# Asphalt-Rubber Stress-Absorbing Membranes: Field Performance and State of the Art

Gene R. Morris, Arizona Department of Transportation
Charles H. McDonald, Consulting Engineer, Phoenix

**Pavement cracking and subsequent reflection through overlays are directly associated with pavement deterioration and maintenance problems. During the early 1960s a process was developed using a composition of 25 percent ground tire rubber reacted with 75 percent hot asphalt. This process has been used in full-scale field projects in the form of stress-absorbing seal coats and interlayers and as waterproof membranes. Results from approximately 3200 lane-km (2000 lane-miles) of construction clearly show that this basic elastomeric material performs as a waterproof membrane and has a high capacity to absorb direct tensile, flexural, and shearing stresses. The paper reviews the performance of the asphalt-rubber seal coats placed since 1967 and the present state of the art of design and construction. It further reviews the potentials of stress-absorbing membranes placed to (a) prevent reflective cracking of overlays placed over both flexible and rigid pavements; (b) provide bridge deck protection; (c) control differential movement of existing pavements constructed over expansive clays; (d) provide economical construction for low-volume roadways; and (e) provide improved elastomeric sealing of cracks and joints.**

A pavement is no sooner built than deterioration begins, and most pavements usually require several major corrective measures and possibly complete reconstruction in a lifetime. The combined actions of traffic, sun, rain, frost, and soil moisture create multiple problems. These problems are all associated with stresses and related strains within the pavement structures, which are manifestations of forces created by the major factors noted.

The problems associated with these strains in pavements may be generally divided into the following three general categories:

1. Cracking of the pavement surface as a result of repeated flexural stresses,
2. Cracking of pavement surface by direct tensile stresses, and
3. Differential vertical movement between adjacent sections.

To state the problem basically, either the elastic properties or the tensile strength of the pavement structure is insufficient in responding without fracture to the forces acting on the pavement.

The most common and costly problem of pavement distress is fatigue cracking of asphalt pavements (1, 3, 9, 12). This type of cracking is due to repeated deflection of the pavement of as little as 0.25 mm (0.01 in) under wheel loads (1). In the advanced stage, it is manifested by an alligator or chicken-wire cracking pattern accompanied by the release of small pieces, which later creates potholes, particularly during wet weather.

Obviously, the problem here is due to a lack of flexibility (6, 10) or elasticity in the asphalt pavement component required to respond, without cracking, to the resilient nature of the substructure under load. This resilience in the substructure is due to the entrapment of air within soil pores and held there by the capillary pressure of moisture between the soil grains. The effect is most pronounced in fine-grained soils and results in a pneumatic or air mattress effect under load.

The second type of pavement distress, direct tensile stresses, occurs immediately after construction of rigid pavements and may be accentuated at later dates. In flexible pavements, direct tensile stress occurs usually after some period of service although it may occur in as few as 3 months; in rare cases, it does not occur during the normal design life of the pavement. The compromise solution to this specific problem is to provide weakened planes in rigid pavement so that the cracks occur at designated intervals, in a straight line; this eliminates potential spalling and provides a reservoir for sealant to prevent entry of moisture and incompressibles into the joint. Although this solution delays the problem, it is common knowledge that it does not eliminate it.

The direct tensile failure in a flexible pavement system is of a different nature and is generally caused by one of the following conditions:

1. The viscoelastic properties of the asphaltic concrete are such that at low temperatures its elastic limit is exceeded;
2. Oxidation and other chemical actions decrease the elastic limit of the asphaltic concrete, and the pavement cracks as a result of repeated temperature re-

Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.

versals in a fatigue mode of failure; or

3. Subgrade and subbase volume changes due to fluctuating moisture and temperature reflect stresses on the asphaltic concrete in excess of its tensile strength.

The third category of pavement distress, differential vertical movement, occurs after the pavement has cracked because of flexural or tensile failure modes. This type of distress is important in that it directly causes poor riding quality. It is also probably the critical factor in the initial reflection in overlays of existing cracks in underlying old pavements.

Efforts to solve these types of pavement deterioration with the limited use of elastomers date back for a number of years. The direction of these efforts has been to modify characteristics of the asphalt, or the asphaltic concrete, to reduce the effects of temperature change on the stiffness and elasticity of the structure (2). Unfortunately, costs have usually limited the percentage of elastomer to an amount inadequate to ensure sufficient elastic protection, particularly in cold weather when the pavement is most brittle.

## SOLUTION TO THE PROBLEM

This paper discusses the development of a system that can be used to correct the problems of a failed pavement and that can also be applied as a preventive measure in the design phase.

In the early 1960s, a concept was developed for overcoming the problem of fatigue cracking. Field trials were initiated in the winter of 1964-65, and results were reported to the Highway Research Board in January 1966 (8). The concept was based on a composition consisting of 25 percent ground recycled tire rubber reacted with asphalt at a high temperature to form a thick, jellied material with good elastomeric properties. To keep costs down and still get the benefit of a high rubber content required that this material be spread in a thin membrane over the cracked surface, covered with chips to provide a wearing surface.

The first full-scale field trial of this material took place in January 1967 on the main taxiway of the Phoenix Sky Harbor Airport (7). This pavement had been designed for DC-3 aircraft and was developing severe alligator fatigue cracking under Boeing 707 and similar aircraft. This application, though crude, served so well that by spring of 1968 the equivalent of some 24 lane-km (15 lane-miles) had been placed at the airport and on the streets of Phoenix.

The Arizona Department of Transportation became interested in this concept for preventing reflection of alligator cracking and, in summer of 1968, constructed an asphalt-rubber stress-absorbing seal over about 4 km (2½ miles) of severely fatigue cracked pavements on frontage and access roads of the Black Canyon Freeway, I-17 (4).

The general appearance of the application was poor because proper equipment and application techniques for the viscous asphalt-rubber composition had not yet been developed. However, with the passage of time and traffic, the unevenness of the application smoothed out until the appearance became reasonably acceptable. Most important, and in spite of construction difficulties, it proved the efficacy of the asphalt-rubber material in preventing reflection of alligator cracking. Today the surface is in excellent condition and shows only minor crack reflection after 8 years of hard service. Thermal or shrinkage cracking did reflect through the asphalt-rubber seal coat, but the cracks were narrow and have not spalled. Reflection of the extensive alligator cracking has not occurred (Figure 1).

The Arizona DOT and other public agencies placed several other projects between 1968 and 1971 by using the asphalt-rubber system and had success in controlling the fatigue cracking problem and variable results in overcoming construction problems, as application techniques were gradually perfected. One of the most notable projects treated with asphalt-rubber during this period was the main street of Tolleson, Arizona (US-80), in the summer of 1969. The street was severely deteriorated with extensive fatigue cracking and innumerable potholes. It actually appeared as though reconstruction would be imperative inasmuch as a conventional overlay of sufficient thickness to control the cracking could not be used because of curb height restrictions and drainage conditions.

The town authorities decided to try an asphalt-rubber treatment. First, the numerous potholes and wider cracks had to be filled. After 6 years of service, this project has required no maintenance and shows only a few minor reflective cracks and no evidence of spalling. Figure 2 shows the condition of the pavement before the treatment and now.

## STATE OF THE ART

A major improvement in the construction process, which improved the reliability of obtaining good workmanship and appearance, was introduced in spring of 1971. This was the solvent dilution process whereby a small quantity of kerosene was introduced into the viscous, reacted asphalt-rubber composition. This dilution temporarily reduces the viscosity of the composition and improves application uniformity and initial wetting of the chips. After not more than 2 hours, the viscosity of the composition increases to approximately its original high viscosity (2). This effect of the solvent dilution is apparently the reaction of the mixture to selective absorption of solvent by the rubber particles. Figure 3 shows laboratory tests confirming this behavior in the viscosity of the material.

As a result of this development and the encouraging performance of the Tolleson and Black Canyon Freeway projects, the Arizona Department of Transportation decided to more fully evaluate the concept. Other public agencies also increased their use of the asphalt-rubber system.

Three projects placed by the Arizona DOT have played an important role in the development of the current specifications, procedures, and evaluation of the capabilities of the system. These projects are commonly known as the Aguila, the Flagstaff, and the Minnetonka.

### Aguila Project

The Aguila project consisted of 9.6 km (6 miles) on US-60 and 9.6 km (6 miles) on Ariz-71 immediately east and north respectively of Aguila.

The pavements on these highways were in an advanced stage of fatigue, and plans called for a 150-mm (6-in) overlay to restore the structural integrity. The typical condition of the pavement is shown in the foreground of Figure 4. Insufficient funds were available for an overlay, so the asphalt-rubber seal coat was placed as an interim treatment. Because of the heavy traffic volume, especially on US-60, which temporarily carried I-10 traffic, synthetic lightweight cover material was used to reduce windshield breakage (13).

The seal coat was placed during July 1972, under extreme climatic conditions with ambient temperatures of approximately 45°C (113°F). In an effort to prevent aggregate rollover and pickup under the heavy traffic and high temperature, the asphalt-rubber was modified to use a harder asphalt (85 to 100 penetration) and 5 percent kerosene diluent. Traffic was held off the newly placed portions of the seal for as long as possible (at least 2 hours) and then directed through at low speeds. In spite of these precautions, some pickup occurred. The problem was finally corrected by applying a light layer of sand [1 to 1.5 kg/m$^2$ (2 to 3 lb/yd$^2$)] before the final rolling. This procedure is included in the present specifications.

On this project the use of abutted longitudinal joints (as opposed to lapped joints) was also specified, as is the case in normal seal coat procedures. The lateral flow of the binder materials in the asphalt-rubber system is insufficient, so longitudinal joints must be lapped. These laps iron out under traffic and pose no permanent problem. This procedure is also part of the current specification. This asphalt-rubber seal coat is serving extremely well, although the cracking in the pavement was so pronounced that the cracking pattern can be observed in the uncracked seal, as shown in the background of Figure 4 and in Figure 5.

### Flagstaff Project

Arizona is basically separated into two climatic zones: The high and cold Colorado plateau runs somewhat diagonally from northwest to southeast across the northern part of the state, and the largely semitropical Sonoran zone is in the warm southern part. The major asphalt-rubber projects that have been discussed were placed in the warmer south although small test installations had been placed in the cold northern area and in other states as early as 1966 (11).

In August 1973, the Arizona DOT placed its first major asphalt-rubber treatment in the northern part of the state (5). This 16-km (10-mile) project is located on US-89 approximately 8 km (5 miles) northeast of Flagstaff and is at an elevation of more than 2200 m (7200 ft). The winters are cold with minimum temperatures as low as -40°C (-40°F) and frost depths of 1 m (3 ft) in shady areas.

The existing surface was severely "alligatored" with fatigue cracking aggravated by frost susceptible base course that caused severe breakup during thawing periods. It was very rough and virtually impassable in the spring of 1973, and it was necessary to place a thin cold-mixed patching course on most of the project to fill the many potholes. In August the asphalt-rubber treatment was placed by using volcanic cinders as cover aggregate.

Some pickup was experienced on this project for a short time as the chip size was small and the asphalt-rubber application rate less than optimum. Normally, a 10-mm (3/8-in) nominal size is used, but these chips had a nominal size of approximately 6 mm (1/4 in). This project has performed excellently without reflection cracking and with zero maintenance to date. The present contrast between the treated and untreated surfaces at the north end of the project is shown in Figure 6.

### Minnetonka Project

In 1971 the Arizona DOT participated in the National Experiment and Evaluation Program on Prevention of Reflective Cracking in Overlays. A 21-km (13-mile) section of I-40 extending east from Winslow to Minnetonka was chosen for the studies. The project included 26 experimental sections, three of which used asphalt-rubber—one placed as a stress-absorbing seal coat and the other two placed between the overlay and the asphaltic concrete friction course as a stress-absorbing membrane interlayer (SAMI).

The final inspection of the project was performed in the spring of 1975, and the report is in preparation. Conclusions are that the asphalt-rubber SAMI was highly effective in preventing reflection of all types of cracks, including fatigue, shrinkage, and differential vertical strain, and the asphalt-rubber seal coat was effective primarily in controlling fatigue cracking (Figures 7, 8, and 9). As a result of this project and other evidence, in 1975 the Arizona DOT implemented the use of the SAMI as standard procedure for all overlays less than 100 mm (4 in) thick that are placed over pavements where cracking is a problem. The cost of this inclusion is absorbed by reducing overlay thickness.

## LABORATORY RESEARCH

To date virtually all of the knowledge of the asphalt-rubber systems has been developed by trial and error on numerous small-scale experiments and full-scale field installations. Although there has been only a limited amount of laboratory work, this work has provided valuable insight on how and why the asphalt-rubber systems have performed in such an excellent fashion.

In most previous work the term rubberized asphalt has been used, but it may be more accurate to describe this process as rubber reacted by asphalt. Laboratory testing has shown that the minus No. 25 to plus No. 40 crumb rubber, when mixed with asphalt and held at a temperature of 190°C (375°F) for approximately 20 min, swells to approximately twice its original volume.

In addition to swelling, the rubber particles become much softer and more elastic. This phenomenon is the result of chemical and physical reactions between the resins (aliphatic oils) in the asphalt and the rubber. The extent of this reaction can be modified by manipulating the composition of the asphalt (Figure 10) and is also obviously subject to change by variations in the gradations and the amount of rubber crumbs. Figures 11 and 12 show that gradations of rubber finer or coarser than No. 10 to No. 40 do not react to produce desired characteristics.

Low-temperature fracture characteristics of various mixtures have been evaluated by extensive laboratory testing. When fracture results are plotted on a graph of temperature versus percentage of rubber, the resulting curve shows a sharp change in slope of a rubber-asphalt ratio of 1:5. Field experience has indicated that a ratio of 1:3 is required to ensure the desired long-term elastic qualities.

The individual rubber particles appear to coalesce with time and react in strain as continuous fibers. To date, no attempt has been made to duplicate this long-term behavior in the laboratory.

Given these phenomena and the high percentage of rubber used in the system, it is postulated that the asphalt is modifying the elastic properties of the rubber rather than the rubber modifying the characteristics of the asphalt. This difference from previous research into the concept of asphalt and asphaltic concrete using low percentages of rubber is basic and must be recognized in concept if the behavior of the asphalt-rubber system is to be understood.

It was previously noted that a major improvement in quality of construction was achieved by adding kerosene (or a high boiling point diluent) to the reacted asphalt-rubber mixture. The addition of kerosene caused a sizable reduction in viscosity, which resulted in improved application and wetting of the cover material. Most important is that the decrease in viscosity is temporary and that in 1 to 2 hours the mixture regained its initial viscosity (Figure 3). Inasmuch as this increase in viscosity occurs long before evaporation of the diluent occurs, this reaction is puzzling and of interest. It is

Figure 1. Asphalt-rubber seal coat on right, after 8 years.

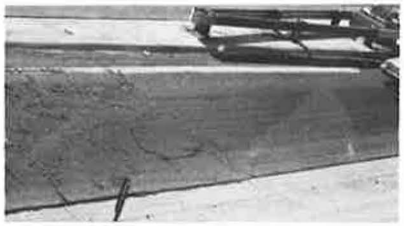

Figure 2. Main street of Tolleson before application of asphalt-rubber (July 1969) and currently (1976).

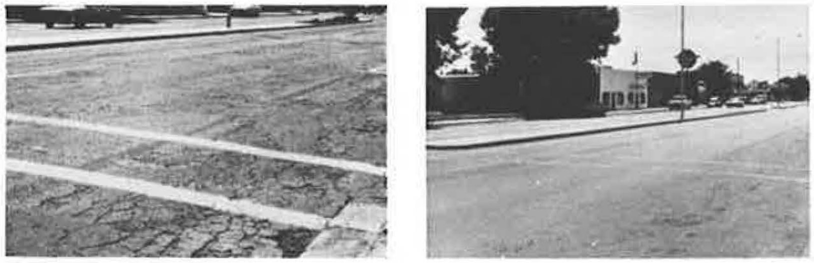

Figure 3. Solvent dilution phenomenon.

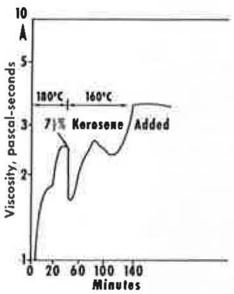


Figure 4. Asphalt-rubber seal coat on Aguila project in background.

Figure 5. Crack pattern under asphalt-rubber seal.

Figure 6. Treated and untreated sections on Flagstaff project.

Figure 7. Minnetonka project in March 1971 before treatment.

Figure 8. Minnetonka project after asphalt-rubber seal coat.

Figure 9. Minnetonka project after asphalt-rubber membrane interlayer.

Figure 10. Increase in volume of rubber by extender oils.

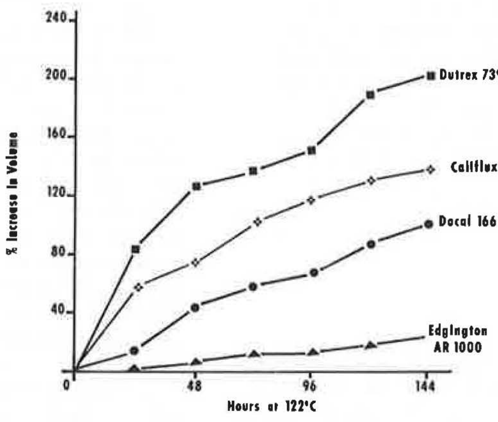


Figure 11. Solvent dilution phenomenon with fine rubber.

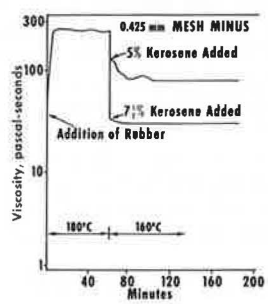

Figure 12. Solvent dilution phenomenon with coarse rubber.

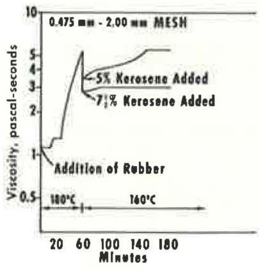


Figure 13. Temperature susceptibility versus viscosity.

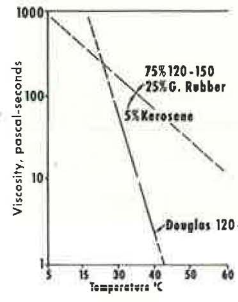


Figure 14. Asphalt-rubber seal coat placed directly on clay loam.

Figure 15. Madison Avenue in Phoenix before and 3 years after treatment.

Figure 16. I-17 partially treated with asphalt-rubber.

theorized, but not confirmed, that the increase in viscosity is caused by the diluent slowly penetrating the asphalt-rubber interface and that the subsequent process of selective absorption of the diluent by the rubber results in the increase in viscosity. Moreover, it should be noted that the viscosity characteristics of the initial mixture and the final mixture appear to be unchanged. It is emphasized that the final mixture is much less temperature susceptible than the original asphalt (Figure 13), and it is also noted that the temperature-susceptibility curve is flatter for the kerosene-diluted mixture than for the asphalt-rubber alone.

The need for and potential benefit of formal research of the asphalt-rubber systems are apparent. Procedures that provide major benefits have been developed, but we know little of the basic character of chemical and physical reactions occurring and even less of rational engineering procedures to optimally utilize the asphalt-rubber system. Arizona DOT, in cooperation with the FHWA, has initiated a research program to explore the basic chemical and physical processes and to develop engineering criteria in relation to pavement deflection, elastic modulus, overlay thickness, and other physical characteristics.

## OTHER APPLICATIONS

Although the discussion so far has been limited to placement of the asphalt-rubber system to control reflective cracking, the potential of asphalt-rubber systems extends far beyond that of reflective crack control.

During the course of developing the design and construction procedures for asphalt-rubber for seal coat applications, the city of Phoenix and the Arizona DOT constructed experimental projects containing more than 200 experimental sections. The performance of these projects indicated that the asphalt-rubber not only serves as an elastomer but also provides an impervious membrane.

An interesting application was made directly on the subgrade of a street in Phoenix in April of 1971. The street (55th Avenue north of Clarendon Street) had previously been paved half the width on the west side with a standard asphalt pavement. An irrigated alfalfa field, at a slightly higher elevation than the street, occupied the east half. The alfalfa field was bladed back, and the clay loam soil (plasticity index of 18 with 80 percent passing the No. 200 sieve) was spongy, cloddy, and difficult to compact. Approximately 25 mm (1 in) of disintegrated granite was spread to smooth the surface. To control the dust the surface was lightly primed and allowed to cure for 1 week. Asphalt-rubber and chips were then applied to the surface of the roadway and ditch slope next to the alfalfa field. Although the street carries an ADT of 6000 vehicles (predominately cars), it is serving well to this time and has had only minor maintenance (Figure 14). This application is, of course, a modification of the membrane-encapsulated pavement structure as developed by the Corps of Engineers. The performance of this project and discussions with Corps of Engineers research staff have indicated that the lower membrane is not necessary where adequate drainage and a low water table exist. A 16-km (10-mile) experimental project to develop reliable data on moisture contents, density, and strength parameters of this concept is now in the planning stage by the Arizona DOT. The potential savings on roadways with low traffic volumes is obvious.

Asphalt-rubber has been used and tested as a waterproof membrane on several bridge decks to date. The Arizona DOT performed standard wet condition resistivity tests and found substantially infinite resistivity through the surface of these decks even though they all consisted of a single application. A double application is recommended for this use, however.

The realization that the system was also serving as a moisture barrier led to other considerations. A major problem exists with high-volume-change clays and shales in northern Arizona. The montmorillonite clays derived from the Chinle formation shales are the principal offenders, although there are some limited areas in the northeast portion of the Mancos formation that has also been troublesome to the states north and east of Arizona. If subgrade moisture can be maintained in a uniform condition, volume change will not occur.

In these semiarid ranges, the primary sources of moisture are surface runoff and moisture generated through the process of hydrogenesis in open-graded base course materials. Brakey and Carroll showed that, for new construction, a membrane placed over the subgrade effectively controls the moisture content and subsequent expansion of the clay (14). Effective procedures have not been developed, however, for existing highways constructed over expansive clays. In 1975, major overlays were scheduled for 38.6 km (24 miles) of I-40 where expansive clays had caused serious heaving and cracking of the pavements. A SAMI was planned to control reflective cracking of the overlay, and it was decided to extend the membrane to cover the shoulders in an effort to reduce the problem of subgrade expansion. There is little question that this membrane will prevent entrance of surface moisture. It is not known, however, whether the membrane will prevent development of water through hydrogenesis or whether redistribution of existing moisture will result in excessive differential swelling of the clay. This section of pavement has not been in service for a sufficient time to arrive at any conclusions.

The use of subgrade materials to provide structural base course led to a review of problems connected with stabilized subgrades. Everyone in highway and street engineering is familiar with the normal shrinkage cracking inherent in soil cement and similar treated bases, which reflects through thin bituminous surfaces. An asphalt-rubber treatment appears to offer an answer to this crack reflection. In the city of Phoenix, many kilometers of soil cement pavement were placed with a 38-mm (1½-in) bituminous surfacing and an asphalt-rubber treatment. The earliest of these projects was placed in 1972, and reflective cracking from the soil cement has not occurred to date.

Before the interlayer concept was tested and developed, one weakness of the asphalt-rubber seal coat application was that rideability of the pavement was not significantly improved. Many distressed pavements are rough, as well as cracked, and in need of a leveling course. In 1971, the city of Phoenix began to combine the asphalt-rubber in some form with a leveling course, and several experimental sections were placed on the main taxiways at Sky Harbor International Airport.

After a few months it was apparent that the only test section controlling reflective cracking was an asphalt-rubber composition flushed into a lean open-graded asphalt mix. This result and the experience with soil cement interested the Arizona DOT in the possibility of using the process as an overlay for leveling rough concrete paving. A cooperative project was arranged with the city of Phoenix, and a test section was placed in summer of 1973 over a very old, rough, cracked pavement subject to heavy industrial truck traffic. The basic elements of this test were essentially the same as the successful one at Sky Harbor International Airport. After 3 winters the experimental section has exhibited only minor hairline reflective cracking in isolated spots (Figure 15).

The Arizona Department of Transportation extended the experiment to the concrete pavement of the Black Canyon Freeway (I-17), which runs through the city of Phoenix and which over the years had developed considerable roughness and an undesirable level of skid resistance. A 1.8-lane-km (1.14-lane-mile) test section was placed in the spring of 1974 and contained most of the elements involved in the 1971 Sky Harbor International Airport tests plus a control section consisting of standard open-graded asphalt concrete finishing course. All of the overlays averaged 19 mm (0.75 in) thick, so that reflection cracks from the joints in the underlying concrete pavement, if they were going to occur, would occur quickly. Further, the section carries 35 000 ADT and was located at the end of the concrete pavement where maximum movement occurs.

An unplanned development occurred in connection with the application of the flushed asphalt-rubber composition. Two parallel applications were made, one at 2.0 $dm^3/m^2$ (0.5 gal/$yd^2$) and one at 3.3 $dm^3/m^2$ (0.85 gal/$yd^2$). The work was done at night under difficult visual conditions, and, when the distributor started the second application, it inadvertently lapped the preceding application for approximately 100 m (33 ft) before a correction was made. This resulted in a total application 5.2 $dm^3/m^2$ (1.38 gal/$yd^2$) on the lap and 0.0 $dm^3/m^2$ on the outside edge. With ordinary asphalt this would have resulted in severe bleeding on the lap, but with the asphalt-rubber only blackening of the surface occurred. This confirms previous observations that overapplications of this material are not critical. On the edge that was skipped because of the lap, reflection cracks occurred within 9 months at every joint but stopped where the asphalt-rubber flush began. The contrast is quite dramatic.

The end results of these experimental projects are similar to those on the 1971 airport project in that the underasphalted open-graded mix flushed with the asphalt-rubber composition is the only one that shows no reflective cracking to date (Figure 16).

The elastomeric properties of this material make it a natural for crack sealing, and experimental sections that have been in service for more than 2 years are showing excellent service. The development of procedures that permit modification of mixture to achieve optimal characteristics for climatic and crack width conditions has led to a large experimental program to further develop materials and procedures. Two districts representing extremes of climatic conditions have been supplied equipment and materials and are testing the various compositions and application techniques. From this work it is anticipated that prepackaged mixtures will be developed for specific applications.

## SUMMARY

The beneficial use of recycled tires in an asphalt-rubber system has been demonstrated and tested. When placed as a seal coat (SAM), the system controls reflection of fatigue cracks and is an effective alternate to a major overlay or reconstruction. When placed as an interlayer (SAMI), the system effectively controls reflection of all cracks.

The performance of the system as a water barrier has been demonstrated on bridge decks. Potential applications and experimental projects have been described to evaluate its potential use

1. For membrane-encapsulated subgrades in lieu of

base courses,

2. For control of expansive clay subgrades under existing highways,

3. As a thin overlay for renewing without crack reflection and skid resistance on portland cement concrete pavement, and

4. As an effective crack sealer for maintenance.

In an era of tight money and energy conservation, the use of asphalt-rubber membranes offers a very attractive incentive. In addition, the use of recycled tires in highways provides a solution to a major problem of waste material disposal. The magnitude of this problem is rather overpowering when it is realized that there are more than 2 billion scrap tires currently in storage or littering the landscape and that each year this total increases by an estimated 200 million.

REFERENCES

1. F. N. Hveem. Pavement Deflections and Fatigue Failures. HRB, Bulletin 114, 1955.
2. R. E. Olsen. Rubber-Asphalt Binder for Seal Coat Construction. Federal Highway Administration, Implementation Package 73-1, 1973.
3. C. H. McDonald. Rubberized Asphalt Pavements. 58th Annual Meeting AASHO, Phoenix, Arizona, 1972.
4. G. R. Morris. Asphalt Rubber Seal Coat Projects. Report to Arizona state highway engineer, May 14, 1973.
5. G. Cooper and G. R. Morris. Reclaimed Rubber in Seal Coats and Research in Rubber/Asphalt Products. Proc., Arizona Conference on Roads and Streets, Univ. of Arizona, Tucson, 1974.
6. F. S. Rostler. Rubber in Asphalt Pavements. International Symposium on the Use of Rubber in Asphalt Pavements, Salt Lake City, May 1971.
7. C. H. McDonald. Bituminous Paving as Related to Large Commercial Airports in the Urban Environment. Paper presented at the 50th Annual Meeting, HRB, 1971.
8. C. H. McDonald. A New Patching Material for Pavement Failures. Paper presented at 45th Annual Meeting, HRB, 1966.
9. C. L. Monismith. Design Considerations for Asphalt Pavements to Minimize Fatigue Distress Under Repeated Loading. Fourth Paving Conference, Univ. of New Mexico, 1966.
10. R. A. Jimenez. Viscosity and Durability of Asphalts for Paving Mixtures. Sixth Paving Conference, Univ. of New Mexico, Dec. 1968.
11. C. H. McDonald. Asphalt-Rubber Compounds and Their Applications for Pavement. 21st California Streets and Highway Conference, 1969.
12. The WASHO Road Test, Part 2: Test Data, Analyses, Findings. HRB, Special Rept. 22, 1955.
13. G. R. Morris. Hot Rubber-Asphalt, Lightweight Aggregate Seal Coat—Aguila Projects. Report to Arizona state highway engineer, March 28, 1973.
14. B. A. Brakey and J. A. Carroll. Experimental Work, Design and Construction of Asphalt Bases and Membranes in Colorado and Wyoming. Proc., AAPT, Vol. 40, 1971, pp. 31-63.