allow the whole membrane to relax and if sufficient material has been pushed into the central area, the ridges in the central area may remain.

When the cooling cycle begins, all areas of the membrane will develop tensile stresses but those developed in the central area will be higher since it cools through a greater range of temperatures. Under these circumstances the central area will tend to pull in material from its perimeter as indicated in Figure 4. As the whole membrane relaxes, in time, an increased amount of material may remain in this local area. This mechanism will also lead to the migration of the felts towards the centre resulting in even greater shrinkage at the edges of the roof if the membrane is not restrained at the perimeter. If the membrane is restrained at the perimeter, slippage between overlapping felts could take place without serious consequences and with no evidence of shrinkage at the roof edges.

THE ROLE OF INSULATION JOINTS AND MOISTURE

When a portion of the membrane is under compressive stress, and particularly when material is being pushed into an area, any buckling of the membrane is most likely to occur at a location where the membrane is not held down to the substrate. A joint in the insulation may well provide such a location. If the insulation boards are separated by a crack, a narrow unbonded strip occurs. If the upper surfaces of adjacent insulation boards are not level with one another, a wider unbonded strip will exist. Thermal expansion of the top portion of the insulation at this point could add another assisting force. If moisture had concentrated at the joint previously, some deterioration in the bond between membrane and the insulation could have occurred. Any lateral penetration of moisture into the felt at this location would increase still further the width of the unbonded area.

The role of moisture in reducing the bond between plies or between membrane and substrate is suggested in this analysis as a contributing factor to ridge formation. Arguments based on the moisture expansion of felts as the prime cause of ridging have also been advanced over the years.

Felts will expand due to an increase in moisture content but in many actual ridging cases the increase in the dimension of the membrane required to produce the ridge appears to be many times the increase that could be achieved by moisture expansion alone. Most field observations indicate that a movement of material to the location is necessary to provide the amount required to form the ridge and it is suggested that cyclical heating and cooling can provide this type of progressive movement.

Joints in the insulation are locations where a concentration of moisture due to condensation will occur on the underside of the membrane. Penetration of this moisture into the felts will be inhibited but not necessarily stopped by any bitumen coating such as that on a coated base sheet. The protective effect of the asphalt coating will slow down the rate at which moisture is accumulated, reducing both the amount of localized expansion and the deterioration of the bond at this location. If the felt is unprotected by bitumen at the joint, this lateral migration of moisture will be accelerated and a reduction of bond at this critical location could result in less time.

MEMBRANE SPLITTING

Unequal rates of cooling of various areas of the roofing membrane surface could create localized areas of membrane shrinkage and hence strain in tension. When such an area is rapidly cooled, the temperature of the upper surface of the membrane will drop faster than that of the underlying plies. Any tensile stresses existing in the surrounding membrane could produce a tensile force that is resisted primarily by the upper ply since the lower plies will be warmer and more subject to plastic flow. With all of the tensile force produced by the adjacent area acting on the upper ply it will experience a tensile stress much higher than if all the plies of the membrane were involved.

A further concentration of stress in the upper ply could result from a reduction in thickness due to microcracking of the upper surface. Such fissures may also have permitted moisture to penetrate into the felt, further reducing its strength at this critical location. Any tension failure of the upper ply could lead to the progressive failure of the underlying plies until a split develops completely through the membrane.

CONCLUSION

The daily cycle of heating and cooling of bituminous membranes can result in the development of tension and compression forces which may act to produce membrane movement. This cyclical movement and the localization of strains in the membrane will be augmented by the uneven temperature patterns on the roof occasioned by shading, colour variation and air movement. Consideration of these factors in relation to membrane properties can serve to explain the observed performance of built-up roof membranes in regard to ridging, shrinkage and splitting. Improvements in performance could be obtained by restraining the membrane at the roof perimeter and by reducing the temperature cycle to which it is exposed, through the use of reflective coatings, or the addition of thermal insulation above the membrane.

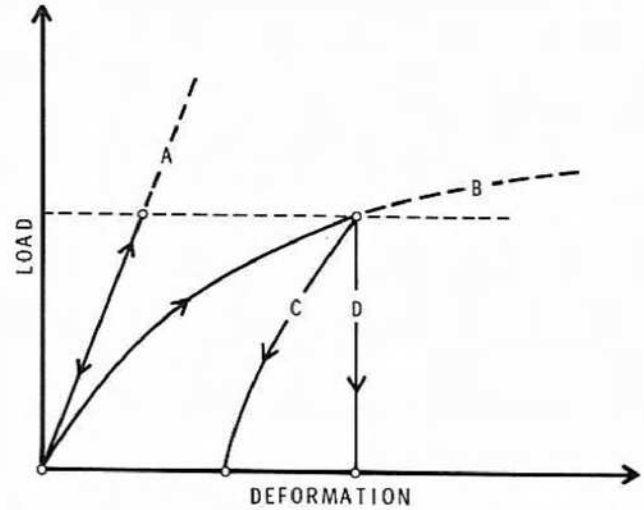

FIGURE 1

LOAD-DEFORMATION CHARACTERISTICS OF BITUMINOUS MATERIALS

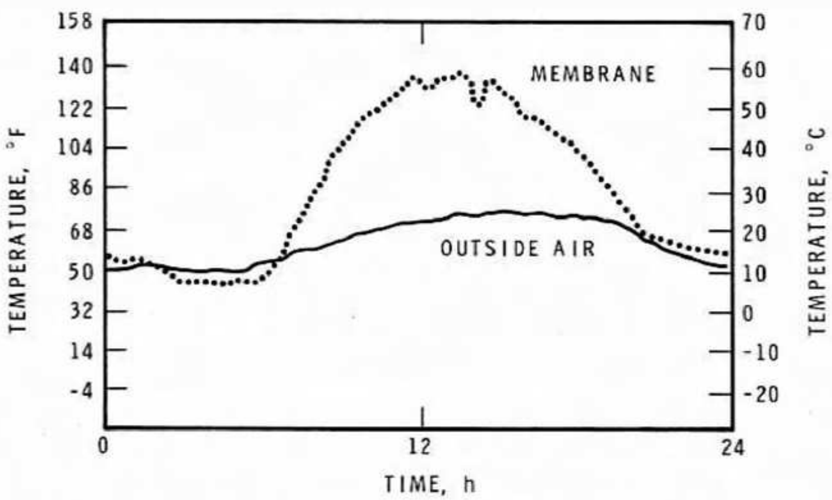

FIGURE 2

DAILY CYCLE OF MEMBRANE TEMPERATURE IN SUMMER

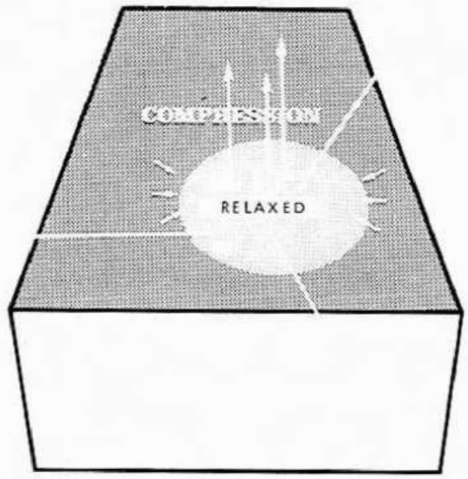

FIGURE 3

MEMBRANE MIGRATION BY NON-UNIFORM HEATING

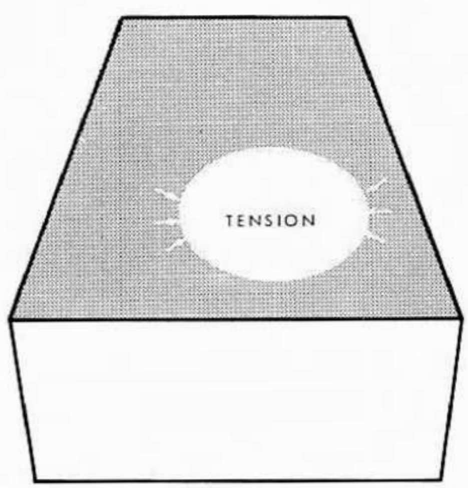

FIGURE 4

MEMBRANE MIGRATION BY NON-UNIFORM COOLING