POLYMER MODIFIED BITUMEN:

Laboratory Evaluation,

Construction Guidelines

And

Field Experience

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The abundance of asphalt compatible polymers now available makes it possible to improve almost every aspect of paving. It is crucial, however, that the various physical characteristics, construction constraints, and ultimate cost-benefits be understood. To this end, numerous standards for quality testing and specification are under development. Comparative polymer modified bitumen trials are currently being planned and executed in many states. Recently polymers have been used for dense- and open-graded hot mix, hot and cold recycling, hot applied and emulsion surface treatments, stress absorbing membranes, slurry seals, joint sealants, and patching materials. Increased durability, improved rutting resistance, better aggregate adhesion, improved temperature susceptibility, improved stiffness moduli, and better overall flexibility are the most beneficial characteristics of polymer modified bitumen.

INTRODUCTION

To meet the demands of technological and demographic changes, the use of polymer modified bitumen has become increasingly important. Increased stress on highways due to heavier loads, higher tire pressures, and ever rising traffic counts are causing premature failures. Severe climates, always a source of concern, and an increased emphasis on safety have prompted research towards the amelioration of highway paving materials. As the network of highways ages, the demand for quality maintenance and recycling products is becoming more important than that for new construction. To address these problems, the highway engineer has turned to polymer modification for custom design of pavement materials.

POLYMERS CURRENTLY USED FOR BITUMEN MODIFICATION

Bitumen soluble polymers are very large molecules, usually 50 to 500 times the size of a typical asphalt molecule. They can be divided into two major groups: elastomers and plastomers. Rubber products are classic examples of elastomers. Their identifying property is their elasticity over a wide temperature range—the ability to stretch under an applied load and to recover the original configuration once that load is released. While the rubber industry has successfully designed all-weather tires, the asphalt engineer has had to carefully choose from a broad range of asphalt grades to meet each specific climatic and traffic condition. The introduction of natural or synthetic rubbers such as styrene-butadiene rubber (SBR), styrene-butadiene block copolymer (SBS), styrene-isoprene (SI), and
polychloroprene gives the asphalt increased flexibility, particularly at the climatic extremes where most pavement damage occurs.

Plastomers are employed to take advantage of the strength imparted by a rigid three-dimensional chemical network. Plastics are stronger but less flexible than their elastomeric counterparts. Products such as ethyl-vinyl-acetate (EVA), polyethylene/polypropylene, ethylene propylene (EPDM), and polyvinyl chloride (PVC) significantly raise the stiffness of a bitumen without sacrificing the low temperature performance.

BINDER TESTING

To identify the unique properties given by polymers and to eliminate ineffective ones, a series of new physical tests must be used to complement the existing standards for bitumen specification. Because the properties of each polymer are specific to its chemical and physical structure, it cannot be assumed that one standard is applicable to all polymers. The conventional tests such as penetration, absolute viscosity at 60 °C (140 °F), kinematic viscosity at 135 °C (275 °F), softening point, etc., while valuable, cannot effectively characterize modified binders because the fluid dynamics of polymer solutions are very different from those of asphalt. The modified rheological behavior (for example the decreased temperature susceptibility, increased elasticity and pseudo-plasticity), is the major reason for using polymers. While the classic asphalt tests do not adequately differentiate these characteristics, methods adapted from those used by the polymer industry do. For example, the testing of tensile strength during elongation, elastic response after removal of an applied load and rheological measurements made at the temperature extremes and stress conditions found on highways are necessary for identifying properties such as elastic modulus, loss angle, material strength maintained during deformation, and temperature susceptibility. We outlined some useful experimental methods for characterizing and specifying Polymer-modified Asphalt Cement (PAC) in an earlier paper (1). Included are sophisticated methods suitable for the research laboratory, as well as simple, inexpensive procedures adaptable for field testing. Some of these are summarized below.

Tensile strength during elongation may be measured by using tension tests (ASTM D-412)(2), force ductility (recently proposed to committee D-04 of ASTM by Don O'Conner of the Texas DOT)(3)(4)(5), toughness and tenacity (6), or dropping ball (7). The elasticity can be measured easily by monitoring the elastic recovery in a ductilometer (8)(1) or by using the Torsional Recovery Test (9)(10). (Author's note: we prefer to modify this last test by holding the 180 degree deformation for 30 seconds and then measuring the entire recovery angle)
after the cylinder is released.)

While these methods are effective for measuring elastomeric properties, they may not be applicable to plastomers. A more complete rheological picture detailing the viscous and elastic moduli can be obtained from dynamic (multiple loading cycle) rheometers such as the Rheometrics spectrophotometer (11) or similar devices (12)(13)(14). Static methods, which entail only one loading cycle, include the modified sliding plate rheometer as developed by the Australian road research board (15), the Dekker falling concentric cylinder rheometer (16), and the thin-film sliding plate rheometer developed by the French Highway Laboratories (17)(18).

To demonstrate the improvement in cohesion, a vialit pendulum test measures the angle to which a pendulum rises after dislodging a metal plate inserted in a bitumen (19).

A measure of the temperature susceptibility is given by the difference between the softening point and Frass point, sometimes called the plasticity range. Alternative temperature susceptibility measurements include Pen-Vis numbers (20), Penetration Index, and the slope of viscosity-temperature curves.

**TESTING OF BINDER WITH AGGREGATE**

In recent years the factors listed in the introduction as prompting the development of polymer modified bitumen have also encouraged the development of laboratory tests which more faithfully predict the quality of an asphalt-aggregate mix. Most of these tests focus on a measurement of resistance to the factors commonly causing failures: rutting, ravelling, cracking, fatigue, stripping, etc. In conjunction with classic specification tests, these new procedures are useful in predicting the relative merits of various polymer systems. A detailed discussion relating the binder rheology to mix properties may be found in an earlier paper (21).

An increased resistance to permanent deformation is perhaps the most universal advantage of polymers; the elastomers have the ability to recover after a load, and the plastomers have increased flexural strength. Preliminary creep compliance data indicate this permanent deformation resistance of polymers is most pronounced under long loading times, such as those encountered in slow moving traffic (22). Simulated rutting tests developed by LCPC in France (23) have shown a specific elastomeric polymer system to withstand 6-10 times more loading cycles than a conventional mix before the formation of comparably deep ruts (24). Creep response tests developed by van de Loo (25) and Finn, Monismith and Markevich (26), are also presently being used to study rutting resistance of PAC systems.
Elastomeric properties also impart improved fatigue response; the high tensile strength at large strain portends an elastic modulus that not only resists rutting, but cracking induced by repeated deformation as well. A French fatigue test using a trapezoidal specimen has shown a 60% increase in fatigue resistance for one polymer system (21). Significant improvements in fatigue life using the Asphalt Institute flexural fatigue method on 3 inch by 3 inch beams have also been observed. The related resistance to reflective cracking has been studied using tests such as one developed at the Texas Transportation Institute (TTI) (27).

Another major advantage of polymers is their ability to increase stiffness with no reduction in flexibility, particularly at higher temperatures. Dynamic modulus testing is a convenient method for demonstrating the reduced temperature susceptibility of polymer modified mixes. Results with an SB modifier have shown a 10% reduction in stiffness at low temperature (-10 C, 14 F) and a 17% increase in stiffness at higher temperature (30 C) over the conventional mix (24). A polyethylene system had 25% higher Marshall stabilities with concurrent 25% higher flow values (28). An EVA modified bitumen is reported to have had a dynamic modulus approximately 2.5 times greater at 33 C (91.4 F) than that of the control (22).

Polymers are incorporated in adhesives formulations because of their natural affinity for various substrates. Because stripping is a major contributor to early pavement failure, the adhesivity of certain polymers gives an added benefit to polymer modified asphalt. Several procedures comparing the strength of specimens before and after exposure to water have been proposed to quantify moisture damage. These include various saturation techniques as well as several methods to monitor changes in the stability of the mix. The Root-Tunnicliffe procedure, recently proposed to ASTM, uses a partial vacuum saturation at 60 C (140 F) and the split tensile test method (29). When stripping sensitive aggregates are used, PAC mixes usually have greatly increased TSR ratios which can equal or exceed those of conventional liquid antistrip or lime treatment. Other tests designed to measure passive adhesivity by exposing the uncompacted mix to hot or boiling water for various periods of time, while informative, do not always correlate to field performance.

The dual elastomeric properties of elasticity and adhesivity yield mixes with both improved cohesion and improved adhesion, resulting in a reduced susceptibility to ravelling. As a result, open-graded friction courses, noted for high skid numbers and resistance to hydroplaning as well as an unfortunate tendency to ravel, become practical when a cohesive, ravelling-resistant polymer is used (30). The vialit test, developed in
France (31), predicts the ability of a material to adhere to a chip.

CONSTRUCTION PRACTICES

As with the testing procedures, standard construction practices should be re-evaluated when applied to polymer modified materials (32). Although in most cases little or no change from standard procedures is required, occasional minor adjustments may be necessary to guarantee the quality of the finished product. It should be noted that construction procedures are also dependent upon the polymer system used.

Polymers that are sufficiently compatible with the asphalt to preclude any phase separation usually require minimal hot mix plant modification. These may be pre-mixed at centralized facilities, mixed on site with equipment furnished by the polymer supplier, or incorporated in the form of pellets or crumb directly into a batch mix plant. Conversely, latex systems usually require an independent injection system involving a dedicated pumping and metering system. When the polymer is added to the aggregate separately from the bitumen, longer mixing times are usually required to assure homogeneity of the product.

Perhaps the most important difference in construction with polymer modified bitumen is in the choice of optimum operational mix temperatures. A mix's stiffness is dependent upon temperature, polymer type and concentration, and the base asphalt. At low polymer levels little adjustment is necessary; however, as the elastomeric properties of the polymer become more pronounced, shear thinning and reduced temperature susceptibility lead to changes in workability and compaction. While plastomers typically require mix and compaction temperatures to be elevated 10 to 30 degrees C (18 to 54 degrees F), elastomers can often be compacted to optimum densities at conventional temperatures. For these materials, a lower temperature than that predicted by low shear laboratory viscometers yields the best field density.

While some polymer systems require major plant modifications and/or decreased plant production rates, others are available which have little, if any effect on standard practices.

FIELD EXPERIENCE

Polymer modified asphalts have been used in most road paving applications. They have had the widest acceptance in those uses where traditional materials have early failures. When the polymer modified bitumen gives longer service life and improved performance, its cost effectiveness can be evaluated.
Surface Treatments

As part of a preventative maintenance program, chip seals are an effective and inexpensive means to extend pavement life. Because of their reputation for slow curing and a tendency to lose aggregate in cold weather or under heavy traffic, surface treatments are an ideal candidate for polymer modified bitumen. For example, because the state of California is liable for windshields broken after chip seal application, it has turned to polymerized emulsions for better early chip retention. To combat the problem of stripping sensitive aggregates, several southeastern states are using polymers for their improved adhesion. Louisiana has raised its restriction for maximum daily traffic count from 1000 to 3000 ADT for polymerized surface treatments because of the modified bitumen's improved cohesion under traffic. In Texas and New Mexico, primary roads in rural areas are seal coated with polymer emulsions because of the problems and high cost associated with trucking hot mix over long distances. The conditions encountered in the mountains of Colorado and Utah, including the use of chains and the severe climatic variations, create a need for specialized binders.

Polymerized emulsion sand seals are also becoming standard practice in many midwestern states. Colorado and Illinois use a particularly interesting form of this application, sometimes referred to as the "magic carpet" method. A distributor applies a polymer emulsion at the very light rate of 0.6 liter/square meter (0.15 gal/square yard). A specially designed chain or astroturf carpet attached to the back of the distributor drags the emulsion into surface cracks and depressions. A light application of sand seals the surface, allowing the road to be immediately opened to traffic. This method is an extremely inexpensive preventative maintenance tool for roads with sound structures but minor surface cracking.

While emulsions are used extensively in the United States for chip sealing, European countries are using hot applied polymerized binders, usually cut back with medium distillates. The cutback materials cure faster in hot weather, but emulsions exhibit better long-term adhesion when applied under cooler conditions.

Considerable research and development continues in this domain. Large scale traffic simulators such as those at Elf/Solaize or LCPC/Nantes laboratories are being used as controls for determining the efficacy of smaller scale laboratory binder and aggregate tests (33).

Slurry Seal

Because slurry seals are applied in such thin layers, their service life is usually short. The addition of polymer significantly extends their
durability. The addition of a natural rubber latex in combination with special emulsifiers yields a material that cures to traffic within one hour. This system, used extensively since the late 70's, is now being joined by other polymers which allow the use of conventional slurry equipment and emulsifiers. Some of these materials have shown improved wet track abrasion results in the laboratory and a corresponding increased durability on the road (34). In some states, slurry seals, which had been all but discontinued five years ago, are currently being re-evaluated and re-incorporated in pavement maintenance programs. Kansas and Nebraska, particularly, have shown a great interest in polymer modified slurry seal emulsions.

In hot, arid climates pavement damage is often initiated by the formation of surface cracks, which are held open and deepened by drifting sand and dirt. Slurry seal surface treatment can prevent eventual failure by covering the small cracks. The widespread use of slurry seals in such countries as Saudi Arabia demands a closer look at the polymer modified materials.

Joint Sealants and Crack Fillers

Possibly the earliest use of polymers was in the filling of cracks and sealing of joints. The first generation products usually incorporated finely ground tire rubber, and required special equipment and very high temperatures for application. Newer polymerized bitumen formulations are homogeneous, more flexible, and can be handled at lower temperatures.

Recent studies have led to the realization that products with low stiffness but high flexibility at low temperatures give the best overall performance, as long as the viscosity at high temperatures is sufficient to prevent draindown or tracking. Much research within the last five years has been directed towards designing materials and specifications which can accurately predict performance. (35)(36)(37)

Hot Mix

The greatest potential for polymer modified bitumen lies in hot mix applications. With the proper choice of polymer and bitumen, one can custom design a material to overcome almost any paving problem. Elastomers with low Frass Points can greatly enhance low temperature flexibility, resulting in less thermal cracking. Plastomers increase the stiffness of the binders at high temperatures to resist permanent deformation, while elastomers diminish rutting by recovering elastically from temporary deformations. The greater cohesion imparted by an interlocking polymeric network can be used to greatest advantage in applications where the binder is most responsible for maintaining the integrity of the
mix. Examples here would include open-graded friction courses, sand mixes, and other thin surface lifts.

Open-graded friction courses

Open-graded surface mixes with void contents of 15% or more offer several important advantages over their dense-graded counterparts. Tires are able to maintain contact with wet pavements by pushing surface moisture through the mix. Skid resistance increases dramatically and traffic noise decreases(30) as the void content increases. Indiana has long used emulsion sand mixes on primary roads to provide smooth, quiet surfaces with skid numbers in the 50's or 60's. Recent studies by Kreich, in conjunction with the Indiana State Highway Department, have shown that the skid numbers decrease rapidly into the 30's if excess fines reduce the water permeability of the mix.(38) Indiana has recently tried experimenting with polymer modified binders as a replacement for the normal high-float emulsion residues. France is also experimenting with styrene-butadiene modified sand mixes as a part of their commonly used surface layer--sables enrobes cloutes. In this technique, a thin sand mix (2 cm/0.8 inch) is laid with a paver and then larger (14-18 grade) conventionally precoated aggregate is dropped on the mix with a chip spreader before compaction (39).

Numerous highway agencies have been testing thin layer open-graded friction courses using uniformly graded aggregates. In 1983 New Mexico placed its first hot mix using an SB modified high float emulsion with uniformly graded 1 cm (3/8 inch) aggregate in a 1 1/2 cm (5/8 inch) lift (40). To date no further maintenance has been required. Comparable surfaces placed in the same area during the same summer with conventional hot AC binders have already been fog sealed once or twice with dilute polymer modified emulsions to stop ravelling tendencies. This technique is now gaining acceptance as a standard practice in the southwest. After receiving Federal Aviation Administration approval in 1985, three New Mexico airports put SB modified friction courses on their main runways. Santa Fe's main 3100 meter (10,000 foot) runway was overlaid with 2 1/2 cm (1 inch) of open graded mix with 7.5% PAC binder. In Clovis the 2800 meter (8000 foot) main runway was overlaid with a 1.85 cm (3/4 inch) open graded mix containing 8% polymerized bitumen. The Alamogordo airport used heater scarification and a rejuvenator emulsion to repair the runway's badly damaged surface before overlaying with a 1.85 cm (3/4 inch) open graded mix modified with 7.5% polymerized binder. Mixing temperatures varied from 110-127 C (230-260 F), depending upon air temperature and distance between mix plant and jobsite. All reports on construction and performance have been quite favorable (41).

Louisiana placed its first polymer modified friction course in 1983. It was a 2 1/2 cm (1 inch) lift.
containing 6% binder on a fairly heavily trafficked road near the Gulf of Mexico. Performance there over the past four years has been good enough to interest the state in further applications of this technique.

Dense-Graded Hot Mix

Although SBR or polychloroprene latex emulsions have been used widely to improve bituminous mixes for 25 years or more, numerous recent laboratory test results have more clearly defined the rheology and expected benefits of the various polymer systems. There are also many closely monitored field trials now in progress which will allow engineers to compare the various polymers under traffic, and hopefully correlate laboratory test methods to actual field performance. Multi-product test projects are in the planning, design, construction, or evaluation stages in the states of Texas, Virginia, Georgia, and North Dakota.

Described below are some of our recent jobs using polymer modified dense graded hot mix; these include standard constructions as well as special cases where it was felt the polymer was justified by a particularly difficult circumstance. U.S. route 41 in Terre Haute, Indiana is a major north-south thoroughfare for truck traffic, as well as a downtown city street with frequent stop lights. The combination of high traffic counts and the standing, slow-moving and braking trucks has resulted in the continuing formation of ruts. In the fall of 1986 and spring of 1987, a test section was built in three lifts (base, binder and surface), each of which used PAC binder. The density of the surface course is quite high (1.5% air voids) in both the PAC and conventional AC-20 control sections. Within two months of placement, the control section was beginning to show signs of rutting near intersections. The polymer modified section currently shows no evidence of permanent deformation.

The Poplar Street Bridge carries traffic for several interstate highways across the Mississippi River to St. Louis. The equivalent axle load carried by this bridge is one of the highest in the U.S. In 1986, the Missouri State Highway Department stripped off the bituminous surface and all metal coatings, and resurfaced it using special epoxies and a PAC modified full depth overlay. Some problems were encountered when hydrogen gas formed near the metal-epoxy interface, causing large bubbles to form in the overlying mix. Fortunately, after the gas bubbles were broken by traffic, the polymeric binder was able to recover from the severe deformations with surprisingly little damage.

Since 1984 a steel deck bridge with a PAC overlay in Hamburg, West Germany has been supporting 85,000 ADT without damage. Several other bridges in this same area are now paved with the same binder.
In 1983 an experimental test section of PAC mix was placed on Interstate 80 in western Iowa. Laboratory recommendations for mixing temperatures based upon kinematic viscosity at 135°C (275°F) as suggested by Marshall design methods were found to be too high. Draindown occurred in the trucks, and there was noticeable heat checking during compaction. When the mixing temperature was lowered to the temperature used for the control mix, the construction phase proceeded without further problems. This mix continues to perform well four years after placement.

Other highway applications for PAC mixes have included such things as deceleration ramps for interstate truck weigh stations. CALTRANS has successfully tested binders with higher polymer concentrations on Interstate highways in mountainous regions where snowchains are compulsory during winter storms. Orange County, California is using PAC for city streets that are concurrently exposed to heavy traffic, high temperatures, and water run-off from the daily watering of median strips. Cities such as Montreal, Canada and Des Moines, Iowa are incorporating PAC mixtures in their routine pavement management programs.

In Europe, where several polymer-bitumen systems originated, the literature reports numerous examples of both laboratory and field experiences. One session of the 1985 Eurobitumen symposium in The Hague was dedicated to bitumen polymer modification (42). Bonnot and Perez have prepared an excellent summary of the papers presented there (43). Work done by Brule and coworkers at the Laboratoire Central des Ponts et Chaussees (LCPC) has also contributed significantly to testing and evaluation of various polymer modifiers (44)(45)(46)(47), as has extensive work done by Zenke (Institute fur Erdolforschung) (48).

Because the loads exerted on airport runways, taxiways, and parking aprons are so severe, portland cement concrete is often the only paving alternative. PAC binders offer an alternative to the high initial expense and lengthy maintenance delays typical of PCC use. The busy international airport in Hamburg, West Germany successfully used 30,000 tons of PAC mix in the binder and friction courses of a new 1.8 km runway and 600 meter taxiway in 1986. Four stationary hot mix plants supplied four simultaneously working pavers so the job could be completed without interrupting airport service. This summer the Riudoso, New Mexico airport authority is using PAC mix to pave the entire airport with base, binder, and surface courses.

**Warm-Mix - Cold-Lay**

Maintenance and patching materials have long been made by mixing cutbacks or emulsions with aggregate at temperatures slightly below 100°C (212°F) and then
stockpiling the mixture for later use as needed. Such practice is most common in winter when hot mix plants are not operational. Unfortunately the distillates content in such products must be fairly high to keep the stockpile workable in cold weather. If the solvents are light naphthas, then the stockpile life is very short. If the solvents are heavier diesel grades, the mix cures slowly after it is placed on the road, and patches are often displaced under traffic. Thus winter patching mixes are usually considered a temporary fix until hot mix plants open in the spring. Recent experience in Michigan, Colorado, New Mexico, and Texas suggests that the use of open-graded aggregates with polymer modified high float emulsions can greatly improve the quality of these patch materials. The open-graded aggregate permits water to escape without stripping or otherwise damaging the mix, and the greater cohesivity of the polymeric binder reduces ravelling and deformation.

Cold Mix - Cold Lay

Emulsions or cutbacks can also be mixed with aggregate in portable pugmills, in mixer-pavers, or in-place with blades or rotary machines. Ambient temperature mixing at the job-site can save significant energy and transportation costs. By adding newly developed chemical coating improvers to polymer modified binders, it is possible to make maintenance materials with a quality comparable to the warm mixes discussed above.

In the USSR, a new polymer system has been developed which exhibits a unique rheological phenomenon. A solventless cold mix can be stockpiled for periods of up to nine months. Under the high shear of compaction the viscosity of the binder decreases sufficiently for proper densities to be achieved (48).

Recycling

Polymer modified binders offer exceptional promise in the rapidly expanding field of recycling. The relatively small quantities of binder typically added to the old recycled asphalt pavement (RAP) must keep the mix together. Since the binder represents a smaller percentage of the job cost than is typical of other paving applications, the extra expense of the polymers is quickly recovered with improved performance.

Hot recycling

Although the use of PAC binders in hot recycling is relatively new, early trials have given encouraging results and demonstrated that the technique is feasible. During the summer of 1987 the State of Wyoming conducted a large hot-mix recycling trial on Interstate 80 to test a number of bitumen modifiers. Since the primary problem in the original pavement was rutting, preliminary
laboratory evaluations concentrated on 50/50 and 60/60 virgin/RAP ratios and virgin binders with fairly high polymer or modifier concentrations. Complete reports on this project should be available soon from the State Highway laboratories or from R. Pavlovitch, the project consulting engineer. The Iowa Department of Transportation completed a hot recycling project near Atlantic, Iowa in 1986. The old surface was milled to a depth of 10-12.5 cm (4-5 inches) to correct rutting. Then 30% RAP was blended with 80% virgin aggregate and 3.6% PAC-30. The penetration was 34 in the RAP binder, but it was increased to 56 in the finished mix. The viscosity at 60 °C (140 °F) was similarly lowered from 17,640 poise to 4300 poise. The contractor reported no problems with the modified mix.

Cold recycling
The use of specially designed polymer modified recycling emulsions is expanding very rapidly with the increasing popularity of cold recycling. A milling machine grinds the pavement and drops it into a portable crusher with screen decks. The RAP is then sent directly to a portable continuous mix plant where the emulsion is blended in carefully controlled quantities. The rejuvenated RAP is windrowed, picked up and laid through a paver. Compaction begins as soon as the moisture content of the mix drops to about 1%. By putting the emulsion transport truck in front of the grinder and using flexible tubing to connect it to the mixing plant, the entire train occupies only one lane, and the distance between grinding and compaction is normally no more than one kilometer (0.6 mile). Such a system causes minimal traffic interruption and minimizes material handling costs. The amount of polymer modified binder added to the 100% recycled mix is small (1-2%), so the polymer cost is only a minor factor in the overall operation. Several contractors now have recycling trains routinely using this technique on rural primary roads throughout the western part of the U.S. The State of New Mexico has successfully completed 15 separate polymer cold mix recycle projects in 1986 alone. A detailed report of one such 13.5 km (8-mile) project is available (49), and the state has also prepared a training film describing the utilization of the technique in some detail (50).

Stress-absorbing Membranes
Highway engineers have attempted to reduce reflective cracking by taking advantage of the inherent elasticity of rubber or comparable polymers. Although laboratory and field tests demonstrate that hot mix made with modified binders can retard cracking, it is evident that the 5-10 micron binder film thickness is not sufficient to withstand the severe strains observed immediately above a large crack in the underlying
pavement. One must then search for ways to increase the modified binder's film thickness such that those same deformations will not stretch the binder to strains from which it can not elastically recover. Stress-absorbing membrane interlayers (SAMI's) made by placing asphalt-rubber or polymerized asphalt products between the old surface and the new overlay have received widespread attention (51)(52).

Recent work with high concentration styrene-butadiene materials in Europe is most encouraging. A specially designed distributor applies hot high viscosity PAC binder (typically 3 kg/square meter or 0.75 gal/square yard). This is followed by 18-22 kg/square meter (33-40 lb/square yard) of clean 10/14 grade (1/2 inch) chips, preferably either heated or precoated. Significant reductions in reflective cracking have been observed.

Similar membrane layers are being used between the aggregate sub-base and bituminous base course to prevent water from percolating up into the mix.

Fog Seals
Open-graded friction courses are prone to ravelling. A very light application of a diluted PAC emulsion prevents this aggregate loss and significantly extends the service life of such pavements. New Mexico routinely treats such surfaces with 0.18 liters per square meter (0.05 gallons per square yard) of a 50% diluted emulsion. This treatment is fast, inexpensive and effective preventative maintenance.

Surface treatments are notorious for chip loss or for the clouds of dust that fill the air shortly after completion of a job with dusty aggregate. Numerous airport and highway agencies have discovered that problems with chip loss and dust control can be reduced with a light fog seal of a diluted polymer emulsion applied soon after compaction. This technique is particularly favored for runways and taxiways, where one loose chip can cause severe damage to an aircraft engine.

CONCLUSIONS
The advent of PAC has generated a lot of interest on the laboratory, user agency, manufacturer and contractor levels. To meet the special needs of this new industry, a number of new binder tests based primarily upon tensile and elastic properties are being developed to supplement classic methods for testing and specifying PAC. The range of products available requires that a different set of specifications be written to qualify each class of polymer.

The reduced temperature susceptibility, improved low temperature flexibility, and better tensile properties given by the polymer yield varying degrees of resistance to cracking and rutting, longer fatigue life, increased
stripping resistance, and higher stiffness moduli at high temperatures.

Polymers can be incorporated into bitumen without necessitating changes in conventional construction practices. They can be used in all standard bitumen road applications, as well as practices impractical before the advent of polymer modification. Their most beneficial applications are in cases where the binder is a small fraction of the total job cost, or where their performance is markedly superior to conventional asphalts. A substantial percentage of the binder market has already been claimed by polymer modified materials, especially for chip seals, cold mix recycling, stress absorbing membranes, slurry seals, joint sealants, and maintenance patch materials. They are also gaining acceptance in specialty applications such as open-graded friction courses, fog seals and airport runways. And finally, they are showing promise in replacing conventional hot mixes.
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