Design Parameters for Use of Reinforced Stress-Absorbing Membrane Interlayers

Thomas R. Jacob

The results of testing conducted on asphaltic concrete test beams with a reinforced stress-absorbing membrane interlayer (SAMI) are presented. Testing was conducted on the Owens Corning Fiberglas traffic and thermal load fatigue tester, located at the Cincinnati Testing Laboratories. Measurements of combined thermal and traffic loading failure points for test beams with different combinations of binder moduli, overlay thickness, simulated base condition, and temperature are presented. Results of finite-element modeling are also presented to support the conclusions. Theoretical conversions to prerepair road deflections are made. The intent of the paper is to identify performance limits from reflective cracking of overlays with reinforced SAMI as a function of road deflection, anticipated minimum temperature, reinforcement tensile strength, and binder moduli. Testing results show significant improvement in both thermal and traffic load-handling capabilities. An even greater improvement is shown if a high-modulus binder is used between the reinforcement and the original pavement layer and a low-modulus binder is used between the reinforcement and the new overlay.

Reflection cracking is a cause of road distress in asphaltic overlays worldwide. It is known to be caused by thermal contraction and by the deflection of repeated traffic loads. Two approaches that have been taken in an effort to prevent reflection cracking have been the use of a stress-absorbing membrane interlayer (SAMI) and a SAMI with reinforcement. However, little testing of these conditions has been undertaken. In pursuing the evaluation of the effects of reinforced SAMIs on reflective cracking due to traffic loading, Owens Corning Fiberglas (OCF) contracted with Robert Lytton, Texas A&M University, and K. Majidzadeh, Resource International Inc., to test beams cycled through various amounts of deflection simulating various loadings or base conditions, and the cycles to failure were measured. However, the measurements were made at room temperature and thermal loading effects were ignored. Because in real life reflective cracking is usually the result of a combination of both thermal and traffic loading and the mechanical properties of asphalt are highly temperature dependent, the useful knowledge obtained from these studies was limited.

To overcome these deficiencies, OCF, in conjunction with the Cincinnati Testing Laboratories (CTL), developed the traffic and thermal load fatigue tester in 1983. This testing device allowed simultaneous thermal and traffic load fatigue testing and also allowed the testing to be done at temperatures from below $-100°F$ to $+180°F$.

This paper incorporates the large quantity of data that has been obtained using this testing device since 1984. The intent of this paper will be to define performance limits due to reflec-

tive cracking of overlays with reinforced SAMIs as compared with basic asphaltic concrete overlays as a function of road deflection and minimum temperatures. Two reinforced SAMI systems are reported here. One uses a single low-modulus binder between the reinforcement and both the original pavement layer and the new overlay. The second uses a high-modulus binder between the reinforcement to the original pavement layer and a low-modulus binder between the reinforcement and the new overlay. The paper also identifies the function of the binder moduli and indicates the type of physical property testing that is required to properly identify performance limits.

SAMI THEORY

Figure 1 shows the general conditions that normally exist when an overlay is placed on an existing cracked road. Because of environmental changes, a varying temperature profile exists in the pavement that extends through the new overlay and the old payment into the base until it reaches an essentially steady-state condition. The maximum rates of change tend to occur at the top of the road surface and the changes decrease with depth in the road. Because of expansion and contraction, varying degrees of stress also exist in the pavement, and the stress profile is similar to the temperature profile (assuming that no movement has occurred).

Because the original cracked road cannot transfer a significant amount of stress across the crack and the road is essentially not bonded to the road base, either the expansion or contraction must result in movement of that layer or the resulting strain must be transferred as stress into the new overlay. The strain is essentially zero at the centerline between cracks in the original road. Assuming a continuous bond between the original road layer and the new overlay, the stress transferred into the new overlay is essentially zero at the centerline between the original layer cracks and increases until it reaches a maximum directly above the original layer crack. At this point the uniform stress from the expansion and contraction of the new overlay and the entire cumulative stress from expansion and contraction of the original road layer are present (see Figure 2). Therefore the new overlay must be either strong enough to withstand this total stress or elastic enough to provide enough elongation to relieve the stress. Assuming that a continuous bond exists up to the edge of the crack, most of the elongation must occur over the width of the crack.

The theory behind a SAMI is to provide an interlayer between the original road layer and the new overlay that isolates the two. Obviously, if there were no bond between the two layers,

the original road layer would be free to move and no stress would be transferred to the new overlay. However, it is just as obvious that this is not practical from a structural standpoint. The compromise is to provide a low-modulus interlayer that allows some relative movement between the original road layer and the new overlay and yet provides a bond between the original road layer and the new overlay. However, in order for this to work, the modulus of the interlayer must be low enough so that the cumulative stress transferred into the new overlay between the slab centerline and the crack tip plus the stress already in the new overlay minus the stress relief from the elongation of the new overlay cannot exceed the tensile strength of the new overlay (Figure 3).

Another compromise approach is to provide only the SAMI in the immediate vicinity of the original crack. The assumption behind this approach is that failure will occur only when the transferred stress plus the existing internal stress of the overlay exceed the tensile strength of the overlay. Therefore only the cumulative stress that exceeds the tensile strength needs to be dealt with. With this approach, the stress transferred into the new overlay is the same as that described for standard roads with no SAMI up to the point where the SAMI begins. However, it is still less than the tensile strength of the overlay. If the modulus of the SAMI is low enough, then the cumulative stress transferred through the direct bond plus the additional cumulative stress transferred through the SAMI plus the existing internal stress of the overlay minus the stress relief from elongation of the overlay will still be less than the tensile strength of the overlay (Figure 4). Because some movement of the new overlay is possible directly above the SAMI, stress-relieving elongation of the new overlay can take place over the entire width of the SAMI instead of just over the width of the crack.

SAMI-WITH-REINFORCEMENT THEORY

The theory behind a SAMI with reinforcement is not only to provide an isolating interlayer between the new and old road layers but to also bridge the crack in the old road layer with a reinforcement that will allow transfer of stress across the crack. This not only reduces the amount of thermal stress that is transferred from the original cracked road to the new overlay but also reduces fatigue cracking from traffic loading as well.

Figure 5 shows in an exaggerated way the bending in the new overlay that occurs from traffic loading. Because the crack in the old road layers allows no load transfer, the new overlay and the road base must totally absorb the traffic load. The bending that occurs in the new overlay has a center point (hinge point) roughly in the center of the new overlay. Therefore roughly the top half of the overlay is in compression whereas the bottom half is in tension. When the overlay is undergoing both thermal load and traffic load, the stress in the bottom half of the overlay resulting from the traffic load tension must be added to the stress already present from the thermal load. The compression in the top half of the overlay from the traffic loading actually reduces the stress present from the thermal load.

When a SAMI with reinforcement has been installed, as also shown in Figure 5, load transfer across the crack is possible. This lowers the hinge point of the system to just above the reinforcement. The result is that most of the new overlay is in compression during traffic loading.
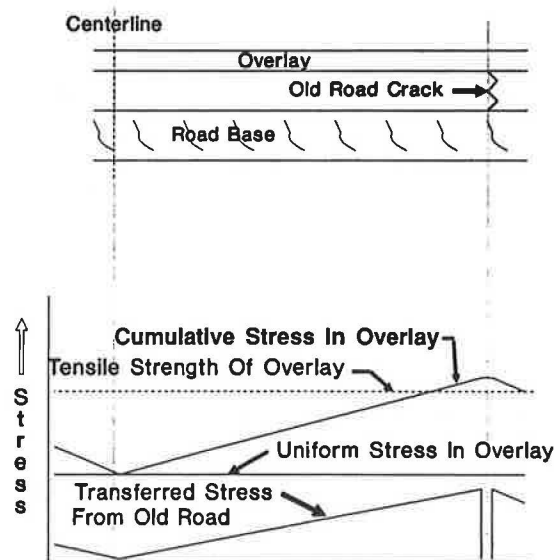

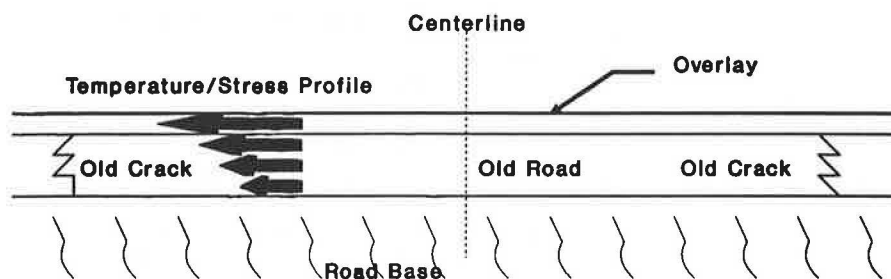**FIGURE 2 Stresses with standard overlay construction.**

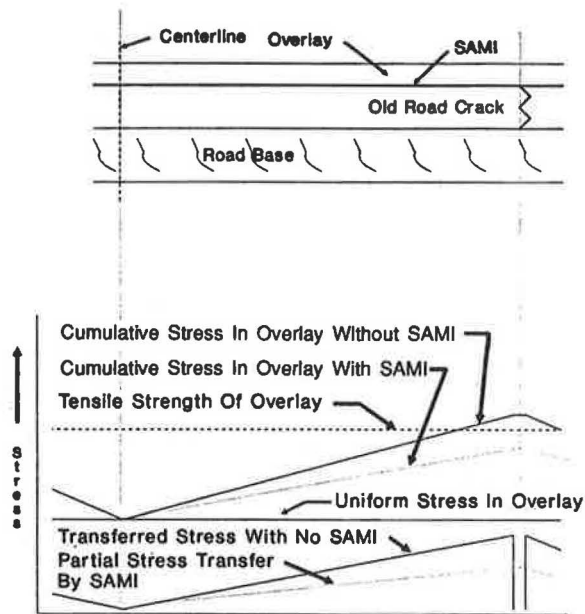**FIGURE 1 General conditions for an overlaid, cracked road.**
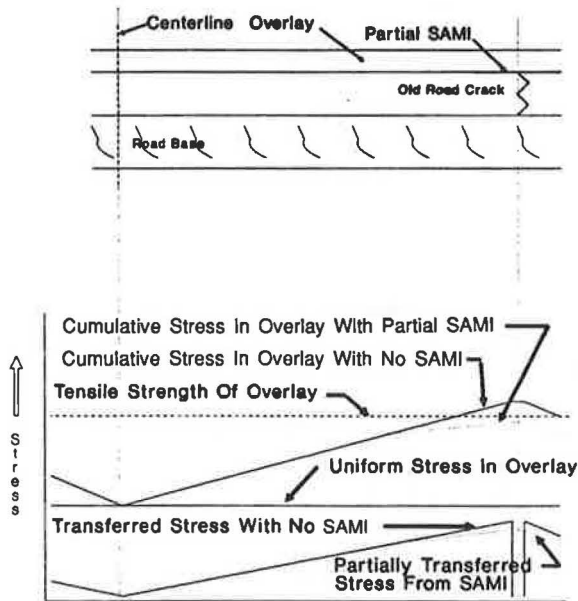
FIGURE 3 Stresses with SAMI construction.

FIGURE 4 Stresses with partial SAMI construction.

FINITE-ELEMENT MODELING OF TRAFFIC LOADING

Finite-element modeling of traffic loading confirmed that increasing the strength of the reinforcement reduced the stress intensity at the crack tip of the assumed starter crack directly above the crack in the old road layer. Figure 6 shows the relative stress intensity at the crack tip as a function of the binder modulus that joins the reinforcement to the old road layer. The finite-element modeling clearly shows that the higher the binder modulus, the better the reinforcement system at reducing traffic-load fatigue cracking.

There is a limit, however, to the amount of stiffness that is desirable in the reinforcement binder. The amount of stress
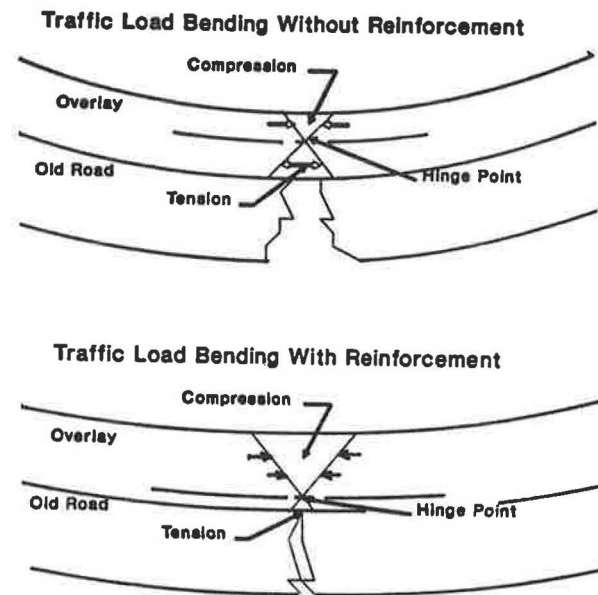

FIGURE 5 Overlay bending with traffic load.

that is transferred to the reinforcement by the binder cannot exceed the tensile strength of the reinforcement, or failure of the reinforcement will obviously occur.

A word of caution must be given about using only a high-modulus binder-reinforcement spot repair system without a SAMI. Finite-element modeling showed that for thermal loading, a high-modulus binder-reinforcement system simply moved the stress concentration from directly over the original crack to the edge of the reinforcement. Field-trial testing confirmed that a high-modulus reinforcement system without SAMI resulted in two-edge cracks.

The effect of a reinforced SAMI with a single binder on thermal stress is shown in Figure 7. The stress that the reinforcement transfers across the crack in the old pavement layer is equally distributed between the old layer and the new overlay. Therefore, half of the stress still ends up in the new overlay. However, if a high-modulus binder is used to join the reinforcement to the old pavement layer and a low-modulus SAMI bonds the reinforcement to the new overlay, the transferred stress from the reinforcement is proportional to the moduli of the binders. The stress in the old pavement layer is increased and the stress in the new overlay is decreased (Figure 8). This is desirable when the old pavement layer is thicker than the new overlay and has a greater strength.

DESCRIPTION OF TESTING DEVICE

The basic design of the OCF Thermal and Traffic Load Fatigue Tester is shown in Figure 9. Asphaltic concrete test beams of overall dimensions 3 in. by 3 in. by 24 in. were tested vertically to accommodate the design of the MTS testing machine (MTS Systems Corporation, Minneapolis, Minn.). The MTS simulated or measured the thermal loads. A second hydraulic actuator perpendicular to the axis of the MTS simulated the traffic loading. An insulated chamber surrounded the test beam to provide a controlled environment. Liquid nitrogen

provided the cooling, and a forced-air electric heater provided the heating.

THERMAL STRESSES

To determine the amount of thermal stress that built up in the asphaltic concrete, temperature profiles in the asphalt were determined under various weather conditions with the HEATING 5 (*1*) computer simulation program. It was determined that the maximum rate of temperature change in the
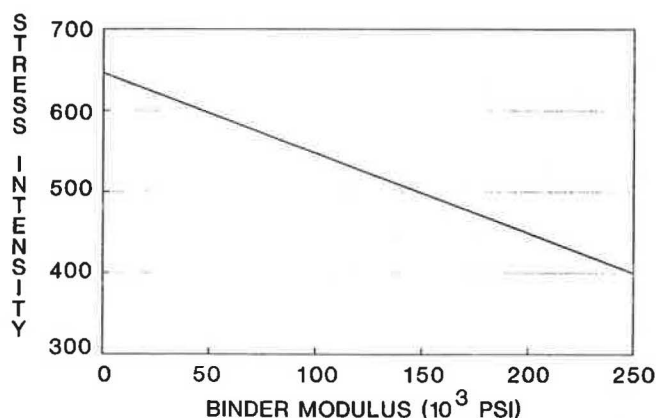

FIGURE 6   Finite-element crack-tip stress intensity for traffic loading.
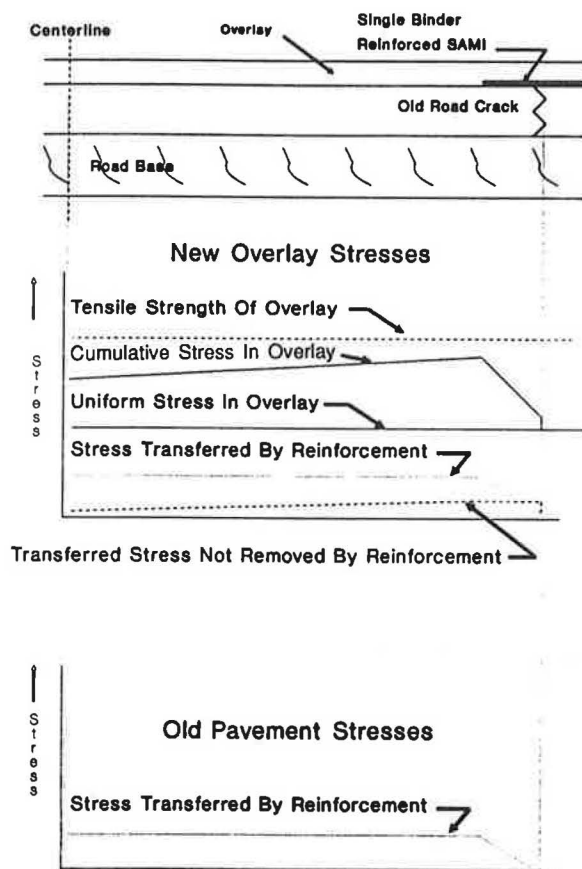

FIGURE 7   Stresses with partial reinforced SAMI: single binder.

asphaltic concrete occurs when solar loading is present in combination with very low temperatures. The typical maximum rate of surface temperature change was about 6°F/hr with solar loading and about 3°F/hr without.

The amount of thermal stress that builds up within the asphaltic concrete (*2*) at the fast (6°F/hr) and the slow (3°F/hr) temperatures drop rates is shown in Figure 10. The fast rate of temperature drop (6°F/hr) was used in the testing reported in this paper.

TENSILE STRENGTH OF ASPHALTIC CONCRETE

The tensile strength of an Ohio 404 design mix asphaltic concrete as a function of temperature is shown in Figure 11. Unless otherwise indicated, the Ohio 404 design mix was used for all of the test results shown in this paper.

THERMAL LIMITS OF ASPHALTIC CONCRETE

Also in Figure 11, the thermal stress of a test beam undergoing a 6°F/hr temperature drop is superimposed over the tensile strength curve for the same beam. Where the two curves intersect, the beam will normally fail from thermal loading alone.

Estimated curves of stress for various thicknesses of overlay are shown in Figure 12 along with the tensile strength of the Ohio 404 design mix. For a 1-in. overlay, the point at which the overlay would fail from thermal loading is about 5°F. A
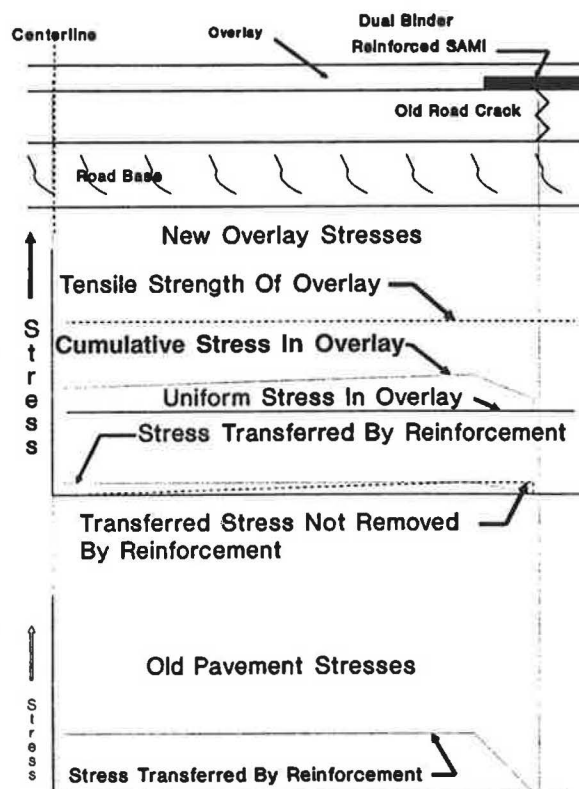

FIGURE 8   Stresses with partial reinforced SAMI: high- and low-modulus binders.

2-in. overlay fails thermally at about −8°F. A 4-in. overlay fails at about −30°F.

The importance of knowing the tensile strength of specific design mixes is clearly demonstrated in Figure 13. When the tensile strength curve from another design mix is superim-
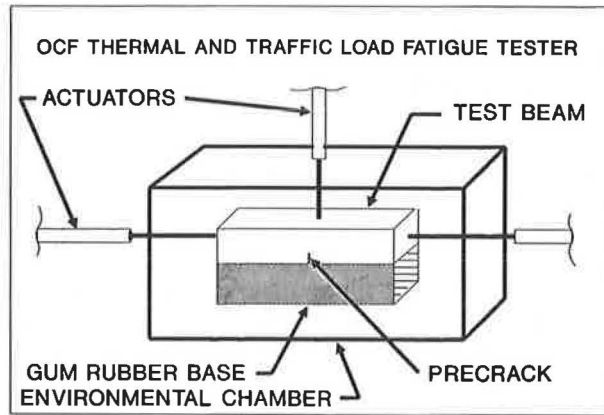
posed on Figure 12, it can be seen that the temperature at which a 1-in. overlay of this mix would fail thermally is about 15°F instead of 5°F, or a loss of 10° of temperature capability. The effect is even more dramatic as the overlay thickness increases. At 4 in. of overlay, this design mix would fail at about −10°F instead of −30°F, or a loss of 20° of temperature capability. This loss of tensile strength is carried over into the performance of SAMIs and SAMIs with reinforcement; therefore, it is important to know the fundamental physical properties of the overlay materials in trying to project ultimate overlay performance.

TRAFFIC LOAD TESTING OF ASPHALTIC CONCRETE ABOVE 40°F

Thermal stress testing indicated that for the Ohio 404 design mix tested, no thermal stress was present above 40°F in an asphalt overlay. Therefore, above 40°F traffic load testing was conducted with no thermal stress. Multi-pivot-point end plates were used to attach the beams to the MTS machine so that bending moment stresses were not introduced. The MTS

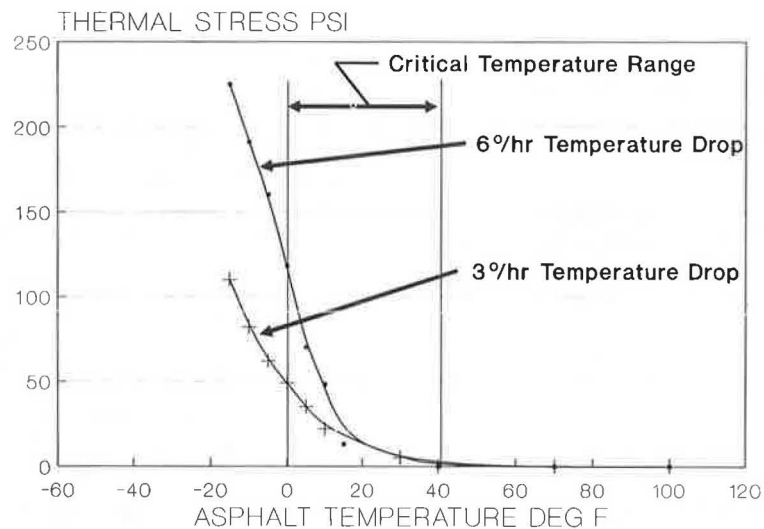FIGURE 9   OCF thermal and traffic load fatigue tester.

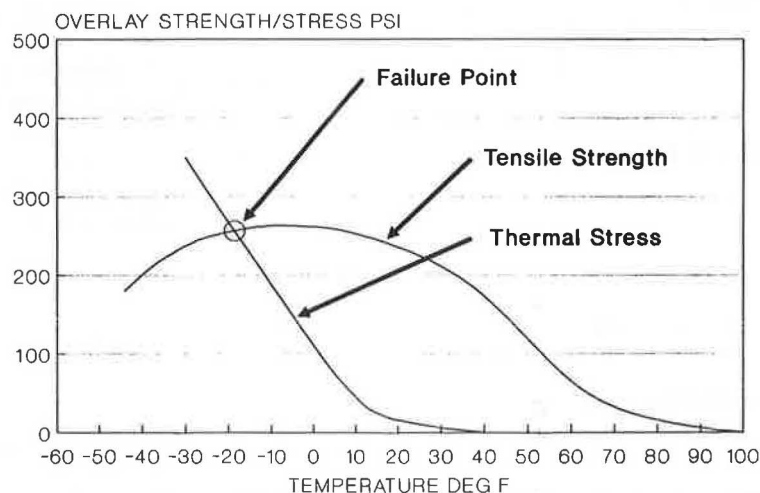FIGURE 10   Thermal stresses in asphalt roads.

FIGURE 11   Expected thermal failure point for Ohio 404 design mix.

machine was run under load control and the thermal load was kept at zero. Traffic load was simulated for an 18-kip axle load (200 lb applied through a 2 by 3 in. rubber loading plate at 1 cycle/sec). Cycling was continued until the beam failed or until 48 hr of cycling (172,800 cycles) was completed. Normally, if a beam were going to fail, it would fail in 100 to 1,000 cycles. Various densities of gum rubber were used to simulate different base conditions. The test temperature was varied from 40° to 160°F. The test beams were made up of a 2-in. or 1-in. asphaltic concrete layer with a preformed crack. The reinforced SAMI was placed over this layer and was in turn overlaid with 1 in. or 2 in. of asphaltic concrete as appropriate to make up the 3-in. test beam.

Previous testing of asphaltic test beams without SAMI indicated that there was a critical deflection that would result in crack propagation. This critical deflection was independent of overlay thickness or temperature. Although thicker overlays required weaker bases (or heavier loads) to achieve the critical deflection, once that deflection was reached, crack propagation was initiated. Similarly, as the temperature dropped and the asphalt became stiffer, more load or a weaker base was required to reach the critical deflection, but once that deflection was reached the crack began to propagate. The critical deflection for the Ohio 404 design mix was 0.055 in.

Similar results were found for overlays with reinforced SAMI. Regardless of the overlay thickness or temperature, a critical deflection was found that resulted in the onset of rapid crack propagation. However, the critical deflections were different for different binder moduli. The critical deflection for the single low-modulus binder was 0.11 in. The critical deflection for the dual-modulus system (high modulus–low modulus) was 0.36 in. Again, weaker bases or heavier loads were required to reach the critical deflection for thicker overlays or lower temperatures. But when the critical deflection was reached, crack propagation was initiated.

THERMAL AND TRAFFIC LOAD TESTING OF ASPHALTIC CONCRETE BELOW 40°F

For temperatures below 40°F, thermal loads are usually also present during traffic loading. Therefore for all simulated traffic load testing below 40°F, thermal loads were also incorporated.

For all testing below 40°F, test beams were thermally soaked at 40°F. The temperature in the test chamber was reduced by 6°F each hour. The thermal tensile loads were measured or applied through steel plates bonded to the entire ends of the
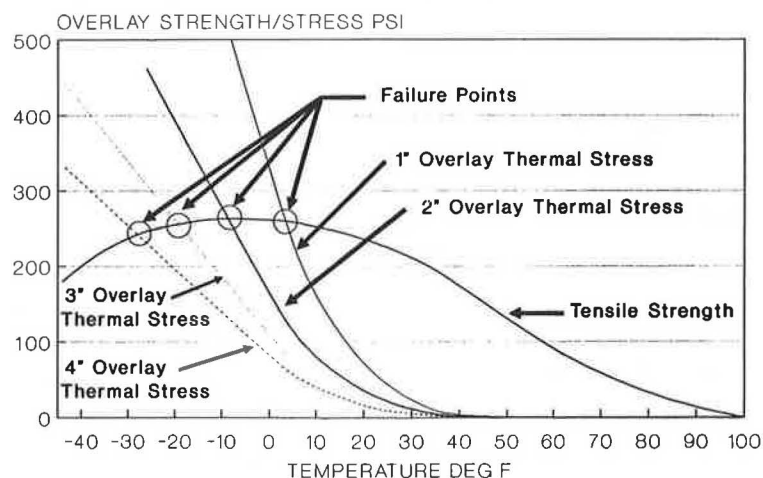

FIGURE 12 Expected thermal failure points with various thicknesses of overlay for Ohio 404 design mix.
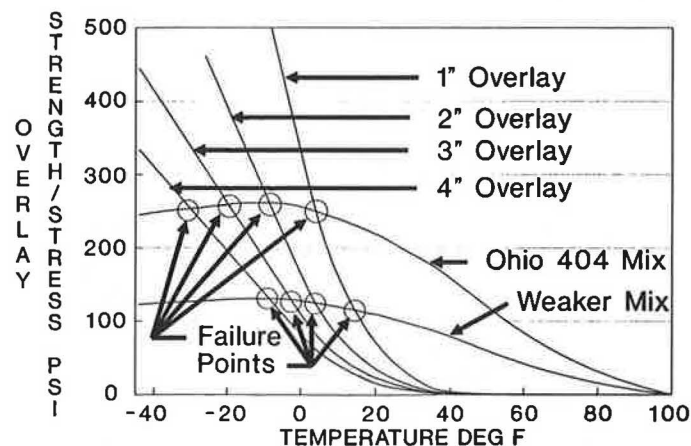

FIGURE 13 Thermal failure points for various thicknesses of overlay for two design mixes.

test beam. At the end of each hour, the thermal stress in the beam was adjusted, if necessary, to the schedule shown in Table 1. This load schedule is representative of the thermal stress for a 6°F/hr temperature rate drop as previously shown in Figure 10. The stress adjustments were made to try to reduce the amount of variability in the test results. If no traffic loading was to be incorporated into the test, the 6°F drop in temperature each hour was continued until the test beam broke.

If traffic loading was incorporated into the test, a set base condition was established and the equivalent 18-kip-axle traffic load was applied at 1 cycle per sec. The temperature was then dropped 6°F each hour and the thermal stress was adjusted to the amounts in Table 1 as previously described. This was continued until the beam broke.

Overlays Without SAMIs

The results for overlays without SAMIs are shown in Figure 14. Note that the traffic loading and thermal loading are additive. The temperature at which failure occurs increases as more deflection is applied and, likewise, the critical deflection for crack propagation decreases as increased thermal tensile

stress is applied. For example, the results show that the ultimate thermal-stress capability of a 1-in. overlay without SAMIs and without traffic loading with an Ohio 404 design mix is about 5°F. However, if a traffic load results in a deflection of 0.02 in., failure will occur at about 10°F. Similarly, a 2-in. overlay will fail at about −10°F without traffic loading but will fail at about −4°F when a traffic load resulting in a 0.02-in. deflection is simultaneously applied.

The general interpretation of Figure 14 is that if the temperature and deflection conditions are below and to the right of the curve for the overlay thickness in question, a reflection crack should not occur. However, if the temperature and deflection conditions are above or to the left of the curve for the overlay thickness in question, a reflection crack should be anticipated.

Reinforced SAMI with Low-Modulus Binder

The results for overlays with a reinforced SAMI using a single low-modulus binder are also shown in Figure 14. Note that the critical deflection for traffic loading for this reinforced SAMI has been increased to about 0.11 in.

The thermal load capability with this reinforced SAMI has gone from about 5°F for a 1-in. overlay to about −10°F. For
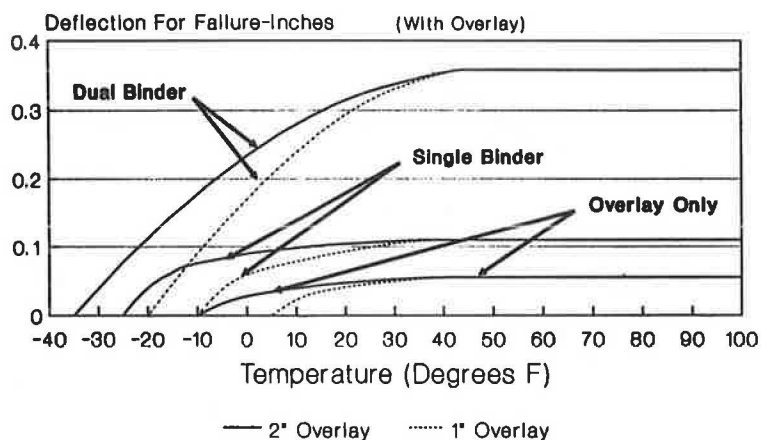

FIGURE 14 Overlay performance boundaries for partial reinforced SAMIs: postoverlay conditions (asphaltic concrete strength, 260 psi at 0°F, deflection for 18-kip load).
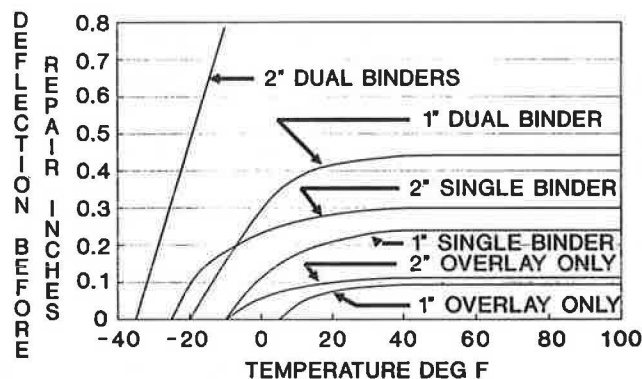

FIGURE 15 Overlay performance boundaries for partial reinforced SAMIs: preoverlay conditions (asphaltic concrete strength, 260 psi at 0°F, deflection for 18-kip load at 70°F).

a 2-in. overlay the thermal load capability has gone from about −10°F to about −25°F.

Again the thermal and traffic loads are additive. At 0.05 in. deflection, the thermal limit goes to about −5°F for a 1-in. overlay and to about −14°F for a 2-in. overlay.

Reinforced SAMIs with High- and Low-Modulus Binders

The results for overlays with reinforced SAMIs using a high-modulus binder to join the reinforcement to the old pavement layer and a low-modulus binder to join the new overlay are also shown in Figure 14. In this case the critical deflection (the deflection at which crack propagation begins) has increased to about 0.36 in. An increase in thermal load capability was also noted for the reinforced SAMI with high- and low-modulus binders. The thermal load limit for a 1-in. overlay went from about −10°F for a reinforced SAMI with a single low-modulus binder to about −20°F for a reinformced SAMI with high- and low-modulus binders. Two-inch overlays went from about −25°F for the reinforced SAMI with low-modulus binder to about −40°F for the reinforced SAMI with dual binders. Again, the traffic load and thermal load are additive.

It should be noted that the critical deflection for a 2-in. overlay could not be reached. The compressive load-carrying abilities of the overlays were exceeded before the critical deflection was reached, and the overlays were crushed. Therefore it is assumed that, as in all other cases, the 2-in.-overlay critical deflection is the same as the 1-in. critical deflection.

ADJUSTMENT OF PERFORMANCE CURVES TO PREOVERLAY CONDITIONS

The results in Figure 14 refer to postoverlay deflections. However, overlay thickness decisions are based on the conditions of the road before overlay application. Therefore, Asphalt Institute design curves (3) were used to adjust the performance limits shown in Figure 14 to preoverlay conditions. These are shown in Figure 15. Note that these curves are normalized to deflections at 70°F with an 18-kip axle load. Also note that a warm-temperature deflection limit is not shown for the 2-in. overlay with reinforced SAMI using high- and low-modulus binders. Again this is because, during testing, overlays were crushed before traffic load–induced cracks could be propagated.

The proper way to use these design curves would be to first determine the minimum anticipated temperature that would

be expected during the design life of the road. This is necessary because a single excursion below the temperature limit capability of an overlay will cause failure. The next step would be to determine the worse-case deflection at 70°F. That is, deflection measurements should be made when base conditions are at their worst (e.g., springtime when the water table is high) and the measurements are adjusted to 70°F. With the minimum design temperature and a maximum deflection number, Figure 15 can be used to determine the minimum amount of overlay necessary to prevent reflective cracking.

An example of this process would be that for Ohio, the 13-year minimum design temperature is −5°F. At that design temperature, a 1-in. overlay without reinforced SAMI would fail. However, a 1-in. overlay with reinforced SAMI with a single low-modulus binder would have a good probability of surviving if the preoverlay worst-case road deflection is less than about 0.05 in. A 1-in. overlay with reinforced SAMI using high- and low-modulus binders would have a good probability of surviving if the preoverlay worse-case deflection were less than about 0.23 in. If the worst-case deflection is known to be roughly 0.06 in., the Ohio design engineer could see that more than 2 in. of overlay would be needed to have any chance of survival. However, if a reinforced SAMI with low-modulus binder were installed, 1 in. of overlay would have a fairly good chance of surviving normal conditions. If the engineer installed a reinforced SAMI with high- and low-modulus binders, a 1-in. overlay would have a fairly comfortable safety margin and should survive under most foreseeable conditions.

COMMENTS AND RECOMMENDATIONS

The data presented clearly show that reinforced SAMI can significantly reduce reflective cracking in asphaltic concrete overlays. The proper use of reinforced SAMI can result in performance that is equal to or better than much thicker overlays without the reinforced SAMI. Therefore, significant cost savings should be possible with comparable performance as compared with using thicker overlays.

The data also show that a reinforced SAMI is significantly more effective when used with a dual binder system that joins the reinforcement to the original road with a high-modulus binder and to the overlay with a low-modulus binder.

It should be noted, however, that the data presented are for several specific sets of conditions and for a specific Ohio 404 design mix that has a tensile strength of 260 psi at 0°F. The tensile strength of other design mixes may be significantly different. It is highly recommended that design mixes be tested for tensile strength at temperatures below 0°F.

The data presented are also for specific high- and low-modulus SAMI binders. As has been indicated in the section on SAMI theory, the rate of stress transfer from one pavement layer to another is a function of the modulus of the binder between them. The modulus-versus-temperature curve is different for various binders. In fact, the difficulty in developing SAMI binders is developing a binder with a modulus that is sufficiently high at warm temperatures to provide the desired mechanical properties yet to have a modulus low enough to provide stress relief at low temperatures.

The data presented are also for specific load conditions as dictated by weather conditions, base conditions, axle loads,

TABLE 1   THERMAL LOAD SCHEDULE

Test Temperature (°F)	Load (lb)	Test Temperature (°F)	Load (lb)
40	0	−2	1,125
34	30	−8	1,540
28	90	−14	1,950
22	170	−20	2,360
16	300	−26	2,775
10	475	−32	3,190
4	720		

and so on. Although the load conditions used for the testing are fairly representative in most cases, significant variations are possible.

It is feasible to design reinforced SAMI systems to function under very specific conditions. With knowledge of anticipated thermal and traffic load stresses, reinforcements of sufficient tensile strength can be applied. Likewise, the binder modulus can be tailored to provide a specific rate of stress transfer at a specific temperature. Although this capability does not currently exist, it is certainly within today's technology limits.

REFERENCES

1. W. D. Turner, D. C. Elrod, and I. I. Siman-Tov. *Heating 5: An IBM 360 Heat Conduction Program*. ORNL/CSD/TM-15. Union Carbide Corporation, Nuclear Division, Computer Sciences Division, undated.
2. T. R. Jacob. Basic Limits of Overlay Performance During Simultaneous Thermal and Traffic Loading. *Proc., Association of Asphalt Paving Technologists*, Feb. 1990.
3. *Asphalt Overlays for Highway and Street Rehabilitation*. Asphalt Institute Manual Series No. 17, Second Edition. The Asphalt Institute, College Park, Md., 1983.