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Contents

Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier

MICHAEL HEITZMAN

This document is a concise overview of the terminology, processes, products, and applications of crumb rubber modifier (CRM) technology. This technology includes any use of scrap tire rubber in asphalt paving materials. In general, CRM technology can be divided into two categories, the wet process and dry process. When CRM is incorporated into an asphalt paving material, it will modify the properties of the binder (asphalt rubber) and act as a rubber aggregate (rubber-modified hot-mix asphalt). The use of asphalt rubber crack and joint sealant is common across the country and is routinely used by many state maintenance crews. A surface treatment using an asphalt rubber spray application is called a stress-absorbing membrane (SAM). The use of CRM in hot-mix asphalt paving materials has broad variability and potential. Composite designs with CRM paving materials are a two-layer system and a three-layer system. The growing nationwide interest in alternative uses for scrap tires has provided CRM technologists with the catalyst to develop new concepts for applying CRM. The major interest has been to develop generic dry process mixes and a continuous blending wet process. There are two principal unresolved issues related to the use of CRM in asphalt paving materials. On the national level, the ability to recycle asphalt paving mixes containing CRM has not been demonstrated. At the state and local level, these modified asphalt mixes must be field evaluated to establish expected levels of performance.

The use of scrap tire rubber as a modifier for asphalt cement has been developing for more than 25 years. However, since the late 1980s, the emphasis for this engineering technology began to focus on its potential as a solution to an environmental solid waste problem: scrap tires. Pavement performance is a key component in determining if the use of scrap tire rubber is cost-effective. Because of the variable conditions that affect pavement performance, it is probable that some areas of the country will not benefit from this technology.

BACKGROUND

Environment and Legislation

Each year the United States discards approximately 285 million tires, more than 1 tire/person/yr. Of that figure, 33 million tires are retreaded and 22 million are reused (resold). Another 42 million are diverted to various other alternative uses. The remaining 188 million tires are added to stockpiles, landfills, or illegal dumps across the country. The Environmental Protection Agency estimates that the present size of the scrap tire problem is 2 to 3 billion tires (*1*).

Of the available expanding markets for scrap tires, only two have shown the potential to use a significant number. They are fuel for combustion and crumb rubber modifier (CRM) for asphalt paving. Combustion already plays a major role, consuming 26 million tires annually. Combustion facilities have the potential to use 0.5 to 10 million scrap tires/facility/yr. In comparison, the second potential new market, CRM, presently consumes 1 to 2 million tires/yr. The CRM technology can incorporate the rubber from 2 to 6 tires into a metric ton of hot-mix asphalt (HMA) paving material. To recycle 10 million scrap tires annually as CRM, 2 to 5 million metric tons of HMA material would require modification.

There are other alternative highway uses for scrap tires. The Transportation Research Board (TRB) initiated a synthesis in 1989 to document these alternative uses. Scrap tires, or rubber processed for scrap tires, have been examined by a number of highway agencies for use in light-weight embankments, retaining walls, safety hardware, and pavement subbase. Details on these potential uses will be documented in the TRB synthesis.

The environmental risks linked to the presence of scrap tire stockpiles and a number of recent, well-publicized tire stockpile fires initiated legislative action at the state and national level. At the beginning of 1991, 44 states had drafted, introduced, regulated or enacted laws to control the scrap tire problem (*2*). Typical provisions of the states' legislation include regulations to control the processing, hauling, and storage (stockpiles) of scrap tires; restrictions on scrap tires in landfills; provisions for funding, normally a tire disposal fee; and in a number of states, incentives for developing new alternative use markets.

Legislation is being considered to consolidate the regulations and stimulate alternative use technology. The Tire Recycling Incentives Act (H.R.871 and S.396) addresses both the regulation and technology issues. Section 1038 of the Intermodal Surface Transportation Efficiency Act of 1991 addresses the study and use of CRM by highway agencies.

Terminology

CRM technology is a general term to identify a group of concepts that incorporate scrap tire rubber into asphalt paving materials. CRM is identified as a modifier because the intro-

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Federal Highway Administration, Office of Engineering and Office of Technology Applications, Room 3118, HNG-42, 400 Seventh Street, S.W., Washington, D.C. 20590.

duction of the scrap tire rubber modifies conventional asphalt paving products.

Publications during the last 20 yr used a variety of terms to define different processes and products as the technology evolved. Conflicting terminology has made it difficult for many user agencies to understand it. It is important that this document standardize the terminology, identify the processes and products, and distinguish between the various concepts as they are introduced. A diagram of this relationship is presented in Figure 1.

In general, CRM technology can be divided into two categories. These categories define the basic process used to add the crumb rubber to an asphalt paving material. They are the wet process and the dry process. The term wet process defines any method that blends the crumb rubber with the asphalt cement before incorporating the binder into the project. The term dry process defines those methods that mix the crumb rubber with the aggregate before the mixture is charged with asphalt binder. The dry process is limited to HMA applications, whereas the wet process has been applied to crack sealants, surface treatments, and HMA mixtures.

It is also important to distinguish between the processes, as defined, and the goods that can be produced. When CRM is incorporated into an asphalt paving material, the CRM will modify the properties of the binder and act as a rubber aggregate. The modified binder is commonly called asphalt rubber. When CRM is used as a rubber aggregate, the HMA is called rubber-modified hot-mix asphalt. Understanding the process-product relationship is the key to developing the design for a specific project.

History in the United States

The use of CRA in asphalt paving did not develop as a solution to an environmental problem. In fact, the development of natural rubber in bitumen was introduced in the early 1840s (*3*). For years, engineers and chemists have worked to blend natural rubber (latex) and synthetic rubber (polymers) in asphalt cements to enhance the elastic properties of the binder. Tire rubber, a compound of natural and synthetic rubber, is an available raw material that has been included in this effort.

In the early 1960s, Charles McDonald, materials engineer for the city of Phoenix, began working with a local asphalt company, Sahuaro Petroleum, to develop a highly elastic maintenance surface patch using CRM. In 1968, the Arizona Department of Transportation (ADOT) placed its first stress absorbing membrane (SAM), a surface treatment using an asphalt rubber binder (*4*). ADOT placed their first stress-absorbing membrane interlayer (SAMI) in 1972 and used the asphalt rubber binder in HMA open-graded friction course in 1975.

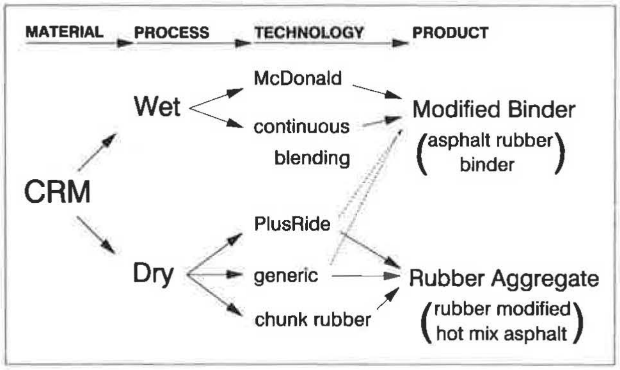

FIGURE 1 Relationship of crumb rubber modifier terminology.

As the Sahuaro technology continued to expand, the Arizona Refinery Company (ARCO) developed a similar wet process technology that added a blend of CRM and devulcanized CRM to the asphalt cement. The Sahuaro and ARCO technologies merged and are presently controlled by the patents' co-owners. In this paper, the wet process developed in Arizona, is referred to as the McDonald technology.

The dry process was developed in the late 1960s in Sweden. The European trade name for this HMA mixture with CRM as a rubber aggregate was Rubit. The Swedish technology was patented for use in the United States in 1978 under the trade name PlusRide. The Alaska Department of Transportation began working with PlusRide in 1976 and is still the principal state highway agency developing this technology. Four corporations have marketed the PlusRide technology since it was introduced in the United States; currently it is marketed by EnvirOtire Inc.

CRUMB RUBBER MODIFIER AND MODIFIED PROPERTIES

Crumb Rubber Modifier

Tire rubber is the principal component in CRM. Tire rubber is primarily a composite of a number of blends of natural and synthetic rubbers and carbon black. Although variations in tire rubber exist, both between tires and within the tire structure, the rubber composition of a bulk sample of CRM is reasonably uniform.

The principal source of raw material for producing CRM is scrap tire rubber. Scrap tire rubber can be delivered to the processing plant as whole tires, cut tire, shredded tire, or retread buffing waste. Shredded tire rubber is the preferred and logical alternative as a raw material for producing CRM. The type of scrap tire raw material and the quality of that material are generally the responsibility of the CRM processors. The capabilities of the processing plant and the buyer's specified CRM properties will direct the processor's operation.

There are three methods currently used to process scrap tire rubber into CRM. The crackermill process is the most common method. The crackermill process tears apart scrap tire rubber, reducing the size of the rubber by passing the material between rotating corrugated steel drums. The granulator process shears apart the scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance. The micro-mill process further reduces a crumb rubber to a very fine ground particle.

As the scrap tire rubber is processed, reducing its size, the steel belting and fiber reinforcing are separated and removed from the rubber. Talc, or other inert mineral powder, is added to the CRM to reduce the rubber particles' tendency to stick together. Typically, the amount of talc required should not

Foreword

Ground tire rubber has been used as an additive in asphalt for highway pavement construction since the mid-1960s. Early use of particulate tires in asphalt was a means to improve performance of the asphalt while simultaneously eliminating a waste product. Although the technology for tire-rubber-modified asphalt has been available for more than 20 years, only recently has the waste tire problem become so acute that the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) includes a schedule of minimum requirements for using recycled tire rubber in asphalt pavements starting in 1994.

Ground tire rubber can be blended with hot liquid asphalt, resulting in a new product known as "asphalt-rubber." This modified asphalt can be used to make any of the various types of asphalt pavements produced using conventional asphalts. Ground tire rubber can also be added to the asphalt concrete mixture as a dry particulate or aggregate. In this case, the properties of the resulting paving mixture containing the tire rubber are affected by the presence of the rubber.

At one of the sessions of the 71st Annual Meeting of the Transportation Research Board, a panel of experts discussed the current technology and practice for using ground tire rubber and asphalt-rubber in asphalt pavements. Six of the papers presented by these experts are included in this Record. These should be of interest to state and local design, materials, construction, maintenance, and research engineers, as well as contractors and material producers.

Heitzman presents a Federal Highway Administration (FHWA) overview of the experience to date with recycled rubber in asphalt pavements. Much of the early research and demonstration work with ground recycled tire rubber was conducted by and for the FHWA during the past two decades. Maupin of Virginia and Page et al. of Florida relate practical experiences with each of the types of tire-rubber-modified pavement processes and describe some of the difficulties associated with putting tires into pavements.

Takallou and Sainton report on some new advances in this emerging technology that have been made recently in France. Estakhri et al. report on the cost-effectiveness of using asphalt pavements as the repository for recycled tire rubber in Texas. Krutz and Stroup-Gardiner present the results of a comparative study of the rutting performance of asphalt concrete containing recycled tire rubber versus that of unmodified asphalt concrete mixtures.

exceed 4 percent by weight of the rubber. In general, a scrap tire weighing approximately 9 kg (20 lb) will produce 4.5 to 5.5 kg (10 to 12 lb) of CRM. The remainder of the tire is fiber, steel, and any rubber removed with the fiber and steel.

Each method of producing CRM generates a unique particle with specific characteristics. The cracker mill process produces an irregularly shaped torn particle with a large surface area. The particles can be produced over a range of sizes from 4.75 mm to 425 μm (No. 4 to No. 40) sieve. These particles are commonly described as a ground CRM. The granulator produces a cubical, uniformly shaped cut particle with a low surface area. The particles can be produced over a range of sizes, typically 9.5 mm down to 2.00 mm (3/8 in. to No. 10) sieve. This material is called a granulated CRM. The micro-mill process produces a very fine ground CRM. The particles can be reduced to a range of sizes from 425 μm down to 75 μm (No. 40 to No. 200) sieve.

The project specifications should establish the required gradation of the CRM and the type of particle, ground or granulated. Every CRM producer should have a quality control program to continually monitor the uniformity of the product for both its chemical composition and gradation. Processing scrap tires into CRM is not a mobile operation. A small industrial facility with moderate capital investment in equipment is necessary to produce a quality product. Most CRM is shipped in 22.7- or 27.2-kg (50- or 60-lb) bags, which are paper or plastic. The average cost of CRM from the producer ranges from 20 to 35 cents/kg (10 to 15 cents/lb) for coarse and medium crumb (above 425 μm) and up to 55 cents/km (25 cents/lb) for fine ground crumb.

Modified Properties

There are two basic products that can be achieved by adding CRM to asphalt paving applications. They are modified binder and rubber aggregate. The size, shape, and texture of CRM required to achieve these end products varies with the proposed application.

Modified Binder

When asphalt cement and CRM are blended together, there is an interaction between the materials (*5*). This interaction, defined as asphalt rubber reaction, is affected by a number of variables. Specifically, the reaction is influenced by the temperature at which the blending-reaction occurs, the length of time the temperature remains elevated, the type and amount of mechanical mixing energy, the size and texture of the CRM, and the aromatic component of the asphalt cement. The reaction itself is the absorption of aromatic oils from the asphalt cement into the polymer chains that are the key component of the natural and synthetic rubber in CRM. As CRM reacts with the asphalt cement, it also swells and softens. The viscosity of the asphalt-CRM blend is used to monitor the reaction. An asphalt cement modified with 15 percent CRM can increase the binder's high temperature viscosity by a factor of 10 or more.

The rate of reaction between CRM and the asphalt cement can be increased by enlarging the surface area of the CRM. The surface area can be increased by reducing the size and specifying a crackermill process. The rate of reaction is also influenced by the temperature at which the blend is reacted. The specified reaction time should be the minimum time (at a preset temperature) required to stabilize the binder viscosity.

This modified binder, asphalt rubber, exhibits enhanced binder properties when compared with conventional asphalt cement in laboratory tests. Changes in the viscosity of the binder over the normal range of operating and mixing temperatures indicates that the addition of CRM flattens the temperature-viscosity curve, reducing the binder's temperature sensitivity.

A majority of the standard binder tests used to measure the properties of asphalt cement can be applied to asphalt rubber binder. Only the conventional capillary-type viscometer tests are known to be ineffective (*6*). The method used to measure the viscosity of these modified binders is rotational shear resistance using the Brookfield Viscometer, ASTM D 2994. Portable versions of this viscometer are commonly used to monitor the binder during the reaction phase and as a production control. Several binder tests may show an increase in standard deviation caused by the nonuniformity of the modified binder. Because the crumb rubber does not dissolve into the asphalt cement, the swollen rubber particles in the binder can affect the consistency of the binder during a particular test.

The enhancements in the binder properties measured in the laboratory can be an indication of better performance of the paving material in the field. However, there are numerous variables, beyond the properties of the binder, that also affect the overall performance of the pavement. Setting these other variables aside, the modified binder properties may influence the pavement's performance related to thermal cracking, rutting, reflective cracking, aging, and chip retention.

There is also the potential for certain undesirable side effects. To develop enhanced pavement performance characteristics, the mix design will generally require the modified binder to increase its role in the paving material. In simple terms, modifying the asphalt binder with CRM will require an increase in the binder content. This affects the paving material's cost, potential to flush-bleed, and may cause tracking.

The ability of CRM to enhance the properties of the binder hinges on the compatibility between the asphalt cement and the CRM. For all practical purposes the ability to change the overall blended composition of CRM is limited. The type and amount of aromatic oil in the asphalt cement plays a major role in determining the compatibility.

Rubber Aggregate

The other product achieved by adding CRM is rubber aggregate. By limiting the time that the asphalt cement and CRM are maintained at mixing (reaction) temperatures and by specifying a coarse granulated CRM, the CRM can retain its physical shape and rigidity. By specifying a granulated CRM, the smooth sheared surfaces of the particle are less reactive (lower surface area than ground CRM) and its cubical shape can be factored into the combined gradation of CRM and aggregate.

This rubber aggregate product is only applied to hot-mixed asphalt designs.

Putting aside the effect of any binder modification that may accompany a design with rubber aggregate, rubber aggregate may influence the pavement performance related to reflective cracking and ice disbonding.

There are potential disadvantages associated with CRM used as a rubber aggregate. Similar to a CRM-modified binder, for rubber aggregate to achieve the benefits of delayed reflective cracking and ice disbonding requires a minimum CRM content in the mix. This affects the cost of the paving material and may cause raveling.

Compatibility is not as critical with CRM as it is with a rubber aggregate. The reaction between the CRM and the asphalt cement does not play a significant role in developing the performance enhancements of rubber aggregate.

CONSTRUCTION PROCESS FOR CRM

Wet Process

The wet process defines any method that adds the CRM to the asphalt cement before incorporating the binder into the asphalt paving project. This process is used to produce a modified binder product. There are three elements to the equipment necessary to achieve the wet process. They include blending the CRM and asphalt cement, reacting the two materials, and transferring the modified binder product to the desired project application. Two limiting factors to the process are having sufficient storage area for the shipment of CRM and the manual effort required to add CRM to the blending unit's hopper.

The blending unit must be capable of properly metering the CRM (a dry ground and granulated material, or both) into the asphalt cement (a hot viscous liquid) at the required proportion established by the mix design. The reaction tank must be capable of maintaining a uniform blend and a uniform constant temperature. Most applications require some method of controlled metering for the modified binder. Special pumps and frequent calibration are essential to ensure that a uniform accurate application of the modified binder is achieved.

Dry Process

The dry process defines any method of adding CRM directly into the HMA mix process, typically pre-blending the CRM with the heated aggregate before charging the mix with asphalt. This process is normally used when a rubber aggregate product is desired. The dry process will generate some reaction between the CRM and asphalt cement. The amount of fine CRM introduced into the mix will determine the degree of modification to the asphalt binder. No special equipment is needed for this process; however, a calibrated proportioning feed system is necessary when drum plants are used. The dry process has only been applied to hot-mixed paving projects. It does not lend itself to other asphalt paving applications like surface treatments.

Incorporating the dry process at a batch mix facility is simple but labor intensive. The bags are made of a low melting point plastic material that allow the operator to charge the mixing chamber with the entire bag of CRM. The batch size usually corresponds to a whole number of bags per batch.

The dry process can be used with drum mix facilities similar to producing mixes with recycled asphalt product (RAP). The process and equipment required for introducing RAP into a drum mixer can also be used to introduce CRM into a drum mixer. Similar to batch mixing, the dry process at a drum mix facility has been labor intensive.

DESIGN AND CONSTRUCTION PRACTICES

Crack and Joint Sealants

The use of asphalt rubber crack and joint (C/J) sealant is common across the country and is routinely used by many state maintenance crews. The choice of a sealant for a given location should take into consideration the type of pavement, type of crack or joint, shape and size of the crack or joint, time before next scheduled major rehabilitation, traffic volume, degree of pavement distress, maximum and minimum temperatures, available equipment and work crews, and traffic control.

The manufacturers of asphalt rubber C/J sealant provide a variety of sealants to meet different climate and pavement conditions. These sealants are normally designed to meet various ASTM specifications. Asphalt rubber C/J sealant is typically preblended and packaged in 22.7-kg (50-lb) blocks. These blocks must be remelted and reacted before the sealant can be applied.

Approximately 80 percent of the states use some amount of asphalt rubber C/J sealant. States that apply a large amount of this sealant include: Arizona, California, Georgia, Nebraska, Nevada, New Mexico, New York, Pennsylvania, Texas, and Wisconsin. The cost of the material generally ranges from 45 to 65 cents/kg (20 to 30 cents/lb). This is the material cost and does not include shipping or the cost of installation (labor, equipment or traffic control).

Surface Treatments

A surface treatment using an asphalt rubber spray application is called a Stress Absorbing Membrane (SAM) (*7*). The design of a SAM should examine both the binder and cover aggregate. The binder is asphalt rubber that may be thinned with a diluent to improve distributor-spray flow. The amount of CRM in the binder is typically 20 to 30 percent by weight of asphalt cement. Cover aggregate is generally a uniform size (9.5 mm to 6.3 mm sieve, 3/8 in. to 1/4 in.) and preferably hot precoated with 0.3 to 0.5 percent (by weight) asphalt cement. The compatibility of the binder and aggregate is a part of the design process.

Once the materials have been selected, the designer must determine the appropriate spray application rate and aggregate spread rate to achieve proper coverage and embedment. Typical values that have been used successfully are 2.7 litre/m^2 (0.6 gall/yd^2) of diluted asphalt rubber binder and 19 kg/m^2 (35 lb/yd^2) of precoated cover aggregate. The construction of a SAM is similar to any surface treatment. The use of an asphalt rubber binder in a surface treatment has particular benefits for the performance of the pavement. Temperature susceptibility and elasticity influence the binder's ability to resist the stresses induced by climate and traffic, thus the name stress-absorbing membrane (SAM).

The engineering properties of a SAM can resist and delay the development of reflective cracks when the cracks are generally inactive, like alligator fatigue cracking and closely spaced random or block cracking. A SAM cannot resist the amount of strain that is typical of transverse thermal cracks in asphalt concrete pavements or transverse contraction joints in portland cement concrete pavements.

Several states routinely design and apply SAMs to their pavement network. Arizona, California, and Texas are predominant states involved with using this product. The present cost of a SAM in place is generally 100 percent higher than a conventional surface treatment. The cost increase is principally caused by the asphalt rubber binder. In Arizona and California during the late 1980s, the in-place cost for a SAM generally ranged from \$1.90 to \$2.30/m^2 (\$1.60 to \$1.90/yd^2).

This section has focused on the application of asphalt rubber as a spray application for surface treatments. Other thin asphalt surfacing techniques may also benefit from CRM technology.

Hot-Mix Asphalt

The use of CRM in HMA paving materials has broad variability and potential. Two of the principal variables are the type of CRM process (wet or dry) and the type of HMA (dense, gap, or open-graded). For clarity, this section on HMA paving applications is divided into two parts, HMA applications using the wet process (McDonald) and those using the dry process (PlusRide).

McDonald Technology

Conventional Marshall and Hveem mix design procedures have been used successfully for dense-graded mixes using McDonald's asphalt rubber (*8*). The characteristics of the modified binder alter the laboratory measured properties of the mix and should be understood when designing these dense mixes. As a general rule, the increase in the designed binder content will be proportional to the amount of CRM in the binder.

The present design concept being developed for modified gap-graded mixes is to maximize the asphalt rubber content of the mix. This design is intended to combine the stability of coarse aggregate contact with the elastic properties of asphalt rubber. Typical asphalt rubber binder contents for gap-graded mixes developed in Phoenix range from 8 to 9 percent.

The design of open-graded mixes (OGFC) with asphalt rubber binder requires two revisions to the procedure. To determine the binder content of OGFC with asphalt rubber will require a revision of the formula to account for the thicker binder film associated with asphalt rubber; in essence, compute a higher binder content. The procedure for establishing the optimum mixing temperature will require a change in the target binder viscosity to better reflect the high viscosity of asphalt rubber. The desired drain-down characteristics do not change. The amount of CRM in asphalt rubber binder for HMA applications generally ranges from 15 to 25 percent by weight of asphalt cement.

The construction of HMA with asphalt rubber binder is similar to constructing conventional mixes. The target temperatures for mixing, laydown, and compaction are typically higher. Release agents for the equipment, particularly the truck beds and steel-wheel roller drums, must not be petroleum-based products. Pneumatic tire rollers are generally not permitted because the asphalt rubber binder tends to build up on rubber materials.

The field inspection of HMA with asphalt rubber is similar to conventional mixes. The use of extraction test procedures is not practical with these modified mixes. The reacted (and unreacted) CRM is not completely soluble in the extraction solvents. Nuclear asphalt content gauges can be used to measure the modified binder content of a mix applying normal calibration procedures for each mix.

There are no state highway agencies that routinely use HMA with asphalt rubber binder for any particular application. The majority of documented field-test sections with appropriate evaluation programs were placed during and after the mid-1980s. California has performed the most extensive amount of field performance research and has not yet resolved all the issues (*9*). The cost of asphalt rubber HMA mixtures (in-place) has ranged from 50 to 100 percent higher than the conventional mix. The projected future cost of HMAs with asphalt rubber could reduce to between 20 and 30 percent above conventional HMA if the mix is routinely applied.

PlusRide Technology

PlusRide is a modified gap-graded mix and the mix design does not follow normal Marshall or Hveem procedures (*10*). The PlusRide HMA is designed to modify the stability of a gap-graded aggregate matrix with the elastic properties of CRM and a certain amount of binder modification (reaction). Conventional specimen preparation equipment and procedures are performed with some modifications, but the specimens are not tested for stability. The only measured specimen property used to establish the mix design asphalt content is percent air voids. The target air void content is 2 to 4 percent. The aggregate gradation and CRM content and gradation are relatively fixed by the patent description. The CRM is predominantly a granulated crumb passing the 6.3-mm (1/4-in.) sieve with the fraction passing the 2.00-mm (No. 10) sieve supplemented with buffings or ground CRM. As specified in the design, the CRM content is 3 percent by weight of the total mix. The asphalt binder content will generally range from 7.5 to 9.0 percent.

There are only a few modifications to the construction practices for PlusRide HMA. Compaction concerns are similar to asphalt rubber HMA. In addition to these modifications, the finish roller must continue to compact the PlusRide mat until it cools below 60°C (140°F).

Poor production, placement, or compaction control will lead to premature failure of the pavement. Inspectors should be knowledgeable about the required construction practices. Extraction methods will not provide accurate means of monitoring CRM content nor binder content. Similarly, asphalt content gauges will measure all the CRM in the sample as a part of the binder content.

Experimental applications of PlusRide began in 1979. Alaska is the only state DOT with a substantial background in developing PlusRide in the United States. The cost of PlusRide HMA (in-place) has ranged from 50 to 100 percent higher than conventional HMA. The projected future cost of this rubber-modified HMA could reduce to between 20 and 40 percent above conventional HMA if these mixes are routinely applied.

Composite Designs–SAMI

Composite designs with CRM paving materials offer similar theoretical benefits as the use of paving fabrics (*7*). The principal theory of the design is to place a membrane beneath the overlay that can resist the stress-strain of reflective cracks and delay the propagation of the crack through the new overlay. Similar to a SAM, the asphalt rubber membrane is called a SAMI.

There are two composite design systems, a two-layer SAMI and a three-layer SAMI. A two-layer SAMI places the SAMI on the existing pavement and overlays the SAMI with 25 to 75 mm (1 to 3 in.) of HMA. A three-layer SAMI begins with the placement of a leveling course of HMA. This initial overlay provides an acceptable uniform surface for placing the SAMI. The SAMI is followed by an additional 25 to 75 mm (1 to 3 in.) of HMA overlay. This system applies when there is deterioration of the existing pavement cracks and joints. If a two-layer SAMI were used, the deteriorated cracks would create a discontinuity in the membrane at the location where the membrane will be subjected to the highest levels of stress and the performance of the SAMI would be diminished.

Construction and inspection of a SAMI is the same as a SAM. The only additional consideration is to assure that the diluent added to the asphalt rubber binder prior to the spray application has adequately evaporated from the membrane before the HMA overlay is placed.

The delay of reflective cracking is the principal benefit of a composite design. This potential performance benefit is similar to the benefit of paving fabrics. The cost of a SAMI is slightly higher than the cost of the fabric.

NEW CONCEPTS

The combination of an existing exclusive, proprietary CRM paving market and growing nationwide interest in alternative uses for scrap tires provided CRM technologists the catalyst to develop new concepts for applying CRM. Initial laboratory work in this area did not begin until the mid- to late 1980s. The first experimental field applications were placed in 1989.

Two conditions should be noted regarding these new concepts. First, the design and construction practices are still being developed and there is no field performance record to demonstrate that they can provide an acceptable level of service over a normal performance period. The second condition is that McDonald's asphalt rubber and PlusRide are patented products. This report did not review the extent of the patents nor examine the association of the new concepts to the patented products. State and local highway agencies should be aware of the known patented products and make their own determination of any conflict between a proposed new concept and its comparable patented product.

Generic Dry Technology

A major interest has been to develop generic dry process mixes. The concept was originated by Barry Takallou as a result of his research and practical experience with PlusRide (*11*). The principal focus of this concept in CRM technology is to incorporate CRM into conventional dense and gap-graded HMA mixes using the dry process. Unlike PlusRide, which specifies a particular gap gradation for the aggregate, the proposed technology considers the available generic gradations for the locality; hence the name, generic dry technology.

Much of the theory and understanding needed to design and construct PlusRide mixes also applies to generic dry mixes. Although the theory is similar, the variability of application is much greater. There are a number of factors that must be considered in the design, particularly how the CRM is to modify the mix. The PlusRide concept modified the HMA primarily through aggregate substitution. It is possible with generic dry process mixes to achieve a greater degree of binder modification. By specifying a smaller particle size ground crumb rubber, the dry process combined with the HMA production sequence may be sufficient to permit the CRM and asphalt binder to achieve a substantial degree of reaction before placement and compaction of the mix.

Because the intent of generic dry process technology is to use conventional aggregate gradations, the design process must determine the appropriate CRM gradation for the proposed mix properties. The designer must take into consideration the capabilities of the CRM manufacturer. Present grading flexibility in most CRM plants is limited. If unusual CRM grading requirements are specified, the cost of the CRM will increase or the gradation may not be attainable.

The generic concept has been successfully constructed in experimental field applications in New York and Florida. The New York projects included three generic dry process designs (*12*). The designs varied the amount of CRM added to the mix from 1 to 3 percent by weight of total mix. The aggregate gradation was a standard 12.5-mm (1/2-in.) nominal maximum dense-graded surface mix. The CRM gradation had a 2.0-mm (No.10) sieve nominal maximum size. The asphalt cement content increased to 7.2 percent for the 3.0 percent CRM mix compared with the 6.0 percent asphalt cement for the conventional design. All the mixes used the same grade of asphalt cement. In Florida, a June 1989 experimental project using CRM included one section of generic dry process. The aggregate was a standard 9.5-mm (3/8-in.) nominal maximum open-graded friction course. Along with four sections of asphalt rubber, the section of generic dry process contained 180 μm (No. 80) sieve CRM at 10 percent by weight of binder. The binder content of the control mix was 6.3 percent compared with the design binder content of the generic CRM mix at 7.0 percent, both using the same grade of asphalt cement.

Additional experimental sections were constructed in a number of states in 1991. Illinois, Iowa, Kansas, and Oregon have constructed projects to evaluate the generic dry technology.

Chunk Rubber Asphalt Concrete

As a part of the Strategic Highway Research Program, the Cold Regions Research and Engineering Laboratory (CRREL) of the U.S. Army Corps of Engineers was contracted to evaluate the ice-disbonding characteristics of several asphalt paving materials. One of those materials was PlusRide (*13*). In addition to this research effort, CRREL began modifying the design to determine if the use of CRM could further modify the properties of the paving material. Their work focused on increasing both the maximum size of the crumb and the percent CRM in the HMA.

The CRREL concept revised the aggregate gradation from the gap-graded PlusRide design to a dense-graded aggregate, while maintaining the same nominal maximum aggregate size. The CRM gradation was revised to a narrow grading band (12.5-mm to 4.75-mm sieve, 1/2 in. to No. 4), with a larger maximum crumb size. This revision of the gradations applies to mixes with CRM contents similar to PlusRide, namely 3 percent CRM by weight of mix. As the CRREL research increased the percent of CRM, adjustments were made in the aggregate gradation to provide space in the aggregate matrix for the substitute rubber aggregate. This research examined chunk rubber asphalt concrete mixes with 3, 6, 12, 25, 57, and 100 percent crumb rubber by weight of aggregate. As expected, the optimum asphalt cement content (based primarily on air voids) increased as the percent CRM increased. Actual Marshall mix designs produced asphalt cement contents ranging from 6.5 percent for 3.0 percent CRM to 9.5 percent for 12 percent CRM.

This research initiative has been confined to laboratory testing. There are no scheduled experimental field applications established for this concept. CRREL is currently seeking sources of research funding to continue the development of these unique mixes. Until the material is subjected to actual field conditions, it is impossible to estimate its performance or practical application.

Continuous Blending Asphalt Rubber

One concern regarding the McDonald wet process is the required batching and reaction time associated with blending CRM and asphalt cement to produce asphalt rubber. As previously discussed, the time required to react these materials is dependent on a number of factors, including the size of the CRM. Rouse Rubber Industries applied wet process technology, blended their 180 μm (No.80) sieve CRM with an asphalt cement, and developed a continuous blending procedure. The prototype blending equipment is still being evaluated.

The first experimental field application of the concept was achieved with the cooperation of the Florida DOT in 1990 (*14*). Results on the performance of this continuous blended asphalt rubber will not be known for several years. Particular attention will be given to the uniformity of the binder properties as they relate to the uniformity of the blending operation.

In addition to the uniformity of the binder, the actual engineering characteristics of the binder may behave differently from the commonly known McDonald asphalt rubber. The very fine gradation of 180 μm (No.80) sieve CRM substantially increases the dispersion of the CRM throughout the asphalt cement. It has not been determined if this additional dispersion will improve or reduce the performance of the modified binder. It is possible that the optimum CRM content will not be the same as that for other asphalt rubber binders with coarser CRM.

FURTHER RESEARCH

There are two principal issues related to the use of CRM in asphalt paving materials that need to be evaluated (*15*). On the national level, the ability to recycle asphalt paving mixes containing CRM has not been demonstrated. At the state and local level, these modified HMA mixtures must be field evaluated to establish expected levels of performance. There are other areas, as well, that are unclear or need further development but are not as critical for acceptance of this technology by the highway community. This section divides the further research areas into three categories: national, state, and industry issues.

National Issues

National issues are areas of concern that can be resolved and addressed and applied on a national basis. As noted, the ability to recycle asphalt pavements containing CRM is a principal research issue. This aspect of the technology is critical to its long-term application. If these modified paving materials cannot be recycled, their benefit is substantially reduced and a new waste problem is created. Two questions need to be addressed in the recycling area. First, can materials containing CRM be successfully processed as recycled asphalt pavement? and second, how does the recycled paving material containing CRM perform?

Another area of national concern is the development of standards, particularly for material testing and the environment. It is important for the highway community to develop and adopt standard material testing methods so that data collected from various sources across the country can be shared on a relatively equal basis.

The area of establishing environmental standards for emissions and fumes is not the responsibility of the highway agencies. Their role is secondary. Highway agencies are responsible for enforcing those standards developed by the environmental agencies, who coordinate with the industry as the standards are developed.

State Issues

State issues are areas of CRM technology that can only be resolved through proper evaluation at the state and local level. The principal research issue at this level is the field evaluation of these CRM-modified materials to establish their expected performance. The performance of CRM has been documented in some applications. In other applications, particularly as an HMA mixture, the use of CRM is still being evaluated. As applications vary, so do the performance criteria and the cost-effectiveness. Therefore, the performance data must be application specific. Studies have concluded that laboratory tests using CRM modified mixes do not correlate with measured field performance (*16*). Therefore, laboratory results used to predict field performance may not be accurate and may not accurately reflect the cost-effectiveness of the material.

Industry Issues

Industry issues are areas of CRM technology that can be addressed to improve the material, process, and technology. The material, process, and technology are continually evolving. An improvement in one area becomes a catalyst for improvements in other areas.

As the technology expands, specification parameters will require the crumb rubber producers to add flexibility and quality control to their production. This may be particularly true for the gradation control. Larger production rates will require larger material-handling systems equipped with mechanical feed systems. Methods and equipment to handle larger containers of crumb rubber could improve the overall efficiency of the wet and dry processes. In addition to the crumb rubber handling system, the blending and metering systems for adding CRM (dry process) and asphalt rubber (wet process) into an HMA facility will need to be interlocked with the other material feed systems to eliminate manual adjustment of feed rates during HMA production.

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Virginia's Experimentation With Asphalt Rubber Concrete

G. W. MAUPIN, JR.

The installation of test sections containing asphalt rubber concrete using the wet process and the testing of samples of the materials in the laboratory are described. Also, some preliminary test data from a laboratory study using both coarse and fine crumb tire rubber with the wet process are included. The installation of the test sections went smoothly with only minor problems. The following laboratory tests were used to evaluate the mixtures: Marshall, gyratory shear, creep, resilient modulus, indirect tensile strength, and stripping. The test results indicated that the asphalt rubber mixtures were more susceptible to permanent deformation than the same mixtures without asphalt rubber; however, the temperature at which the mixtures were compacted and tested may have affected the results, which may not therefore reflect how the asphalt rubber will perform in the field. After being subjected to the indirect tensile stripping test, the mixtures with asphalt rubber displayed less stripping than the mixtures without asphalt rubber. The laboratory study indicated that asphalt rubber binder containing either coarse or fine rubber can be stored for a reasonable period (at least 24 hr) with no breakdown of the rubber. The coarse and fine rubber reacted with the asphalt in a similar way, but the mixture containing coarse rubber required slightly more asphalt cement than the mixture with no rubber. The fine rubber mixtures displayed an optimum rubber content in those cases in which the maximum resilient modulus and indirect tensile strength were achieved.

Attempts to use old tire rubber in asphalt for highways date back to the 1920s (*1*). Rubber may be used in asphalt concrete as an aggregate, or it may be reacted with the asphalt cement to yield asphalt rubber. Most of the rubber that has been used has been asphalt rubber. The success of this product has been somewhat mixed: some agencies have expressed overwhelming satisfaction with it, and others have expressed doubt about the economic advantage of adding rubber to asphalt. Logically, the rubber should impart desirable characteristics that improve the life of the pavement. The use of rubber has changed since its inception; therefore, there is still a need to experiment using the recent changes to determine how it performs. Recently there has been much emphasis on recycling tires to prevent filling landfills with them, and many state legislatures have mandated that the use of tires in highway construction be studied. In 1990, Virginia Senate Bill No. 287, which encouraged demonstration projects using ground rubber from used tires in road surfacing, was passed, and an experimental field project using asphalt rubber concrete was installed in Fairfax County.

The purposes of this paper are to summarize the results of the field project, which are primarily laboratory results, and to report on the initial data from a follow-up laboratory study dealing with the comparison of the properties of asphalt concretes using coarse rubber or fine rubber.

FIELD TESTS

Installation

In August 1990, two sections of control mixture and two sections of experimental asphalt rubber mixture were placed as an overlay on Rte. 1 in Fairfax County in an urban area in which slow-moving traffic often causes excessive permanent deformation. These four-lane sections carry 30,000 to 40,000 vehicles/day (5 to 15 percent trucks).

The asphalt contractor hired a subcontractor to supply the crumb rubber and to blend it with asphalt cement and an extender oil at the hot-mix plant concurrently with the hot-mix operation. The AC-30 asphalt cement containing extender oil was heated to approximately 420°F before being mixed with the crumb rubber, and the resultant binder was stored at 360°F before being mixed with the aggregate in the hot-mix drum plant. The construction operation went smoothly except for a minor problem with pickup on the leading roller drum of the breakdown roller.

Materials

The 1/2-in. surface mixtures (Table 1) were devised with a 75-blow Marshall design. The control mixture contained 4.5 percent of AC-30 asphalt cement, and the experimental mixture contained 6.75 percent of asphalt rubber composed of AC-30 with 6 percent extender oil and 17 percent crumb rubber (14 percent car tire rubber and 3 percent tennis-ball rubber by weight of asphalt cement). The crumb rubber (Table 2) was required to produce an asphalt rubber binder with the characteristics shown in Table 3. Crafco, Inc., which has had considerable experience with asphalt rubber, designed the asphalt rubber mixture.

Testing

Marshall, gyratory testing machine (GTM), creep, resilient modulus, indirect tensile, and stripping tests were conducted on mixtures sampled during construction.

Marshall tests were conducted according to ASTM D1559 (*2*) using the 75-blow compactive effort. Properties that were evaluated were voids in the total mixture (VTM), voids filled

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TABLE 1 GRADATIONS OF MIXTURES

	% Passing	
Sieve	Test Sections	Lab Study
3/4	100	
1/2	99	100
3/8	91	95
4	55	58
8	40	42
30	22	25
50	13	17
100		11
200	5.4	6.2

TABLE 2 SPECIFIED GRADATION OF CRUMB RUBBER

Sieve	% Passing
#10	100
#16	95–100
#30	70–100
#80	0–20
#200	0–5

Note: No gradation tests were performed.

with asphalt (VFA), voids in the mineral aggregate (VMA), and stability.

Under the oil-filled mode of operation, specimens were tested with a GTM using initial gyratory angles of 1 and 0.75 degrees with a vertical pressure of 120 psi. The specimens were compacted until the rate of compaction decreased to 1 pcf/100 revolutions, which simulates the level of compaction after traffic. The angles of gyration are thought to produce compaction that duplicates the compaction of moderate to heavy traffic. Properties used to characterize the mixtures were final voids, shear strength, and gyratory stability index (GSI).

Compression creep tests were performed at 104°F on 2.5-in. by 4-in.-diam specimens that were compacted on the GTM to the predicted void content of pavement after traffic. The specimens were preloaded for 2 min at 30 psi, unloaded and allowed to rest for 5 min, and then loaded for 60 min at 30 psi. Axial deformation was recorded at set intervals when the load was being applied and again for 60 min after the load was released. The stiffness modulus at 60 min and the unrecovered strain after the load had been released for 60 min were analyzed.

The indirect resilient modulus and indirect tensile strength at 104°F were measured according to ASTM D4123 (*2*) with the Retsina device using the same specimens that were used in the creep tests. Because vertical deformation could not be measured, Poisson's ratio was assumed to be 0.35.

TABLE 3 PHYSICAL PROPERTIES OF ASPHALT RUBBER BINDER

Minimum viscosity, 350°F	1500 cp
Minimum cone penetration, 77°F (ASTM D1191)	20
Minimum softening point (ASTM D36)	125°F
Minimum resilience, 77°F (ASTM D3407)	15%

Stripping tests performed were the indirect tensile strength test (ASTM D4867)(*2*) and the Virginia boiling test for field mixtures (*3*). The tensile strength test determined susceptibility to moisture damage by testing two sets of specimens: one set was conditioned to simulate potential moisture damage and tested, and one set was tested in an unconditioned dry state. The tensile strength ratio, which is the ratio of the conditioned strength to the dry strength, was used to predict moisture damage. The boiling test was performed by boiling a sample of mixture in water for 10 min. The sample had to be as well coated as an unboiled dry sample in order to pass the test.

Results

The design criteria and Marshall properties for the mixtures are listed in Table 4. The VTM was lower than desirable, and the VFA was higher than desirable for the southern section of asphalt rubber mixture. The VTM was at the upper limit for the northern control mixture and slightly greater than the upper limit for the southern control mixture. If the Marshall void properties are indicative of pavement performance, then it is to be expected that the southern asphalt rubber section may tend to bleed or become overly dense, and the control sections may tend to be open and age prematurely.

The GTM results—predicted voids after traffic, shear strength, and gyratory stability index—are displayed in Figures 1, 2, and 3, respectively. Both asphalt rubber mixtures failed all of the tests, and the southern control mixture failed shear strength at both pressure levels and GSI at 120 psi. These test results indicate that the asphalt rubber mixtures and southern control mixture may deform if the traffic is severe enough. Because the properties of the binders may be similar at high temperatures (as used in this test) but very different at lower summer pavement temperatures, performance of the asphalt rubber mixtures may have been predicted better by performing the traffic compaction simulation at lower temperatures.

A summary of the results of the creep test are listed in Table 5. It was expected that the addition of rubber would increase the modulus and decrease the unrecovered strain; however, the asphalt rubber mixtures had a lower modulus and a higher unrecovered strain compared with the same

TABLE 4 MARSHALL DESIGN CRITERIA AND TEST RESULTS

	Southern		Northern		Design Criteria	
Property	Rubber	Control	Rubber	Control	Rubber	Control
VTM (%)	2.4	6.1	3.8	6.0	3–4	4–6
VFA (%)	87	65	80	67	—	60–75
VMA (%)	17.7	17.5	18.9	18.3	≥15	≥15
Stability (lbs)	2580	2960	2660	3120	—	—

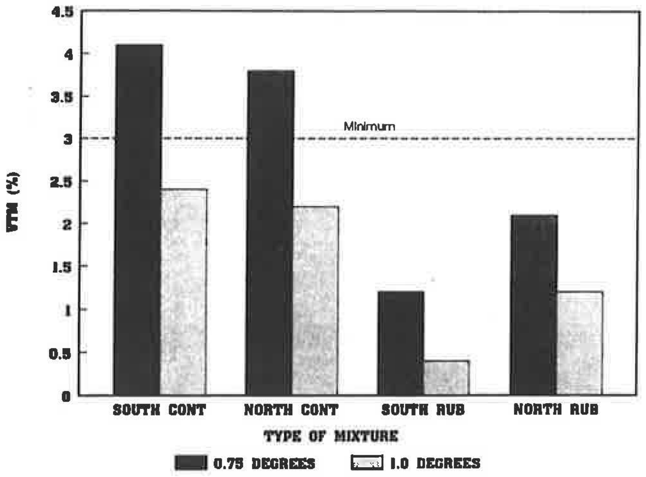

FIGURE 1 Pavement voids predicted by GTM.

properties of the control mixtures. The average differences were significant at a 95 percent confidence level. Although some research has shown that asphalt rubber increased stiffness and strength (*4,5*), other research has shown that asphalt rubber decreased the stiffness of mixtures that were already performing well with a normal binder (*6*).

The resilient modulus of the southern control mixture was significantly higher than the resilient modulus of the northern control mixture at a 95 percent confidence level (see Figure 4). It was anticipated that rubber mixtures would follow the trend observed with the creep test, in which the modulus of the rubber mixtures was lower than that for the control mixtures; however, the reason for the difference between the control mixtures could not be explained.

The indirect tensile strengths of the rubber mixtures (see Figure 5) were significantly lower than the control mixtures at a 95 percent confidence level, which was the same trend previously observed.

In those cases in which the GTM was used for testing or compacting the specimens, the results are probably biased favorably toward mixtures without rubber. The GTM test was performed at high temperatures at which the deformation resistance of the asphalt rubber is minimal. Also, the high temperature during the GTM traffic-compaction simulation allowed the specimens containing asphalt rubber to densify more than is normally observed in pavement, thereby resulting in low air voids and low values for strength and modulus, which may be misleading.

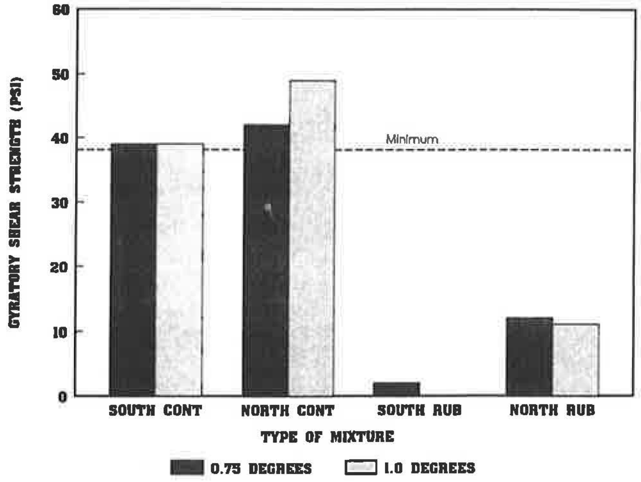

FIGURE 2 Gyratory shear strength.

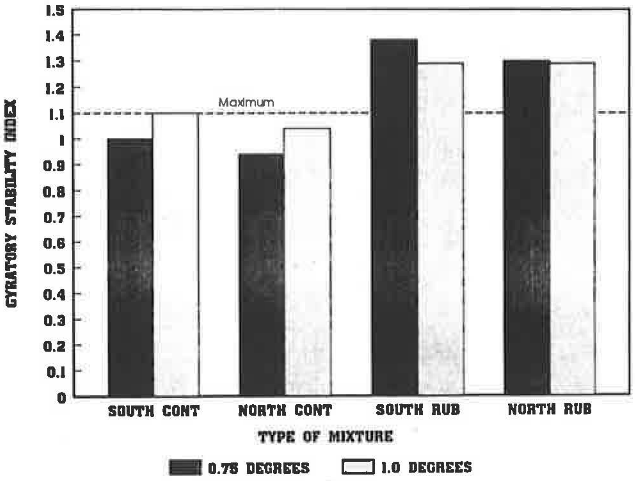

FIGURE 3 Gyratory stability index.

The tensile strength stripping test indicated that the control mixtures may be susceptible to stripping. The southern control mixture had a TSR less than the acceptable 0.75, and both control mixtures had considerable visual stripping. None of the mixtures failed the boiling test.

LABORATORY STUDY

Several gradations of crumb rubber that are used in other applications are available for use in asphalt rubber. A follow-up laboratory study was conducted to determine how the properties of asphalt rubber concrete containing coarse crumb rubber compared with the properties of asphalt rubber concrete containing fine crumb rubber. When rubber is mixed with asphalt cement, the rubber particles swell (react) causing the viscosity to increase, and if heat is maintained for a prolonged time, the rubber may melt and break down, resulting in an undesirable decrease in viscosity. Reaction curves were developed for asphalt rubber binders containing various percentages of fine and coarse rubber to determine whether the fine rubber should be used differently in the field. It is desirable to use the asphalt rubber binder after it has reached its maximum viscosity but before the rubber breaks down; however, rubber breakdown is not the only concern. If a short time is required to achieve maximum viscosity, the fine rubber will require less elaborate blending equipment than the coarse rubber. Perhaps the fine rubber could be added during the

TABLE 5 CREEP TEST RESULTS

Sections	Modulus, (psi) Average	Modulus, (psi) Std. Dev.	Unrecovered Strain (%) Average	Unrecovered Strain (%) Std. Dev.
Control	7,900	900	0.080	0.027
Asphalt Rubber	5,500	550	0.200	0.074

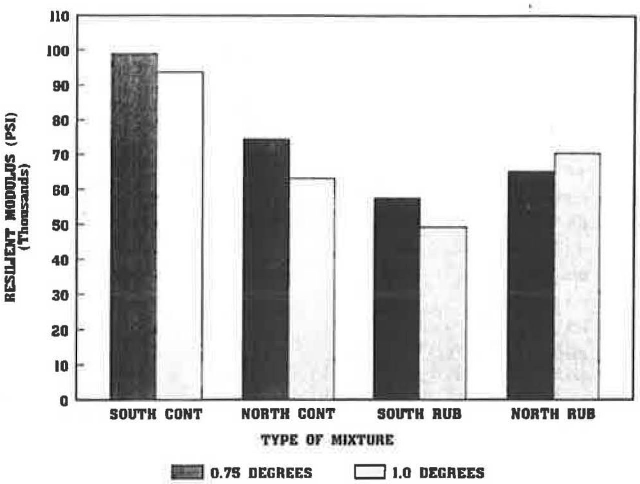

FIGURE 4 Resilient modulus at 104°F.

mixing of the binder and aggregate without blending equipment.

Materials

A 1/2-in. surface mixture using an AC-20 asphalt cement and a 75-blow Marshall design was used (Table 1). The gradation of the coarse rubber was the same as that used in the field experiment, and the fine rubber had 100 percent passing the No. 80 sieve and a mean particle size of No. 200 (0.074 mm).

Testing

Reaction (viscosity-time) curves for the asphalt rubber binders were developed using rubber contents of 5, 10, and 15 percent for both the coarse and fine crumb rubber. A portable Haake viscometer was used to measure viscosity. The rubber was mixed with the asphalt cement and maintained at 350°F, and viscosity measurements were taken at regular intervals for approximately 24 hr.

Marshall designs were performed on each binder at each rubber content to determine the optimum asphalt content at 4.5 percent VTM. The remaining tests—gyratory shear, resilient modulus, and indirect tensile—were performed at the optimum asphalt content.

Although the GTM was used, the procedure was changed from the procedure used in the study of the field mixtures. Only one initial gyratory angle of 1.0 degree and a vertical pressure of 120 psi were used. Also, the specimen was compacted to the expected density of pavement after rolling, removed from the machine, cooled to 140°F, and compacted until the rate of compaction decreased to 1 pcf/100 revolutions. Compacting at 140°F to simulate the effect of traffic was done in an attempt to show the potential advantage of rubber in resisting permanent deformation at normal pavement temperatures.

Resilient modulus and indirect tensile tests were performed on the specimens made on the GTM by the same procedures that were used in the study of field mixtures.

Results

The reaction curves for coarse and fine rubber are shown in Figures 6 and 7, respectively. It is obvious that there is considerable variation in the test results because the curves were not as smooth as expected. The variation is caused by difficulty in maintaining a constant temperature when removing a binder from the oven for viscosity testing, and the accuracy of the Haake viscometer is limited. It appears that the viscosity reached a maximum after approximately 1 hr with all of the binders except the one containing 15 percent coarse rubber, which appeared to still be gaining viscosity after 20 hr. For a rubber content of 10 percent or less, the reaction appears to be almost instantaneous. The rubber did not appear to break down after 20 hr, which would have resulted in a decrease in viscosity; therefore, these binders could be safely stored at 350°F for this time period without deleterious effects. It is evident from both sets of curves that viscosity increases significantly between 10 percent and 15 percent rubber content. The engineering properties would also change

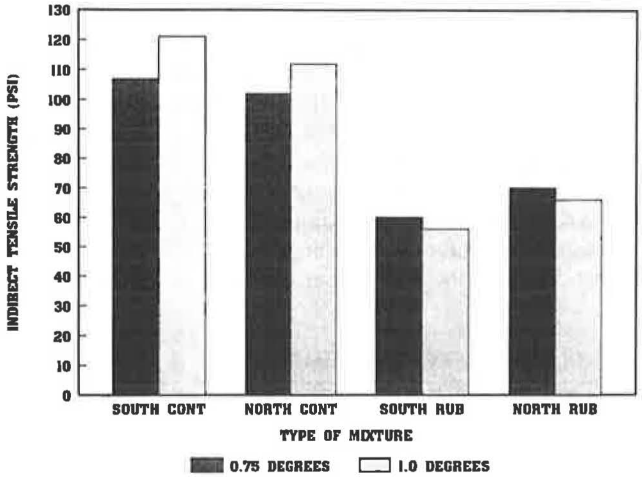

FIGURE 5 Indirect tensile strength at 104°F.

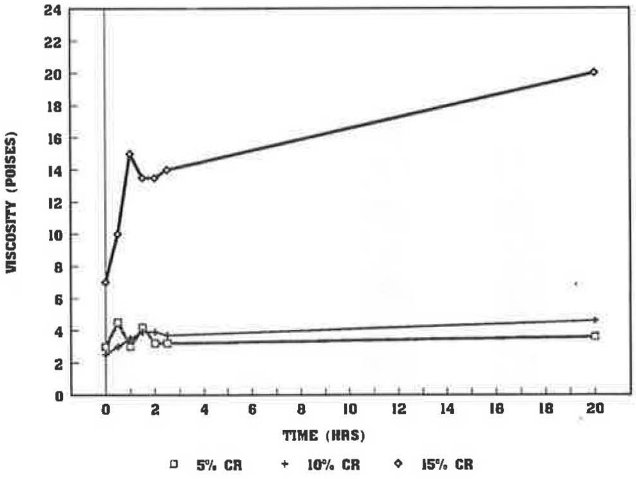

FIGURE 6 Reaction curve: coarse crumb rubber.

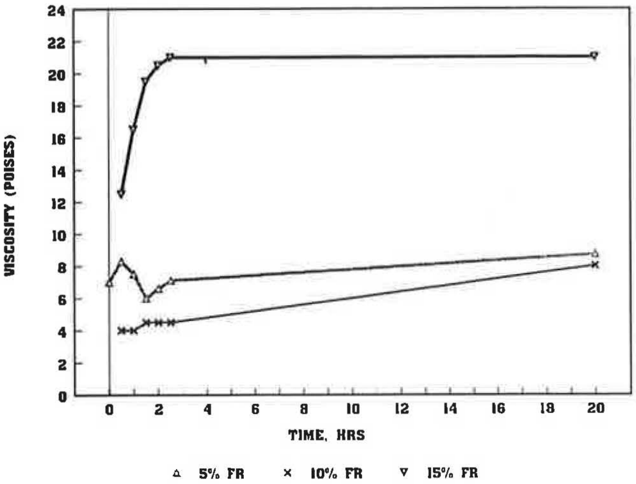

FIGURE 7 Reaction curve: fine crumb rubber.

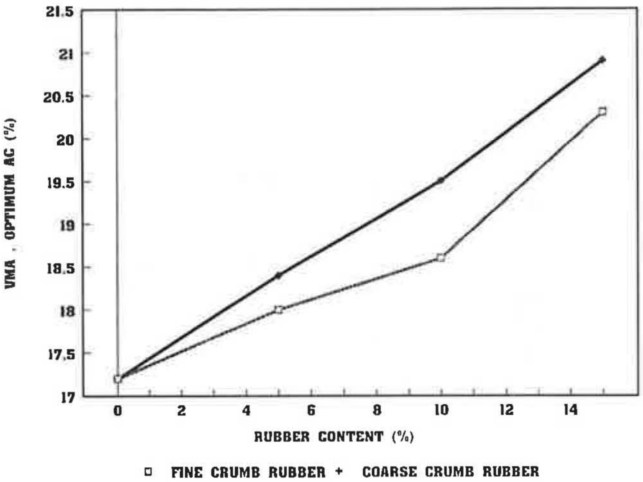

FIGURE 9 Voids in mineral aggregate at optimum asphalt content versus rubber content.

dramatically in this range. There does not appear to be a significant difference in the viscosity of the coarse and fine rubber at a similar rubber content, and both would be expected to behave in a similar way in blending operations in the field.

The "optimum" asphalt content, which was selected at 4.5 percent VTM, and the associated VMA from the Marshall designs are shown in Figures 8 and 9, respectively. The change in asphalt content with change in rubber content (i.e., slope of the curve) was consistent between the coarse and fine rubber mixtures. The mixtures with coarse crumb rubber required approximately 0.6 percent more binder than similar mixtures with fine crumb rubber. Because the rubber particles do not melt completely, they tend to push the aggregate particles apart, as indicated by an increase in VMA in all mixtures that have a higher rubber content. As expected, the coarse rubber particles created higher VMA than the fine rubber particles because the larger particles forced the aggregate particles further apart. If they are stable, it would be anticipated that the coarse rubber mixtures with higher asphalt content would be more flexible than the fine rubber mixtures with lower asphalt content.

The predicted voids after traffic, shear strength, and stability index are shown in Figures 10, 11, and 12, respectively. The mixture with 15 percent coarse rubber had a significantly higher percentage of voids (i.e., less densification) than the other mixtures, which indicates a possible greater resistance to permanent deformation. The GSI of the mixtures with 10 percent and 15 percent rubber was greater than 1.1, which indicates that they may have contained too much binder and would be prone to instability. These results are contradictory; therefore, the method of testing and analyzing asphalt rubber mixtures with the GTM needs further study. The shear strengths showed no trends for mixtures with different rubber content; however, all of the strength values were very low.

The bar graphs of resilient moduli and indirect tensile strengths (Figures 13 and 14) of the specimens made on the GTM revealed some trends. There appeared to be an optimum rubber content at which the maximum value of resilient modulus and indirect tensile strength was achieved for the

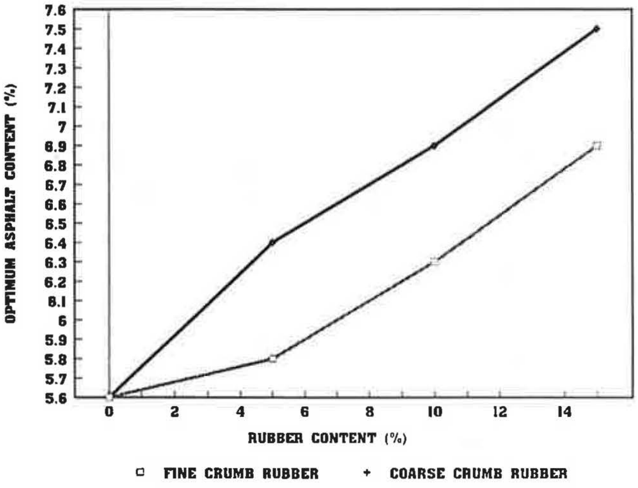

FIGURE 8 Optimum asphalt content versus rubber content.

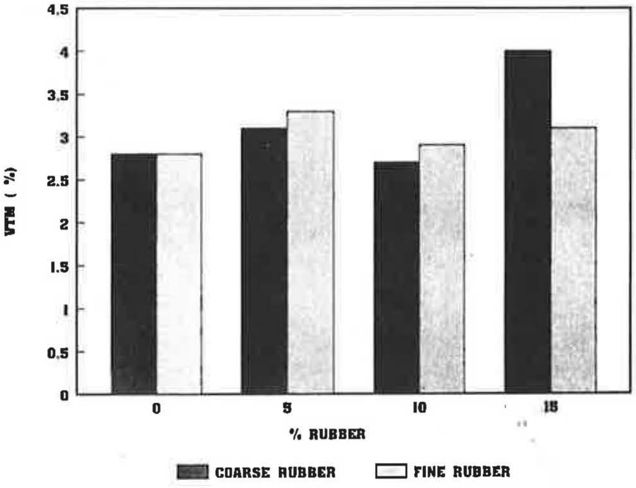

FIGURE 10 Pavement voids predicted by GTM.

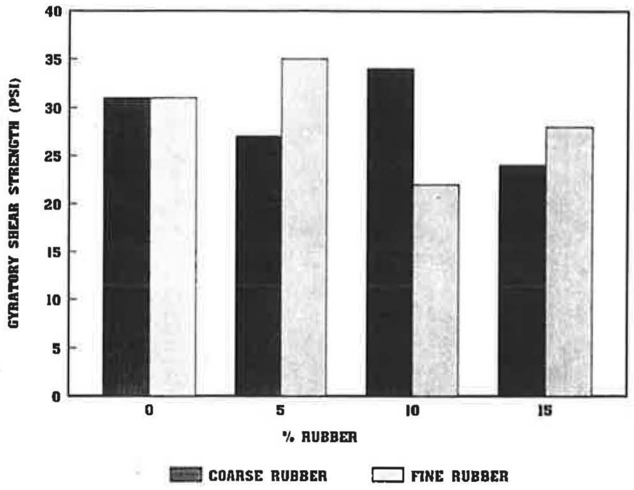

FIGURE 11 Gyratory shear strength.

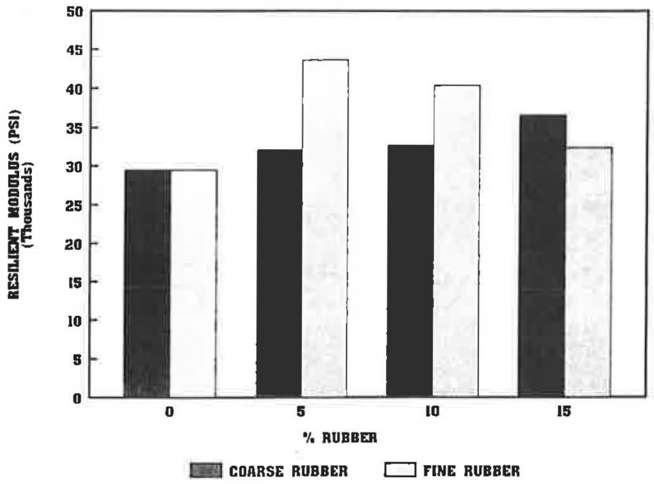

FIGURE 13 Resilient modulus at 104°F: laboratory study.

fine rubber mixtures for both resilient modulus and indirect tensile strength. There was a significant difference at a 95 percent confidence level between average values at 0 and 5 percent, 5 and 15 percent, and 10 and 15 percent, but not between 5 and 10 percent, which confirms the optimum value observation. This optimum condition was not apparent for the coarse rubber mixture. The magnitude of the resilient modulus for the coarse rubber appeared to increase as the rubber content was increased. When the average values were tested, there was no significant difference between any of the average values; therefore, this apparent trend could not be confirmed.

CONCLUSIONS

Field Study

1. Laboratory test results on the mixtures sampled during contruction indicate that mixtures containing asphalt rubber using the wet process may be less resistant to permanent deformation than mixtures without rubber; however, laboratory tests may not be able to simulate pavement behavior for these types of mixtures.
2. The mixtures with asphalt rubber displayed less stripping than the mixtures without asphalt rubber when tested with the indirect tensile stripping test.

Laboratory Study

1. Coarse and fine rubber reacted with the asphalt cement similarly.
2. The rubber did not break down over a 24-hr time period.
3. Approximately 0.6 percent more asphalt cement was required for the coarse rubber mixtures than for the fine rubber mixtures.
4. An optimum rubber content of 5 to 10 percent yielded the maximum resilient modulus and indirect tensile strength for mixtures containing fine rubber.

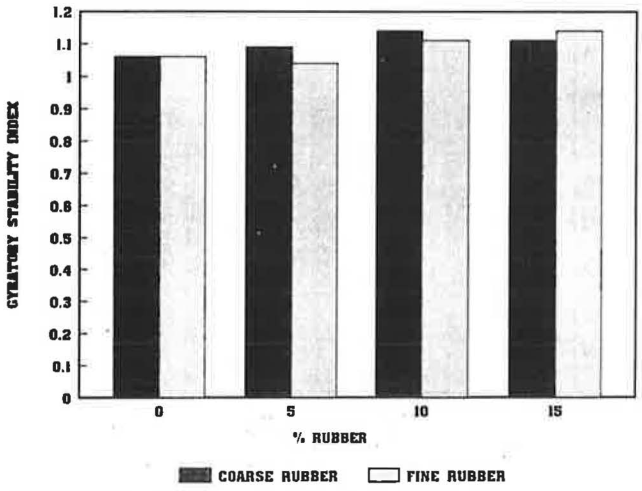

FIGURE 12 Gyratory stability index.

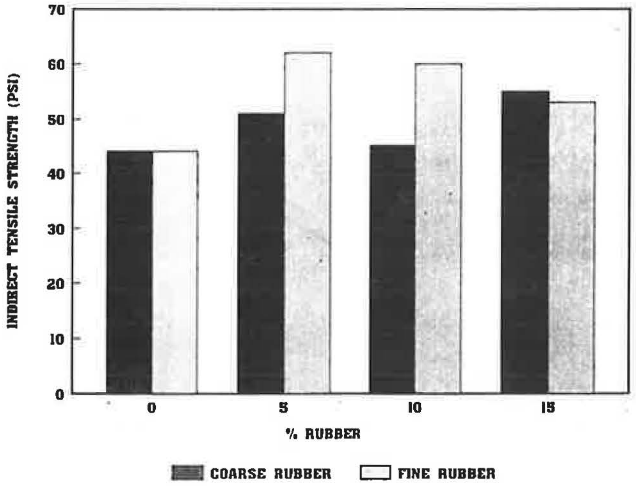

FIGURE 14 Indirect tensile strength at 104°F: laboratory study.

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Florida's Approach Using Ground Tire Rubber in Asphalt Concrete Mixtures

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In 1988, under a legislative mandate, the Florida Department of Transportation (FDOT) began a concentrated effort to evaluate the potential uses for reclaimed tire rubber in asphalt pavement construction. FDOT indicated that the most advantageous use of rubber would be as a binder modifier to improve the performance of friction course mixtures. Three demonstration projects were constructed. The field construction operations with the rubber-modified mixtures were essentially the same as those with conventional friction course mixtures. Currently all of the test sections are performing well. The optimum rubber content for dense-graded friction course mixtures has been identified as 5 percent (by weight of asphalt cement) using a maximum nominal 80-mesh ground tire rubber. It is believed that the rubber will provide improved elasticity to the binder and therefore greater resilience for these mixtures in recovery from high strains at intersections. The optimum rubber content for open-graded friction course mixtures was determined to be 12 percent (by weight of asphalt cement) using a maximum nominal 40-mesh ground tire rubber. In open-graded mixtures, the rubber has allowed a significant increase in the total binder content, which increased in the film thickness on the aggregate particles resulting in improved durability. On the basis of these demonstration projects, specifications have been developed for using ground tire rubber in friction course mixtures as a standard practice.

The provisions of Section 336.044(3) of the Florida statutes created by Senate Bill 1192 in 1988 directed the Florida Department of Transportation (FDOT) to expand, where feasible, its use of recovered (waste) materials for highway construction. Specifically, the bill directed that an investigation be conducted to determine how ground tire rubber (GTR) from recycled waste tires could be used in quality asphalt concrete mixtures for highway construction by undertaking demonstration projects as part of currently scheduled construction projects. It further stipulated that within 1 year after the conclusion of the demonstration projects the FDOT should report to the governor and the legislature on the maximum percentage of GTR that can be effectively used in road construction projects. Concurrently with this report, the FDOT should review and modify its standard road and bridge construction specifications to allow and encourage the use of GTR consistent with the findings of the demonstration projects.

The purpose of this report is to provide a concise overview of all FDOT and University of Florida activities pertaining to the development of the use of GTR in asphalt-rubber binders for specific asphalt concrete mixtures and other highway construction applications, and to document the steps taken by the FDOT to facilitate the use and quality control of this material. The term asphalt-rubber in this report is defined as a binder with GTR blended in a paving-grade asphalt cement.

BACKGROUND INFORMATION

The first investigation conducted by the FDOT in the use of asphalt-rubber for highway construction was performed nearly 10 years before the passage of Senate Bill 1192. That project was to evaluate asphalt-rubber as a stress-absorbing interlayer and a binder for seal coat construction. A demonstration project constructed on SR 60, Hillsborough County, was used to evaluate the performance of asphalt-rubber in these applications. The results of this study are documented in an August 1980 report prepared by the FDOT for the U.S. Department of Transportation (*1*). As a result of this demonstration project, the FDOT has permitted the use of GTR in selected surface treatment and interlayer construction. In addition, FDOT currently permits the use of GTR in certain joint sealers and in railroad crossing pads.

Upon passage of Senate Bill 1192 by the 1988 Florida Legislature, FDOT personnel, in cooperation with University of Florida researchers, established and implemented a detailed plan to address the legislative mandate. The relatively short time period allocated for this investigation required concurrent activities. One primary activity was to document pertinent information from technical literature on asphalt-rubber and its application in asphalt concrete mixtures. The National Center for Asphalt Technology (NCAT) at Auburn University was selected to conduct this investigation because of the knowledge and experience of the investigators with asphalt-rubber, paving mixtures, and construction processes. Their report, dated August 1989, provided a comprehensive documentation of material properties, benefits, limitations, and recommendations for the use of GTR and asphalt-rubber binders for asphalt concrete mixtures (*2*). This state-of-the-art overview of asphalt-rubber in an asphalt concrete application confirmed and validated the direction of FDOT in the development of the subsequently constructed demonstration projects.

DEMONSTRATION PROJECT DEVELOPMENT

The purpose of the demonstration projects is to evaluate the constructibility and short-term field performance of different amounts and sizes of GTR in a number of plant-produced FDOT asphalt concrete mixtures in order to develop specifications and procedures for its use.

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Current standard specifications for gradation and mixture properties would continue to be used to determine acceptable characteristics. This is a conservative approach believed to be warranted at this time, and is consistent with the legislative requirements for this investigation.

A number of decisions were made about the demonstration projects that were based on the relatively short time frame (approximately 2 years) for the development of specifications and procedures imposed by the legislation. The FDOT mixtures for the demonstration projects were limited to the friction course mixtures both dense-graded (FC-1 and FC-4) and open-graded (FC-2). This was based on two considerations:

1. Improvement in the properties of these mixtures had previously been identified as desirable: improved durability and resistance to shoving at intersections for the dense-graded mixtures, and increased binder film thickness for improved durability and aggregate retention, with improved resistance to binder drainage for the open-graded mixtures.
2. The compatibility of the GTR with the efficacy of a recycling agent (soft asphalt) to rejuvenate the existing asphalt cement in reclaimed asphalt pavement (RAP) was an unknown. Therefore only mixtures using virgin components would be included.

It was decided to concentrate on the use of fine (−80 mesh) GTR at relatively low percentages in the demonstration projects based on previous experience in the laboratory in obtaining acceptable mix properties. These initial laboratory results are not included in this report.

It was also decided to concentrate on the process under which the GTR was preblended or dispersed in the asphalt cement before mixing with the aggregates. This was done on the basis of a "common sense" approach assuming that if the GTR "reacts" or "swells" in the asphalt cement, then that process should take place under controlled conditions before mixing with aggregates in the asphalt plant.

DEMONSTRATION PROJECT CONSTRUCTION

From 1989 through 1990, three demonstration projects were constructed to evaluate the use of GTR in asphalt concrete friction course mixtures. A summary of key information for the three demonstration projects is presented in Table 1. The specification requirements for both the dense-graded friction course (FC-4) and open-graded friction course (FC-2) are shown in Table 2. Each project required a substantial preliminary effort to ensure the best possible operational conditions for production, construction, and testing of materials evaluation. This involved development of work plans, special provisions, mix designs, laboratory testing, and considerable interaction with the prime asphalt contractor and the subcontractor providing the blending of GTR with the asphalt cement. During construction, extra sampling and specialized tests were performed in addition to the standard quality-control and quality-assurance tests. A concentrated effort was required to furnish a sufficient number of qualified personnel to conduct these tests and to observe construction procedures for assessment of any problems or deficiencies.

TABLE 1 SUMMARY OF ASPHALT-RUBBER DEMONSTRATION PROJECTS

	1st Project	2nd Project	3rd Project
Date:	March 1989	June 1989	September 1990
Location:	N.E. 23 Ave. Gainesville, FL	State Road 16 Starke, FL	I-95 St. Johns Cty
Mix Type:	Dense-Graded (FC-4)	Open-Graded (FC-2)	Open-Graded (FC-2)
Test Section GTR Size/% (a)	(1) 80 mesh/3.1% (2) 80 mesh/5.3% (3) 40 mesh/11.1% (4) control/0%	(1) 80 mesh/5.3% (2) 80 mesh/11.1% (3) 80 mesh/17.7% (4) 24 mesh/20.5% (5) control/0% (6) 80 mesh/11.1%(b)	(1) 80 mesh/10% (2) 80 mesh/10% (3) 80 mesh/10% (4) 80 mesh/10% (5) Control/ 0% (6) Control/ 0% (7) Control/ 0% (8) Control/ 0%
Total Binder Content	(1) 7.1% (2) 7.3% (3) 8.2% (4) 7.0%	(1) 8.0% (2) 8.4% (3) 11.4% (4) 10.3% (5) 6.3% (6) 6.9%	(1) 7.78% (2) 7.78% (3) 7.78% (4) 7.78% (5) 6.30% (6) 6.30% (7) 6.30% (8) 6.30%
Test Section Length - ft.	(1) 3520 (2) 3656 (3) 2460 (4) 2640	(1) 2100 (2) 2532 (3) 1818 (4) 2880 (5) 1761 (6) 263	(1) 5260 (2) 5655 (3) 5513 (4) 5937 (5) 5280 (6) 5280 (7) 5280 (8) 5280

(a) By weight of asphalt cement. GTR contents originally specified as a percent of total binder.
(b) Not preblended - mixed in pugmill

The first demonstration project was constructed in Gainesville during March 1989 using a dense-graded friction course (FC-4) containing 3.1, 5.3, and 11.1 percent GTR by weight of asphalt cement. (Note: Rubber contents were originally specified as a percentage of total binder. As such, these sections contain 3, 5, and 10 percent GTR by weight of total binder. A decision was made later to specify GTR as a percentage of asphalt cement to simplify calculations. All amounts of GTR in this report are shown as a percentage of asphalt cement.) Dense-graded friction course mixtures were found to be generally more susceptible to change in binder content and particle size of GTR than open-graded mixtures. Tests conducted on the hot-mix samples with different levels of GTR indicated that the mix from Test Section 2 with 5.3 percent GTR appeared to be the mix for which the standard

TABLE 2 FRICTION COURSE MIX REQUIREMENTS

	Mix Type	
Requirements	Dense-graded (FC-4)	Open graded (FC-2)
Gradation (% passing)		
1/2	100	100
3/8	—	85-100
No. 4	---	10-40
No. 10	75-90	4-12
No. 200	2-8	2-8
Marshall Properties		
Min. Stability	500 lbs.	---
Max. Flow	8-16	---
Void Criteria		
Min. VMA	15%	---
Air Voids	12-16	---
Asphalt Content		
Min. Effective	5.0%	---

specification requirements were met, and in addition had increased resistance to shear as measured in the Corps of Engineers Gyratory Test Machine. Although all of the asphalt-rubber mixtures exhibited some degree of sticking to the pavers' screed, it was only considered excessive during paving of Test Section 3, which had 11.1 percent GTR. Otherwise, no major problems were encountered during construction of these asphalt-rubber friction courses. The data, discussion, and conclusions for this first demonstration project are contained in a separate report (*3*).

The second demonstration project was constructed on SR 16 near Starke in June 1989 with 4 sections using 5.3 to 20.5 percent GTR in an open-graded friction course (FC-2). Construction was accomplished without any significant difficulty or observable problems. Test Sections 3 and 4 with 17.7 and 20.5 percent GTR, respectively, had high total binder contents that could result in long-term performance and hydroplaning problems. The results obtained from construction of this demonstration project indicated that about 10 to 15 percent GTR can effectively be used in open-graded friction course mixtures, but the total binder content for mixtures with this rubber content should probably be less than that used in mixtures on this project. The evaluation of binder content relied to a large extent on subjective visual determinations in the field. The data, discussion, and conclusions for this second demonstration project are contained in a separate report (*4*).

The University of Florida provided technical assistance and documentation of these demonstration projects (*3,4*). A report prepared by the FDOT Materials Office (*5*) also provides a general overview and summary of FDOT involvement through the construction of the first two demonstration projects. Of primary importance to the development of draft specifications were the preliminary laboratory investigations for each of the demonstration projects conducted by the FDOT to establish asphalt-rubber blends, verify blend times, and develop mix designs. Other special studies were conducted to evaluate asphalt-rubber blending requirements and the effectiveness of extraction testing (*6*).

The third and last demonstration project was constructed on Interstate 95 during September 1990 using 10 percent GTR. The purpose of this project was to determine whether asphalt-rubber could be blended and incorporated into an open-graded friction course mixture using a prototype continuous production blending unit on a conventional construction project without encountering any problems that would contribute to construction defects or delays. The information collected on this demonstration project is documented in a technical report from the University of Florida (*7*). This demonstration project was constructed without any major technical problems. However, the blending time required to provide adequate reaction of GTR with the asphalt cement had to be increased with this prototype blending unit because of the lower-than-anticipated temperature (275°F instead of 310°F) of the asphalt cement. This indicated the need either to increase the blending unit capacity or provide additional heating for the unit to assure adequate blending to maintain hot-mix production rate at the desired 100 tons/hr.

The constructibility and short-term performance of these asphalt-rubber test pavements indicates that it is feasible to use GTR in a modified binder for friction course construction without any major change in construction operations. These projects also verified that current standard specified criteria for friction course mixtures (as shown in Table 2) could be met at design and during production for mixtures with an asphalt-rubber binder. In addition, current standard acceptance tests and criteria could be applied and met with the exception of modifying the method of measurement for the asphalt-rubber binder.

Although the long-term performance of these pavements cannot be evaluated until some time in the future, sufficient test data and corroborating information suggest that asphalt-rubber friction courses, particularly open-graded, will have improved durability over conventional friction course mixtures. This improvement is related to (a) reduced age hardening because of anti-oxidants in the rubber and increased film thickness, and (b) improved retention of aggregate because of increased film thicknesses and greater resiliency of the binder. Greater binder contents and the retention of thicker binder films on the aggregate are possible because of the increase in viscosity produced by the addition of GTR.

TYPE AND AMOUNT OF GTR IN FRICTION COURSE MIXTURES

The type of rubber currently determined to be satisfactory for use in asphalt-rubber friction course mixtures is that produced by ambiently grinding tires to a suitable fineness (*2*). Cryogenically produced rubber is not currently acceptable because the effect of its smooth-faced particles on reaction time and the material properties of the modified binder has not been evaluated.

The amount and fineness (gradation) of the GTR to be used in asphalt-rubber blends is based on the application. In dense-graded friction course mixtures, 5 percent of GTR passing the No. 50 sieve (e.g., a maximum nominal 80 mesh) is recommended. In open-graded friction courses, 12 percent of GTR passing the No. 30 sieve (e.g., a maximum nominal 40 mesh) is recommended to be blended with the asphalt cement. Open-graded mixtures are more tolerant of larger rubber particulate size and greater GTR contents. From experience of these demonstration projects, it was found that the calculations for blending are simplified if the amount of GTR is specified as a percentage of the asphalt cement rather than of the total binder.

Another application of GTR is in the asphalt-rubber binder for an asphalt-rubber membrane interlayer. In this case about 0.6 gal/yd^2 of asphalt-rubber binder is sprayed over the prepared pavement surface and uniformly sized aggregates are spread and rolled into the membrane before placement of the asphalt concrete structural layers. This asphalt-rubber blend uses 20 percent of GTR passing the No. 10 sieve (e.g., a maximum nominal 20 mesh). This provides a membrane that should seal the pavement from intrusion of moisture and retard reflective cracks, particularly for asphalt overlays of portland cement concrete pavements.

Requirements for the GTR and asphalt-rubber binder for each application are presented in subsequent sections.

BLENDING REQUIREMENTS

GTR must be blended with asphalt cement for a sufficient period of time to achieve a uniform product with fairly stable consistency (usually determined by viscosity measurements). This "reaction" time is significantly reduced when using finer GTR, softer asphalt cements, and higher blending temperatures. This was identified in FDOT laboratory blending studies as part of the demonstration projects. Another advantage of fine GTR is that the resulting asphalt-rubber blend is more homogeneous and is better suited for viscosity testing and other quality control tests than blends containing coarser GTR (particle sizes retained on the No. 30 sieve). Although "reaction" time is reduced at higher blending temperatures, holding the blended asphalt-rubber at elevated temperatures for long periods will degrade the quality of asphalt-rubber binder because of volatile loss and accelerated hardening. Field and laboratory studies by FDOT have shown that holding the blended asphalt-rubber binder at normal asphalt cement storage temperatures (300° to 350°F) does not degrade the quality of the binder for typical storage periods. These recent data, which are to be published, show that viscosity and softening point increased slightly and resilience increased four-fold during storage. It is necessary, however, to provide periodic agitation of the blended binder to present separation of the GTR.

Conventionally, GTR is packaged in plastic bags that are opened and dumped into the hopper of a feeding unit. The feed of GTR and asphalt cement into a blending unit is adjusted to achieve the desired percent GTR in the asphalt-rubber binder. The size and operation of the blending unit may differ according to the approach selected by the asphalt-rubber blending contractor. Blending at the asphalt cement terminal and shipping to the project site appear technically and economically practical. The blending temperature and reaction time requirements are given in the developmental specification for asphalt-rubber binder presented in subsequent sections.

EFFECTS ON CONSTRUCTION AND PAVEMENT PERFORMANCE

Properly proportioned asphalt-rubber binders can be used in dense or open-graded friction course mixtures without any significant effect on conventional mix production operations. However, standard asphalt metering pumps on asphalt hot-mix plants may not be adequate to handle the higher viscosity binders. Plants with asphalt weigh buckets will generally operate without any problems provided that the spray bar orifices do not restrict flow.

Conventional paving operations for friction course mixtures can be used for the paving of asphalt-rubber mixtures. Long-term performance data do not exist for asphalt-rubber mixtures, but the following performance effects are inferred. Dense-graded friction course mixtures with asphalt-rubber should tend to reduce pavement distortions at intersections in urban areas because of the improved resilient properties of the asphalt-rubber. Open-graded friction course mixtures with asphalt-rubber will tend to reduce or eliminate binder drainage from the aggregate in trucks even with increased binder contents. Increased binder in combination with the improved resilient properties of asphalt-rubber should provide improved aggregate retention and improved durability and life. Limited performance measurements of pavement friction (ASTM E 274) and rut depth have been made on the three demonstration projects and no differences have been identified attributable to the use of GTR.

The recycling of asphalt concrete pavements with asphalt-rubber friction course surfaces is not anticipated to be a problem because of the low rubber content present in the total amount of reclaimed asphalt pavement (RAP) for normal milling depths (*2*), and it is thought that the rubber has "absorbed" all the asphalt it can and asphalt demand has stabilized.

Issues of air quality and toxic fumes were not specifically addressed by FDOT in this evaluation, but data and reports from the Asphalt-Rubber Producers Group indicate that these issues are of no more concern than those for asphalt cement.

ESTIMATED GROUND-TIRE RUBBER USAGE AND COST

The estimated annual use of GTR is based on the total tonnage of open and dense-graded friction course mixtures normally used during one construction year. In addition, the asphalt-rubber membrane interlayer is included in the GTR use calculations, based on the estimated number of lane miles per year. These calculations and the yearly GTR usage projections are as follows:

	Tons Rubber/Year
Open-Graded Friction Course (FC-2)	
$640{,}000 \frac{\text{Tons}}{\text{Year}} \times 6.8\%\ \text{Asphalt} = 43{,}520 \frac{\text{Tons Asphalt}}{\text{Year}}$	
$43{,}520 \frac{\text{Tons Asphalt}}{\text{Year}} \times 12\%\ \text{Rubber}$	5,222
Dense-Graded Friction Course (FC-1 & 4)	
$160{,}000 \frac{\text{Tons}}{\text{Year}} \times 7.0\%\ \text{Asphalt} = 11{,}200 \frac{\text{Tons Asphalt}}{\text{Year}}$	
$11{,}200 \frac{\text{Tons Asphalt}}{\text{Year}} \times 5\%\ \text{Rubber}$	560
Asphalt-Rubber Membrane Interlayer	
$600 \frac{\text{Lane Miles}}{\text{Year}} \times 0.6 \frac{\text{Gal}}{\text{S.Y.}} \times 20\%\ \text{Rubber}$	2,160
Pavement Marker Adhesive, Joint Filler, Railroad Crossing Pads, Guardrail Spacers	1,200
Total Estimated FDOT Usage Per Year	9,142

The total yearly generation of waste tires in Florida was estimated based on 0.75 tire/yr/capita and the 1990 population in Florida of 13,000,000. Approximately 10 lb of GTR is recovered from each tire, which results in 48,750 tons of rubber/yr.

On this basis, the FDOT can consume about 20 percent of the generated waste tire rubber in highway construction applications. Because the amount of road construction activity done by cities, counties, and developers exceeds that used by FDOT on an annual basis, it is assumed that their use of GTR would equal or exceed that of the FDOT. Therefore, the projected highway construction usage of GTR from waste tires in Florida is estimated at less than one half of the total generated per year. However, the amount of waste tires available is questionable because at the present time two major national suppliers of GTR already obtain some of their waste tire supply from Florida. Also, the roofing and tire manufacturing industry incorporate GTR in some of their products. Consequently, the exact status of usage cannot be determined unless a very detailed and comprehensive study and inventory is undertaken.

Cost estimates performed by the FDOT State Materials Office indicate that an optimistic increase in cost of $4.80/ton of mix, or about a 15 percent increase in cost, would occur when using GTR in the binder (assuming $32.00/ton of conventional hot mix). This additional cost translates into an increase in binder cost of about 70 percent. This cost estimate is based on using asphalt rubber binders for all FDOT friction course mixtures on a continuing, not an experimental, basis. It includes reasonable costs for materials and processing. It should be noted that the third demonstration project (I-95) went through the normal bid process. The bid price (yd^2) for mix with GTR was 31 percent higher than mix without. This project contained 4 lane miles with GTR in the open-graded friction course (FC-2) compared with the remainder of the project with more than 30 lane miles of FC-2 without GTR. Others have experienced substantially higher costs for specific limited experimental construction (*2*). How, or whether, this increase in cost is funded is beyond the scope of this engineering investigation but is a definite area of concern. In addition, there may be other asphalt additives that can have the same effect in these mixtures. There is a concern that they should be able to compete economically, but the direction is to specify GTR exclusively.

APPROACH TO THE DEVELOPMENT OF SPECIFICATIONS

It was necessary to develop new specifications and to revise existing specifications before attempting to use asphalt-rubber friction course mixtures in construction on a conventional production basis. Therefore, the FDOT State Materials Office prepared tentative or developmental specifications for use on these construction projects. The current draft of these specifications was prepared using the compilation of information generated during the asphalt-rubber friction course demonstration projects.

The developmental specifications are presented in the following sections. The specification for GTR for use in asphalt-rubber binder was developed with input from tire recyclers and the ASTM specification being developed on this subject. This includes physical, chemical, packaging, and certification requirements for GTR use in dense-graded and open-graded friction courses and for asphalt-rubber membrane interlayers. A requirement that GTR be produced from Florida tires was dropped on the advice of legal counsel as being restraint of trade. The specification for the asphalt-rubber binder materials, blending requirements (temperature and time), and the method of measurement was developed for GTR and the asphalt-rubber blend based on the laboratory and field testing as a part of the demonstration projects in Florida. A specification was developed for an asphalt rubber membrane interlayer, but is not included in this report. Section 337 of the *Florida Department of Transportation Standard Specifications for Road and Bridge Construction*, which pertains to Asphaltic Concrete Friction Courses, was revised to require the use of asphalt-rubber binder in friction course construction.

It should be recognized that these developmental specifications may be further revised before actual implementation with input of additional data and review. Furthermore, as experience is gained on asphalt-rubber construction projects, it is probable that some modifications to the specification will be needed to improve their effectiveness.

These specifications are not meant to be the only approach to incorporating GTR into asphalt concrete mixtures. It is a documentation of the approach taken by FDOT in using GTR incorporated into asphalt cement as a modified binder to improve specific asphalt concrete mixtures currently used by FDOT.

FLORIDA DEVELOPMENTAL SPECIFICATION FOR GROUND TIRE RUBBER

Scope

The specification controls GTR for use in asphalt-rubber binders for use in a variety of road and paving applications. The specification does not address any safety or environmental concerns associated with its use.

General Requirements

The GTR should be produced by ambient grinding methods. It should be sufficiently dry so that it is free flowing and foaming is prevented when it is mixed with asphalt cement. The rubber should be substantially free from contaminants including fabric, metal, mineral, and other nonrubber substances. Up to 4 percent (by weight of rubber) of talc (such as magnesium silicate or calcium carbonate) may be added to prevent sticking and caking of the particles.

Physical Requirements

- Gradation: when tested in accordance with ASTM C-136 using a 50-g sample, the resulting rubber gradation should meet the gradation limits shown in Table 3 for the type of rubber specified.
- Specific gravity of the rubber as determined by ASTM D-297, pycnometer method, should be 1.15 ± 0.05.
- Moisture content: maximum 0.75 percent by weight as determined by AASHTO T 255 using a controlled oven temperature of 140°F and a 50-g sample.
- Mineral contaminants: maximum 0.25 percent by weight (test method to be developed).
- Metal contaminants: none (test method to be developed).

Chemical Requirements

- Acetone extract: maximum 25 percent
- Rubber hydrocarbon content: 40 to 55 percent
- Ash content: maximum 10 percent
- Carbon black content: 20 to 40 percent

TABLE 3 GRADATIONS OF GROUND TIRE RUBBER

SIEVE SIZE % PASSING	TYPE I	TYPE II	TYPE III
10	--	--	100
20	--	100	85-100
30	--	95-100	40- 65
40	100	85-100	20- 45
60	98-100	30- 60	--
80	90-100	15- 40	5- 20
100	70- 90	5- 25	--
200	35- 60	--	--

Packaging and Identification Requirements

The GTR shall be supplied in moisture-resistant packaging such as disposable bags or other appropriate containers. Each container or bag of GTR shall be labeled with the manufacturer designation for the rubber and the specific type, maximum nominal size, weight, and manufacturer batch or lot designation.

Certification Requirements

The manufacturer of the ground rubber shall furnish the engineer with certified test results covering each shipment of material to each project. These reports shall indicate the results of tests required by this specification. They shall include a certification that the material conforms with the specification and be identified by project number and manufacturer's batch or lot number.

FLORIDA DEVELOPMENTAL SPECIFICATION FOR ASPHALT-RUBBER BINDER

Scope

This specification controls the production of asphalt-rubber binder for use in asphaltic concrete friction courses and asphalt-rubber membrane interlayers. This specification does not address any safety or environmental concerns associated with its use.

Materials

Asphalt cement: The particular grade of asphalt cement as specified in Table 4 for the respective uses shall meet the requirements of the standard specifications. The asphalt cement shall be fully compatible with the proposed GTR as determined by the State Materials Office.

Ground tire rubber: The type of GTR as specified in Table 3 shall meet the requirement of Developmental Specification on Ground Tire Rubber.

Asphalt-rubber binder: The asphalt cement and ground tire rubber shall be thoroughly mixed and reacted in accordance with the requirements of Table 4. The rubber type shall be in accordance with the approved design mix. The blending unit may be batch or continuous type and shall provide for sampling the blended and reacted asphalt-rubber binder material during normal production.

Equipment

The meter for the asphalt rubber binder shall meet the requirements for accuracy, condition, and so on, of the Bureau of Weights and measures of the Florida Department of Agriculture and such fact shall be recertified every 6 months either by the Bureau of Weights and measures or by a registered scale technician.

Method of Measurement

The GTR content in the asphalt-rubber binder shall be monitored by the department on the basis of the weight of ground rubber used versus the gallons of asphalt-rubber binder used. The weight/gal for the various types of asphalt-rubber binders included in Table 4 are to be used for these calculations.

The quantity of asphalt-rubber binder material used shall be determined by a certified meter meeting requirements as previously specified.

OTHER METHODS FOR USED TIRE RECYCLING

The use of GTR in asphalt concrete and other highway applications previously discussed will not solve the waste tire problem. Other uses for recycled tires have to be developed. A variety of products exist that can be constructed from whole tires. The U.S. Forest Service has used tire-faced retaining walls for construction of narrow mountain roads (*8*). However, this is not practical for major highway construction because of aesthetics and safety for off-road vehicular accidents. Tires have been used to control erosion along drainage channels and to stabilize highway slopes (*9*). Malaysia is currently seeking 35 million tires to use as a barrier reef (*10*). Other products such as crash barriers, playground equipment, breakwater, and installations to control soil and beach erosion can be constructed from whole used tires.

Whole tires are being used as the fuel in a power plant in Modesto, California (*11*). Tires are burned at a rate of 700/hr or about 4.5 million tires/yr to produce electrical energy. No preprocessing of the tire is apparently necessary in this operation.

TABLE 4 ASPHALT-RUBBER BINDER

USES	Dense-graded FC	Open-graded FC	Asphalt-Rubber Membrane Interlayer
Rubber Type	Type I	Type II (or I)[a]	Type III (or II or I)[a]
% GTR (by wt. of AC)	5	15	25
AC Grade	AC-30	AC-30	AC-20
Minimum Temp., ^{0} F	300	300	335
Maximum Temp., ^{0} F	335	350	375
Minimum Reaction Time	10 min.	15 min. (for Type II)	30 min. (for Type III)
Unit Weight lb/gal.[b]	8.6 lbs	8.7 lbs	8.8 lbs

[a] Use of finer rubber could result in the reduction of the minimum reaction time.

[b] Conversions to standard 60^0 F are not necessary.

NOTE: The minimum reaction time may be adjusted if approved by the State Materials Office depending upon the temperature of the blend, size of the ground tire rubber and viscosity measurement determined from the asphalt-rubber binder material prior to or during production. Hold-over time of the asphalt-rubber binder material in excess of six hours will not be allowed. Any corrective action in hold over situations in excess of six hours will require the approval of the State Materials Office.

Research being conducted by the University of Wisconsin is directed toward the use of shredded tires to replace sand and gravel fills (*12*). Potential benefits include reduced weight of fill constructed with rubber chips and soil, conservation of mineral aggregates, and elimination of some of the 20 million discarded tires in the state of Wisconsin. Small quantities of metals in the leachate from these fills apparently are too small to affect the groundwater.

Shredded tires have been successfully burned as a fuel in power plants, in cement kilns, in pulp and paper production, and by tire manufacturing facilities (*10*). Generally a "fluidized bed" burning system is required to achieve sufficiently high temperatures for combustion of the rubber. Often a combination of fuels is used that promotes efficient burning and reduced emissions. Although this is technically feasible, modern scrubber systems are necessary to remove particulate and undesirable emission such as sulfur dioxides and nitrous oxides.

Crumb rubber can be mixed with other materials and processed to make mud guards, floor mats, carpet padding, adhesives, new tires, or other rubber products (*10*). However, a Minnesota company established recently to produce rubber products from crumb rubber could not achieve the quality desired by its customers. Their inability to meet the purchaser's specifications apparently led to bankruptcy.

In summary, the solution to the waste tire problem needs to be a comprehensive one.

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Advances in Technology of Asphalt Paving Materials Containing Used Tire Rubber

H. BARRY TAKALLOU AND ALAIN SAINTON

The blending of crumb rubber with asphalt cement has been in practice for years and a number of manufacturing processes have been developed in Europe as well as in the United States. However, all these processes have a major drawback: the asphalt rubber binder must be used within a few hours after being manufactured. In 1987, Beugnet, a road contractor in France, designed a new rubberized asphalt formula. This new formula improved rheological properties of the asphalt rubber binder, including increasing the shelf life of the binder for up to 8 days. Therefore, this new asphalt rubber binder could be used just like conventional asphalts or polymer-modified asphalts. The dry system of rubber-modified asphalt concrete has historically been limited to only a patented process. Major drawbacks of this system include the addition of crumb rubber to a unique "gap-graded" aggregate gradation, and nonconventional design criteria. These factors contribute to the high cost of using the material when compared with conventional asphalt concrete. The dry system of rubber-modified asphalt concrete has also experienced a major advance. A rubber-modified asphalt concrete system has been developed by H. Barry Takallou. This system relates to a process for producing an asphalt concrete composition made up of coarse crumb rubber and fine crumb rubber incorporated into a standard dense-graded aggregate mixture. This process is characterized by the various constituents of the asphaltic binder and fine crumb rubber, mixed intimately by a physical reaction. This will result in a higher viscosity binder in which the optimum reaction is achieved when the fine crumb rubber particles reach optimum swelling. A pre-reaction or pre-treatment of crumb rubber with a catalyst may be needed to achieve the optimum crumb rubber particle swelling. This system can be designed using conventional testing procedures and complies with conventional design criteria. The use of this system is in the public domain.

Research to improve and enhance the performance of asphalt concrete by the addition of natural and synthetic rubber to an asphalt concrete binder has continued worldwide for more than a century (*1*). Historically, the objective of the research of the addition of rubber—natural, synthetic, and combinations of both—to asphalt binder, was to develop a mixture to improve the physical characteristics of asphalt concrete by improving elasticity. Results of several demonstration projects using rubberized asphalt indicate increased fatigue resistance, retardation of reflective cracking, improved skid resistance, and increased durability (*2*). However, current interest in rubberized asphalt has been heightened by its potential as a recycling option for used tires.

The addition of crumb rubber to an asphalt cement binder was successfully accomplished in the United States in the early 1960s (*1*). This process of heating and reacting crumb rubber with asphalt cement has continued to be developed and used since those early applications. Success of initial patching placements using the rubberized asphalt led to its use as a "stress-absorbing membrane" (SAM) in the late 1960s. Continued research and development led by 1972 to the development of a stress-absorbing membrane interlayer (SAMI). By 1975, the next milestone in the development of the rubberized binder was to be seen in its use in an open-graded friction course (*1*).

In these processes, crumb rubber was added to the asphalt binder, heated and interacted, to form a rubberized binder. In an effort to standardize a description of the rubber asphalt technologies, this process is now widely referred to as the wet system.

A different asphalt rubber technology was also developed in the early 1960s in Europe. It was first used in the United States in a late 1970s demonstration project in Alaska. In this process, the design required a unique mineral aggregate gradation. This unique gradation was required to allow a gap in the aggregate gradation curve. This gap, in the range of 1/4 in. to sieve size No. 10, was to be filled by the addition of coarse crumb rubber. The majority of the crumb rubber is larger than sieve size No. 10. The addition of the crumb rubber is either at the pugmill with the hot aggregate before the addition of the asphalt cement, or at the recycle fit opening in a continuous, or drum drier operation. The crumb rubber is added as a separate constituent to the mixture, and therefore referred to as the dry system.

Both wet and dry systems have been used in demonstration projects throughout the world. The systems have continued to increase in use with each passing year. The engineering community has recognized an improved performance when using crumb rubber in asphalt concrete mixtures. Also, the addition of crumb rubber from whole tire recycling is a recycling option to the used tire disposal problem.

Each year in the United States, approximately 240,000,000 used tires need disposal. Landfills are reluctant to accept used tires for disposal because they resist compaction, take up a disproportionate amount of space, and may also become buoyant, penetrating the covering membrane of the landfill (*3*). Through state and local action, many landfills across the United States no longer accept used tires. This lack of a practical or efficient means of used tire disposal has led to the nationwide practice of used tire stockpiling. In the early 1980s,

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recognition of the dangers associated with used tire stockpiling came the public's attention. Used tire stockpiles were an excellent breeding ground for mosquitoes, ideal habitat for vermin and, as evidenced too often, a potential fire hazard, capable of great environmental damage.

The need for used tire disposal and recycling options capable of eliminating large quantities of waste tires is needed. One solution to the used tire problem is the widespread use of asphalt concrete containing crumb rubber from whole tire recycling. Currently, there are major barriers to widespread use of asphalt rubber. However, the technological advances in both the wet and dry systems described in this paper can reduce those technological barriers.

Passage of the Intermodal Surface Transportation Efficiency Act of 1991 contained a section directing the use of recycled paving materials. This act requires that states use crumb rubber from whole tire recycling in 5 percent of their asphalt concrete usage beginning in 1994. This usage increased by 5 percent/yr to a maximum use of 20 percent in 1997. Mandated use of crumb rubber in asphalt concrete is required by Congress as a means to alleviate the used tire problem by establishing a market for crumb rubber produced from whole tire recycling.

MAJOR BARRIERS TO WIDESPREAD USE OF RUBBER ASPHALT

There are several barriers to the widespread use of both the wet and dry systems of asphalt rubber, including use of specialized equipment, unique aggregate gradations, specialized mix designs, lack of standard design criteria, cost of crumb rubber, and use of patented processes. In both the wet and dry systems these combined barriers result in the major barrier to the use of asphalt rubber: the high cost of asphalt rubber when compared with the cost of using conventional asphalt concrete.

Although high cost is a barrier to both systems, the factors causing the increase are different in both.

In the wet system the increases in cost are attributable to the following factors:

- Rubberized binder must be used within hours of its production; therefore the high cost of mobilizing the specialized equipment (blending unit, metering unit, storage tanks, etc.) at the production facility must be recovered in the cost per ton of rubberized binder used on that project.
- License fee for using the patented process.

In the dry system the increases in cost are attributable to the following factors:

- Unique aggregate gradation,
- Introduction of crumb rubber to asphalt plants,
- Higher asphalt and filler content design requirements, and
- License fee for using the patented process.

The following sections describe advances in technology that address the barriers to widespread use of asphalt rubber.

Advances in Technology of Rubber Asphalt Binder (Wet System)

The incorporation of crumb rubber into an asphalt cement binder has been researched in Europe since the 1960s. In France, the incorporation and reaction of crumb rubber particles of particular sizes into the an asphalt matrix was initiated in 1981 by Beugnet Company. In this process, finely ground crumb rubber is mixed directly with asphalt cement at an elevated temperature (200°C) by means of an oil extender. The proportions of crumb rubber varied from 10 to 30 percent and of the oil extender from 3 to 15 percent by total weight of the binder. This rubberized asphalt binder is marketed under the trade name Flexochape.

The reaction of the rubber with the asphalt binder, creating an asphalt rubber binder, displayed several improved properties:

- High viscosity (8 poises at 200°C),
- Ball and ring softening point greater than 60°C,
- High elasticity and high resilience at low temperatures, and
- Cohesiveness 10 times greater than for asphalt alone at 20°C.

In 1985 it was discovered that the reaction processes could be improved by incorporating a catalyst into the mix. The improvements on the original binder were

- Greater viscosity stability (i.e., better ductility for field use);
- Increase in the softening point temperature (as much as 15 to 20 percent depending on the amount of catalyst). This suggests that the binder remains less sensitive to temperature;
- Longer preservation of the original elastic properties of the binder; and
- Better adhesion.

Production Barriers

Even with the improved properties achieved by adding crumb rubber to asphalt cement binder at evaluated temperatures with a catalyst, the contractor faced the same problems in France that were seen in the United States. A major disadvantage of the use of the rubberized asphalt binder was that it had to be used within hours of production. Mobile units were employed to produce the asphalt rubber mixture at the project production site. All costs associated with the transportation, setup, and removal of the mobile equipment had to be recovered in the unit cost of the tonnage produced.

Technical Barriers

Technical questions remained on the quality and consistency of the binder produced because the product is the reaction of several constituents. As in any chemical reaction, the kinetics are determined by reaction temperature and reactant proportions; these also affect storage time.

Viscosity testing shows that the viscosity of asphalt rubber binder at a digestion temperature of 200°C reaches its peak after 45 min; then remains constant for 1 or 2 hr. Afterwards, viscosity declines steadily and the quality of the binder is diminished, as demonstrated in Figure 1.

Softening Point Temperature follows the viscosity curve, falling after a certain reaction time, indicating that the binder is degrading. Therefore, it must be recognized that there are certain practical considerations in the production of asphalt rubber binder: (a) the binder must be mixed on-site and (b) the binder must be used no later than 6 hr after mixing.

As a result, production of an asphalt rubber concrete mixture is limited to the amount of asphalt rubber binder that can be produced by the mobile equipment at the asphalt plant site. It seemed obvious that a major technological barrier to the widespread use of asphalt rubber binder is faced without the product being storable. Therefore, a major study was undertaken in France in 1987 to formulate an asphalt rubber binder that could be stored in vats for several days after mixing without appreciable changes in viscosity or other properties. The asphalt rubber binder could thus be produced in central terminal locations and shipped to different asphalt paving production plant locations, similar to conventional asphalt binder.

Evaluation of Storable Asphalt Rubber Binder

A laboratory study was performed to evaluate the effect of mix variations on properties of asphalt rubber mixtures. The purpose of this study was to develop an asphalt rubber binder (Figure 2) that had a storage time of up to 8 days and would meet the following criteria: (a) a ball and ring softening point temperature greater than 65°C and (b) a penetrability of 70 to 100/10 mm at 25°C.

The effect of crumb rubber, oil extender, and catalyst content on the properties of asphalt rubber binder are presented in the following sections.

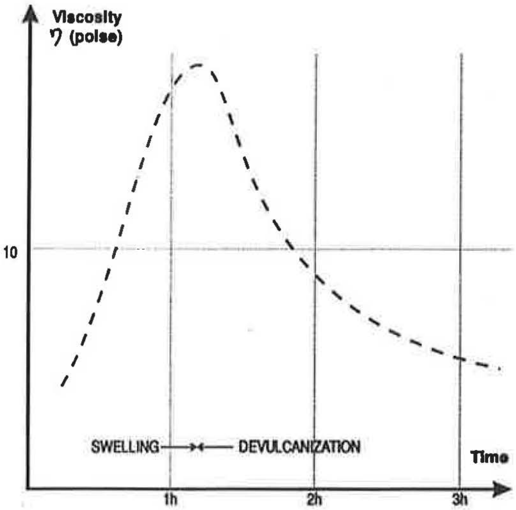

FIGURE 1 Viscosity evolution through rubber digestion.

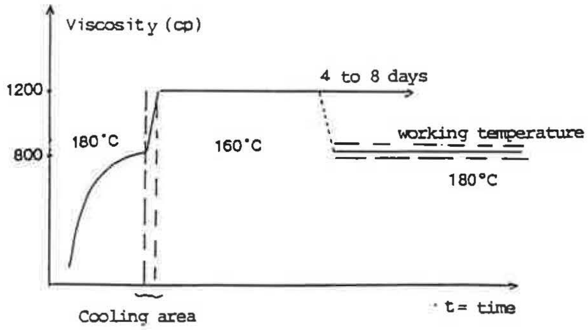

FIGURE 2 Desired viscosity characteristics.

Effect of Crumb Rubber

The effect of three different crumb rubber contents (8 percent, 9 percent and 10 percent rubber) on the viscosity, softening point, resilience, and penetrability of asphalt rubber binder was evaluated. The results are presented in Figures 3, 4, and 5. The results indicate that the optimum properties can be achieved at 10 percent crumb rubber content.

Effect of Oil Extender

The effect of four different content levels of oil extender was evaluated (3 percent, 4 percent, 5 percent, and 6 percent oil extender). The results indicate that an increase in the percentage of oil extender will decrease ring and ball softening point, increase penetrability, increase the capacity for stretching and tension, and reduce resistance. A maximum of 6 percent of oil extender provides optimum asphalt rubber binder properties. The results of this testing are presented in Figure 6.

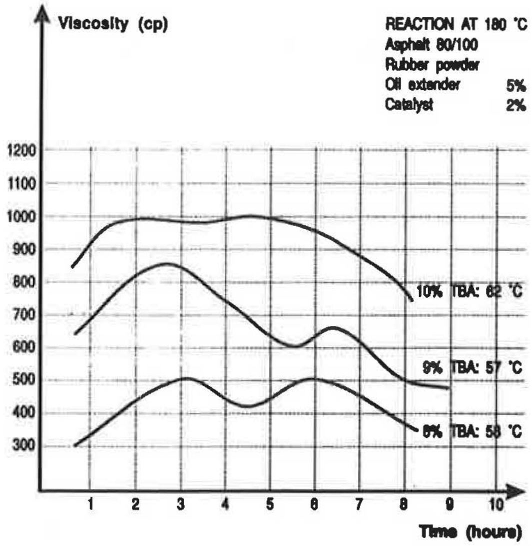

FIGURE 3 Change in viscosity for different rubber percentages.

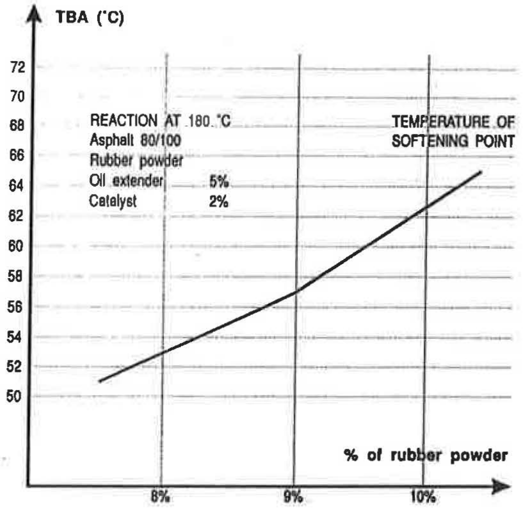

FIGURE 4 Change in ball ring softening point as a function of the percentage of rubber.

Effect of Catalyst

Two levels of catalyst, 2 percent versus 3 percent, were evaluated. The results indicate a maximum of 2½ percent catalyst provides the optimum asphalt rubber binder properties. This catalyst can be selected from ethylenically unsaturated polymers or copolymers that historically have been recommended for incorporation into sulphur-vulcanized bitumen intended for road surfacings or similar products. The results of this testing are presented in Figure 7.

A formulation was developed to provide a storable asphalt rubber binder composition based on the test results previously presented.

Storable Asphalt Rubber Binder	*Composition (percent)*
Asphalt 80/100	81.5
Rubber powder	10.0
Oil extender	6.0
Catalyst	2.5

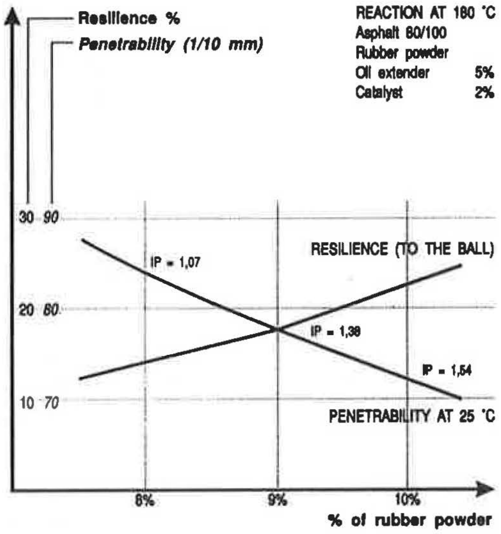

FIGURE 5 Change in other properties as a function of the percentage of rubber.

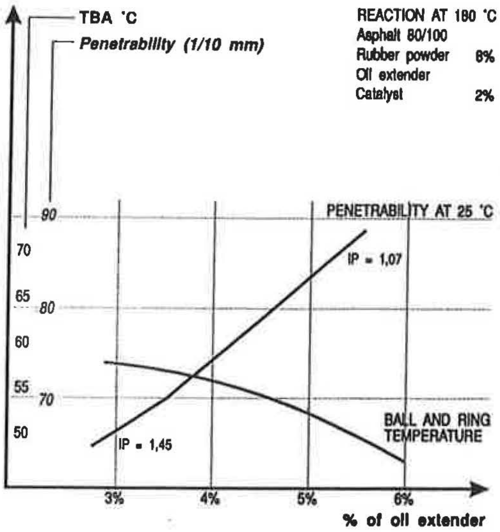

FIGURE 6 Changes in penetrability and ball and ring softening point properties as a function of the percentage of oil extender.

The asphalt rubber binder was produced using the optimized storable asphalt rubber binder formulation. The binder was produced at 180°C (the production process takes about 2 hr), then stored in tanks at 160°C in a hermetically sealed vessel without agitation. Samplings were taken at regular intervals in order to monitor the change in the product. Properties of the asphalt rubber binder after production were as follows:

Ball and ring softening point	65°C
Penetrability in 1/10 mm at 25°C	70
Viscosity (Rheomat)	640 cp at 180°C 1070 cp at 160°C
Stretching under tension to rupture point at −10°C	330 percent

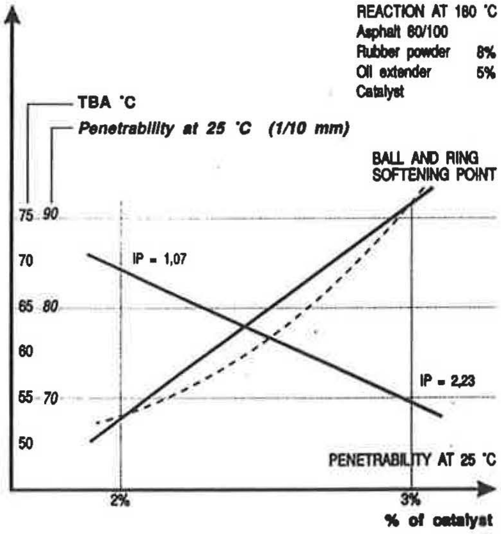

FIGURE 7 Change in penetration and TBA properties as a function of the amount of catalyst.

Results of the evaluation of the properties of the storable asphalt rubber binder after 6 days of storage provided the following results:

Ball and ring softening point	72.5°C
Penetration at 25°C in 1/10 mm	85
IP Pfeiffer	+1.34
Viscosity (Rheomat)	1040 cp at 160°C 1070 cp at 180°C
Rupture point stretching under tension at −10°C	350 percent

Conclusions of the laboratory study show that the formulation developed was consistent with the predetermined specification. After a week of storage at 160°C, there was no noticeable degradation of the asphalt rubber binder.

Advantages of Storable Asphalt Rubber Binder for Industrial Applications

Until development of the storable asphalt rubber binder, it was necessary to prepare the asphalt rubber binder just before use in plant production. Hence, it was mandatory to have a mobile asphalt rubber binder blending unit at the site of the asphalt paving plant. Without storable asphalt rubber binder the following production disadvantages are encountered:

1. Inability to supply high-capacity hot-mix plants with enough asphalt rubber binder to meet their design production rates.
2. If there is a failure, either at the hot-mix plant or in the paving operation, the storage of the asphalt rubber binder at high temperature is impossible (because of the loss of quality).
3. For small projects, it is cost-prohibitive to use the mobile unit considering the cost of mobilization. In most cases, it was impossible to compete with other techniques using, for example, polymer-modified bitumen that was prepared in fixed units and could be stored for several days.

However, with storable asphalt rubber binder, it is possible to prepared in advance the asphalt rubber binder to meet the high production rates of asphalt plants. Moreover, climate conditions, plant operations, or paving-equipment failures no longer have an influence on the production or quality of the asphalt rubber binder.

Advances in Technology of Rubber-Modified Asphalt Concrete (Dry System)

The addition of crumb rubber to replace some of the mineral aggregate in asphalt concrete mixtures was developed in Europe at approximately the same time that the asphalt rubber binder process was gaining notoriety in the United States. The system of adding crumb rubber directly to the mixture, either at the recycle fit opening at a drum plant or with the dry aggregate at the pugmill, is referred to as the dry system of rubber-modified asphalt concrete.

This system, developed in Sweden, was patented in North America and marketed under the trade name PlusRide. This process used relatively large pieces of crumb rubber (1/4 in. minus) produced from used tires. The crumb rubber is then added at the rate of 3 percent of total weight of the mixture. The patented specification requires a unique gap-graded aggregate gradation (*4*).

Production Barriers

In the PlusRide rubber-modified asphalt concrete system, the major components that increase cost are as follows (*5*):

- Specialized aggregate crushing to obtain the unique gap-graded aggregate gradation,
- High mineral filler content (8 to 12 percent),
- Increase in optimum asphalt cement content (7.5 to 9.5 percent),
- Increase in mixing temperature (300 to 350°F discharge temperature), and
- License fee for using the patented process.

Technical Barriers

The technical barriers encountered with the use of the PlusRide system are a combination of a lack of design criteria and nonconventional testing methods (*6*).

Evaluation of Rubber-Modified Asphalt Concrete (TAK System)

A new asphalt rubber system was developed in 1986 by H. Barry Takallou, referred to as the TAK System (*7–9*). This system relates to a process for producing an asphalt concrete composition made up of a coarse crumb rubber, a fine crumb rubber, asphaltic binder, and mineral aggregate. A catalyst to improve the reaction between fine crumb rubber and asphaltic binder, and anti-stripping agents may be added as determined by asphaltic binder and crumb rubber compatibility tests.

This process is characterized by the various constituents of the asphaltic binder and fine crumb rubber, mixed intimately by a physical reaction. This will result in a higher viscosity binder in which the optimum reaction is achieved when the fine crumb rubber particles reach optimum swelling. A pre-reaction or pre-treatment of crumb rubber with a catalyst may be needed to achieve the optimum crumb rubber particle swelling. The coarse crumb rubber will be added as part of the composition to act as an elastic aggregate, to improve elastic properties of asphalt concrete pavement, and to reduce temperature susceptibility.

The aim of this system is to remedy the drawbacks found in other systems. These include the use of specialized mixing equipment, specialized mineral aggregate gradations, and specialized design criteria. The TAK System combines coarse and fine crumb rubber to produce a binder that has asphalt rubber binder quality, and provides superior elastic properties for asphalt concrete pavement. Therefore, there is no need for specialized mixing equipment. In this system the mineral aggregate is constant while the crumb rubber gradation is variable in the composition. The crumb rubber gradation is optimized per each mix design. However, the size of a majority of the crumb rubber should be less than U.S. sieve size

No. 10. Also, the TAK System can be designed with conventional testing equipment and conventional design criteria.

The asphaltic composition of the asphalt binder can be any of a variety of conventionally available materials; this includes, but is not limited to, any polymer-modified asphalt binder, and any modified asphaltic binder material as long as the asphaltic binder and crumb rubber are compatible.

In this system, the rubber content in the composition should not exceed 2 percent for open-graded or dense-graded wearing course, and 3 percent for binder course, by total weight of the mixture.

The crumb rubber used should be processed from whole passenger and semi and truck tires. Heavy equipment tires should not be used. The crumb rubber larger than 16 mesh size should be processed by ambient granulation. The crumb rubber smaller than 16 mesh size may be produced from either granulation or grinding. Uncured or devulcanized rubber is not acceptable. Rubber tire buffings from either recapping or manufacturing processes may not be used as supplement to the crumb rubber. The crumb rubber provided should not be elongated in shape and should be free of contaminants including fiber, metal, and mineral matter.

The use of this system is in the public domain; therefore, there are no license fees required to use it. The system uses a standard dense-graded aggregate so that no unique or gap-graded aggregate gradation requirement is necessary.

Demonstration projects using the TAK System have been constructed by several state departments of transportation. The New York Department of Transportation has adopted and issued design specifications for the incorporation of crumb rubber from whole tire recycling using the TAK System concept.

The Province of Ontario, Canada, has also investigated the use of crumb rubber incorporated into asphalt concrete mixtures. In 1990, The Ministry of Transport constructed two demonstration projects using the rubber-modified asphalt concrete TAK System. These demonstration projects were constructed in an effort to evaluate its constructibility and performance, and to monitor air emissions during production and paving operations.

The two projects were constructed in separate regions of the province without any significant problems. In one project, the mixture was produced at a drum drier-type plant and in the other project a batch plant was used. The rubber-modified hot mix material was laid with a standard paving machine and compacted and rolled with standard equipment. Preliminary results show the rubber-modified sections to be performing as well as the conventional control sections and again, laboratory testing indicates superior performance is to be expected with rubber-modified asphalt concrete.

The air emission testing was performed for both rubber-modified asphalt concrete, TAK System, and conventional asphalt concrete. Results of the air emissions testing, from samples taken at the stack in the production of the mixtures and from personal air monitoring devices worn by the paving crew, indicate that the emissions from rubber-modified asphalt concrete Tak System are virtually identical to those of conventional asphalt concrete.

These demonstration projects also addressed the recyclability of rubber-modified asphalt concrete, TAK System, and stack emission testing was performed when the recycled rubber asphalt pavement was introduced to produce a recycled rubber asphalt concrete mixture. The rubber-modified asphalt concrete material proved to be recyclable.

CONCLUSION

The major barrier to the widespread use of rubber-modified asphalt concrete has been the increase in cost of using the material compared with conventional asphalt concrete. In the wet system, specialized equipment that had to be mobilized with each project led to a high cost for asphalt rubber binder. The mobile equipment was required because the binder had to be used within hours of production. With the development of storable asphalt rubber binder (Flexochape), it can be produced in central terminal locations and shipped like conventional asphalt cement to the production facility for use. This development will lower the cost of asphalt rubber binder, provide uniform and consistent binder qualities, and generally have a positive impact on a more widespread use of the material.

Technological advances in the dry system have also reduced the barriers to its use on a more widespread basis. The major barriers to widespread use were the unique aggregate gradation, high asphalt content, high filler content, high mixing temperature, nonuniform rubber gradation, lack of adequate design criteria, and use of a patented system. These barriers have been addressed with the introduction of the TAK System of rubber-modified asphalt concrete. This system allows the roadway engineer to specify a standard dense-graded aggregate specification using standard mix designs, test procedures, and criteria. TAK System uses conventional mixing procedures, compaction equipment, and quality-control testing procedures. These developments have lowered the production and construction costs of using the material. The use of the TAK System is in the public domain.

Air emission testing of the TAK System was performed in the Province of Ontario. Emissions tests were taken during production at both a drum drier plant and a batch plant for TAK System and conventional asphalt concrete. Air emission test samples were also taken during the paving operation, gathered from personal air-monitoring devices worn by the crew. Analysis of the air samples taken, both in production and at the job site, indicates no difference in air emissions with rubber-modified asphalt concrete compared with conventional asphalt concrete. The recyclability of rubber-modified asphalt concrete, TAK System, was also confirmed in these demonstration projects.

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Use, Availability, and Cost-Effectiveness of Asphalt Rubber in Texas

CINDY K. ESTAKHRI, JOE W. BUTTON, AND EMMANUEL G. FERNANDO

A study was conducted for the Texas Department of Transportation (DOT) by the Texas Transportation Institute (TTI) to address the following issues: (a) the current extent of use of asphalt rubber by the department, (b) the availability of crumb rubber produced from scrap tires and the availability of asphalt rubber in the state of Texas, and (c) the cost-effectiveness of asphalt rubber compared with conventional paving materials on the basis of existing information and the experience of department personnel. Published information was reviewed, phone interviews with knowledgeable department personnel were conducted, and existing laboratory information was evaluated. The Texas DOT currently uses asphalt rubber in four different applications. Listed in order of their volume of asphalt rubber consumption, these are (a) chip seal or stress-absorbing membrane (SAM) construction, (b) stress-absorbing membrane interlayer (SAMI) construction (c) crack or joint sealing, and (d) hot-mixed asphalt concrete pavement construction (on a very limited experimental basis). These applications of asphalt rubber are described in detail in the body of this paper. Results of this study indicated that the major obstacle for widespread use of asphalt rubber in Texas is its high cost.

Texas Senate Bill 1516 became effective in September 1989 and gave the following mandate (among others) to the Texas DOT:

> (1) If the State Department of Highways and Public Transportation uses rubberized asphalt paving, the Department shall use scrap tires converted to rubberized asphalt paving by a facility in this state if that paving material is available.
> (2) In comparing bids submitted for road construction that require paving, the Department may give a preference to bids, the paving materials portion of which includes the use of rubberized asphalt paving made from scrap tires by a facility in this state if the cost of those materials does not exceed by more than 15 percent the bid cost of alternative paving materials for the same job.

In order to make rational decisions about materials selection based on comparative cost-effectiveness, the department initiated the study described herein (*1*). The objective of this study is to provide the following information to the department: (a) the cost-effectiveness of asphalt rubber compared with more conventional paving materials based on existing information and on the experience of department personnel, (b) the availability of asphalt rubber in Texas, and (c) the current extent of usage of asphalt rubber in Texas.

To meet these objectives, an extensive review of pertinent literature was performed, phone interviews of cognizant department personnel in each district were conducted and other individuals were contacted. Applications of asphalt rubber in chip seals, sometimes called stress-absorbing membranes (SAM), stress-absorbing membrane interlayers (SAMI), crack fillers, and hot-mixed asphalt concrete were addressed. For this study, asphalt rubber is defined as a blend of 17 to 26 percent ground tire rubber by total weight of the blend. The blend is typically formulated at elevated temperatures to promote chemical and physical interaction of the two constituents. Various petroleum distillates are sometimes added to the blend to reduce viscosity and enhance workability.

AVAILABILITY AND USE OF ASPHALT RUBBER

Governmental agencies including state highway departments and municipal street divisions are under public pressure to use waste materials to the greatest extent possible. Without question, this is the direction in which our society must move. Using waste materials and by-products is logical, sensible, and many times cost-effective. Incentives are sometimes offered by federal and state legislative bodies to promote the use of waste products.

Waste Tire Availability

According to industry figures, there are as many as 2 billion scrap tires currently on the ground in the United States, with approximately 240 million tires being discarded in the United States each year (*2*). Of these, 200,000,000 are passenger car tires and 40,000,000 are truck tires (*3*).

It is estimated that Texas is accumulating scrap tires at a rate of 18 million annually and that there are approximately 150 million located at various storage sites around the state. These figures are based on the number of passenger cars and commercial vehicles registered in the state and an average tire life of 4 years.

A typical worn-out passenger car tire weighs approximately 20 lb and will provide about 60 percent rubber, 20 percent steel, and 20 percent fiber and other reusable products. On the basis of these estimates, Texas drivers are generating each year the following potentially reusable materials: 108,000 tons of rubber, 36,000 tons of steel, and 36,000 tons of fiber. These estimates are conservative because they were computed using an average weight for passenger car tires, and truck tires are much heavier.

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Asphalt Usage

Approximately 32 million tons of asphalt were produced in the United States in 1987. Of this, about 27 million tons were used for paving, 4 million tons for roofing, and fewer than 1 million tons for other purposes. At $100/ton (a reasonable average cost), this translates into $2.7 billion worth of asphalt cement per year for paving purposes. Approximately 90 percent of this was used in hot-mixed asphalt concrete (HMAC) and the other 10 percent was used for chip seals and surface treatments. The approximate quantity of HMAC produced in the U.S. was 500 million tons. At an average cost of $30/ton, it is estimated that more than $15 billion dollars were spent on HMAC during 1987. Although these values have varied somewhat, they are reasonably typical of the last 18 years.

In Texas, about 20 million tons (or $0.6 billion worth) of HMAC was produced in 1989 according to the Texas Hot-Mix Association. Just under half of this was purchased by the Texas Department of Transportation (DOT). The remaining went to municipalities, airport authorities, and private buyers.

In fiscal year 1988, the Texas DOT used 1,100,000 tons of asphalt cement, 200,000 tons of emulsified asphalt, and 110,000 tons of cutback asphalt—a total of 1.4 million tons of asphalt products. These figures were obtained from the Materials and Tests Division (D-9) of the Texas DOT.

Potential Tire Use in Asphalt Rubber

If 10 percent of the paving asphalt cement used annually by the State DOT were routinely replaced with asphalt rubber (using Texas tires), this would result in partial recycling of more than one-fifth of all the scrap tires accumulated annually in the state. Recall that only 60 percent of a tire is used in producing asphalt rubber. Therefore, the remaining 40 percent must be either disposed of or used in some other recycling process.

On the basis of information from asphalt rubber suppliers in Texas, it is estimated that the Texas DOT is currently using 12,000 to 14,000 tons of asphalt rubber/year in paving operations. Another 1,200 tons are used as asphalt-rubber crack sealant. Assuming that 20 percent tire rubber was used in the modified binder and that 12 lb of rubber/tire (60 percent of 20 lb) were used, this quantity of asphalt rubber would account for approximately 430,000 scrap tires. However, it should be pointed out that at the time of this study, more than 85 percent of these tires were coming from out of state. Most of the crumb rubber comes from suppliers in California, Indiana, and Ohio.

According to asphalt-rubber suppliers and tire-rubber suppliers to the asphalt-rubber industry, a continuous supply of 1 to 3 million tires annually and about $1 million in capital will be required to open and maintain operations of a profitable facility for grinding tire rubber for use in asphalt. There is one producer of ground tire rubber at this time in Texas and several reports of others going into this business. It is anticipated that there will soon be an adequate supply of crumb rubber produced in Texas to handle the current asphalt-rubber market.

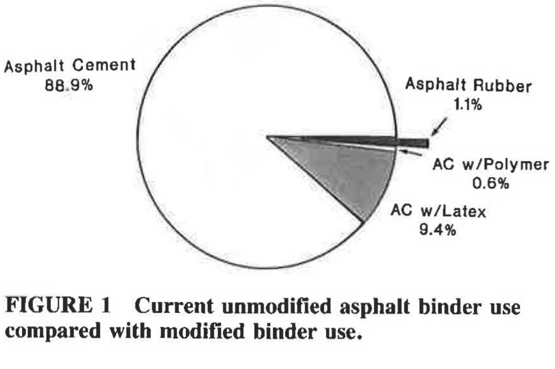

FIGURE 1 Current unmodified asphalt binder use compared with modified binder use.

Use of Asphalt Rubber in Texas

All of the 24 highway districts in Texas have experimented with asphalt rubber as a paving material. As stated previously, the Texas DOT currently uses 12,000 to 14,000 tons of asphalt rubber in paving operations annually. Another 1,200 tons are used as asphalt-rubber crack sealants. The amount of asphalt rubber used as a paving material is compared with other modified binders in Figure 1.

ASPHALT-RUBBER CHIP SEALS (SAMs)

Research on SAMs in Texas

Texas Transportation Institute

A research study (*3*) was conducted by Texas Transportation Institute in 1982 for the Texas DOT on asphalt-rubber membranes. An evaluation of performance was made for 45 separate projects in 13 highway districts. Approximately 850 lane miles of highways were represented by materials constructed as asphalt-rubber chip seals or SAMs. All projects reviewed were constructed between 1976 and 1981. Data on 148 conventional chip seal projects throughout Texas were reviewed and a comparison of performance was made. Some of the more significant conclusions are listed below.

1. Flushing distress occurs more often with asphalt-rubber chip seals than with conventional seals at a ratio of 99 percent of all asphalt-rubber projects and 74 percent of conventional projects.
2. Shrinkage cracking appears in both asphalt-rubber and conventional seals at approximately the same level, occurring in about 50 percent of all projects.
3. With all other environmental factors being equal, alligator cracking appears in conventional seals at approximately twice the frequency it does in asphalt-rubber chip seals.
4. Shelling of the cover stone appears in approximately 44 percent of the conventional seals compared with 17 percent of the asphalt-rubber seals.
5. The improved resistance to alligator cracking and raveling by asphalt-rubber chip seals and poorer flushing performance is not surprising because the typical normal application rate for asphalt rubber is significantly higher than that for conventional chip seals.

6. The present performance of asphalt rubber suggests that improved design methods for these new systems may alleviate the problems described here.

Much of the early research shows that asphalt-rubber chip seals typically exhibit more distress than the conventional asphalt chip seals; however, this distress is attributed to construction practices rather than to the asphalt-rubber material itself. The primary type of distress in asphalt-rubber chip seals is flushing, which is caused by inappropriate quantities of binder and aggregate. It should be noted, however, that flushing on an asphalt-rubber chip seal is not as critical as it is on a conventional asphalt chip seal. Experienced department personnel report that although an asphalt-rubber chip seal can be flushed on the surface, it will still have adequate skid resistance to remain serviceable for a number of years, which is not true for conventional asphalt chip seals. This may be because the rubber particle provides increased skid resistance or the asphalt-rubber binder is much stiffer than an asphalt cement.

District 24: El Paso

District 24 has applied a total of 606 lane miles of asphalt-rubber SAMIs and 1,751 lane miles of asphalt-rubber chip seals or SAMs. The typical practice of District 24 is to use asphalt rubber on their three main highways: I-10, U.S. 90, and U.S. 62/180 from El Paso east to New Mexico. Because of the costs associated with asphalt rubber, it is considered cost-effective only when used on the higher traffic-volume roadways, but "Yes, it is cost-effective," states the district operations engineer. It is reported as lasting twice as long as a conventional seal. In El Paso, a conventional chip seal is reported to last for 7 yr and an asphalt-rubber chip seal is reported to last for 14 yr.

Conclusions about the use of asphalt rubber in SAMs after a number of years of experience in District 24 are as follows:

1. An excellent material for use in a dry, hot area. Some have reservations about use in other climates.
2. Should use only precoated aggregate. Best results will be obtained using ⅜-in. maximum size.
3. Restrict "asphalt (construction) season" to hottest months of the year (e.g., June, July and August).
4. Permits seal application on high traffic volume roads.
5. Most things applicable to conventional seal coats apply to this material—this is a very "forgiving" material.
6. General appearance of asphalt-rubber seal is best after about 3 yr.
7. "This is a significant advancement in asphalt technology."

Texas Highway District Survey

As a part of this study, a telephone survey of all the districts in Texas was conducted. Texas is divided into 24 highway districts, and personnel in each district were queried about their experiences with asphalt rubber.

Although there are a significant number of asphalt-rubber projects in Texas, many of these were built on an experimental basis and the use of asphalt rubber in most districts is not standard practice. These districts are shown shaded in Figure 2. The primary reason cited by most districts for not using asphalt rubber is that it is too expensive. Some of these districts, which have used asphalt rubber in the past but have no future plans, report that there were some performance benefits associated with the material, but the benefits do not offset the additional cost. District 21 tried an asphalt-rubber chip seal 5 yr ago but believes a conventional AC chip seal is just as good.

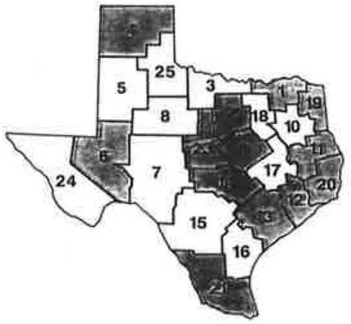

FIGURE 2 Districts with no interest in using asphalt-rubber chip seals in near future.

During the earlier years of asphalt-rubber technology, many of the performance problems that emerged were caused by poor design and construction techniques. Now, asphalt-rubber technology is more advanced and improved. The five districts that are beginning to give asphalt-rubber chip seals another try and those that use asphalt-rubber chip seals on a somewhat regular basis are shown shaded in Figure 3. District 17 uses asphalt rubber regularly. The managing resident engineer in Brenham states: "When the pavement is badly cracked but appears structurally sound, asphalt rubber is the answer." He further stated that he uses asphalt rubber as often as his budget will allow.

Cost-Effectiveness

To determine the cost-effectiveness of an asphalt-rubber chip seal, the life of that seal must be known. There are many variables that affect the life of any pavement surface: environment, traffic, quality of construction and materials, condition of pavement before surfacing, design, and substrate.

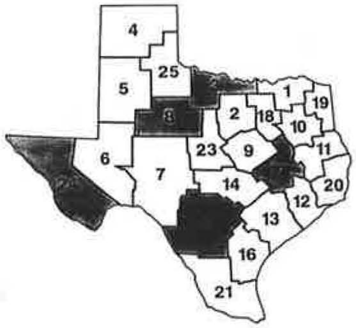

FIGURE 3 Districts currently using asphalt-rubber chip seals.

Even with construction techniques that are backed by many years of experience, such as conventional chip seals, it is difficult to estimate the serviceable life for a given roadway class and condition. For asphalt-rubber chip seals, this task is even more difficult. From Arizona (*4*) comes the report that the life of an asphalt-rubber chip seal is 5 yr on the Interstate, 8 yr on U.S. routes, and 10 yr on state routes. District personnel in El Paso report that, on U.S. highways, the life of an asphalt-rubber chip seal is 14 yr, and a conventional chip seal lasts 7 yr. It must be kept in mind that the climate in both El Paso and Arizona is very arid. In an area of low rainfall, a badly cracked pavement may remain structurally sound longer than it would in a wet region. If a pavement is structurally sound before placement of an asphalt-rubber chip seal, or any type of chip seal, that seal is likely to have a relatively long life.

Because of the many factors influencing the life of any pavement surface, it is difficult to assess the cost-effectiveness of asphalt rubber. Although reports of experience with asphalt rubber in some locations are quite good (*4*), research results from across the United States (*3,5*) do not indicate that there are significant improvements in performance with asphalt-rubber seals over that of conventional seals. However, it must also be kept in mind that much of the research involving asphalt rubber was done at a time when the technology was still in an experimental stage. Many reports of negative performance were related to improper construction and design practices rather than to the material itself. With the present state of the art on asphalt rubber, it is not possible to accurately estimate the life of asphalt-rubber seals under specific climates, traffic conditions, and underlying pavement conditions. For the purposes of this study, an annualized cost evaluation was performed for a range of service lives of an asphalt-rubber chip seal, a conventional chip seal, and a thin overlay. To determine the costs of conventional chip seals and asphalt-rubber chip seals, actual construction bids from 1989 were reviewed. All compared bids were for jobs of more than 2,000,000 yd^2. The following are unit costs for the different pavement surfaces used to calculate annualized costs for different pavement lives:

Conventional AC chip seal,	\$0.47/yd^2.
Asphalt-rubber chip seal,	\$1.14/yd^2.
Thin overlay, 1-in.	\$1.60/yd^2.

The cost of the overlay is based on an in-place cost of \$30/ton of HMAC. The formula for equivalent uniform annual cost used in this analysis is

$$A = \frac{P[i * (1 + i)^n]}{[(1 + i)^n - 1]}$$

where

A = equivalent uniform annual cost
P = initial construction cost
i = interest rate
n = pavement life in years

It must be kept in mind that the annualized cost is based on initial construction cost only with an effective interest rate of 4 percent (interest rate with inflation accounted for). It does not include any user costs or expected maintenance costs.

When comparing a conventional AC chip seal with an asphalt-rubber chip seal, on the basis of this analysis, an asphalt-rubber chip seal would have to last three times longer than a conventional seal to have the same annual cost. Although this may be possible, there is little information to document these service life extensions in the field. As stated earlier, El Paso reports that the asphalt-rubber chip seal lasts twice as long as the conventional seal. Arizona reports a maximum life of 10 years on a state route. It is commonly reported that a conventional chip seal will last about 7 yr in Texas. The asphalt-rubber seal would have to last 21 yr to have an equivalent cost. This seems unlikely. Asphalt rubber is usually only placed on high-volume roads where a conventional chip seal might have a much shorter life of 3 to 4 yr.

Originally, it was intended to compare asphalt-rubber chip seals with polymer-modified chip seals. Most of the districts in Texas, at the present time, use a polymer-modified AC or polymer-modified emulsion for standard chip-seal construction. The addition of a polymer into the binder does not significantly increase the bid price of the chip seal for relatively large jobs. In fact, many bids show an equivalent cost/yard^2 of chip seal. Although there is no doubt that the addition of a polymer into asphalt increases the cost of the binder, this is not evident in the overall cost of the chip seal examined in this study, as shown in Figure 4. There are several factors that enter into the cost of the chip seal: size and location of job, aggregate, traffic control, and mobilization. For the jobs examined herein, the polymer-modified chip seals were not really any more expensive than the conventional AC chip seal. Although those districts that use polymer-modified binders report that there are benefits associated with the material, none are able to identify whether or not there is an increase in the service life. Therefore, the polymer-modified chip seals were not included in the cost analysis because they appear to be similar in cost to a conventional chip seal (on a yard^2 basis), as shown in Figure 4. Furthermore, no information is available about the life of polymer-modified chip seals.

It should be pointed out that an asphalt-rubber chip seal contains more binder than a conventional chip seal. The conventional chip seal used in this analysis contains 0.35 gal of AC/yard^2, whereas the asphalt-rubber chip seal contains 0.55 gal/yard^2. Because of this difference, comparisons with conventional chip seals are not completely valid. Engineers in the department who have experience with asphalt rubber often report that they do not use this material in a location at which a conventional chip seal is a viable option. An asphalt-rubber chip seal is typically used as a rehabilitative measure rather than a preventive measure when a pavement is badly cracked. Therefore, a bigger burden is often placed on an asphalt-rubber chip seal than on a conventional chip seal. Jacobson and Schnormeier (*6*) of the Asphalt Rubber Producer's Group report that asphalt rubber applications have been most successful when the pavement lost 80 to 90 percent of its quality and funds were not available to reconstruct.

Perhaps a more valid performance comparison for an asphalt-rubber chip seal would be with a thin overlay. If an asphalt-rubber chip seal lasted 9 yr, a thin overlay (1-in. thick) would need to last 14 yr to have an equivalent annual cost.

Jacobson and Schnormeier (*6*) stated, "Cost comparisons (of SAMs) are usually based on the direct cost of asphalt rubber versus conventional asphalt. This is O.K. if one is

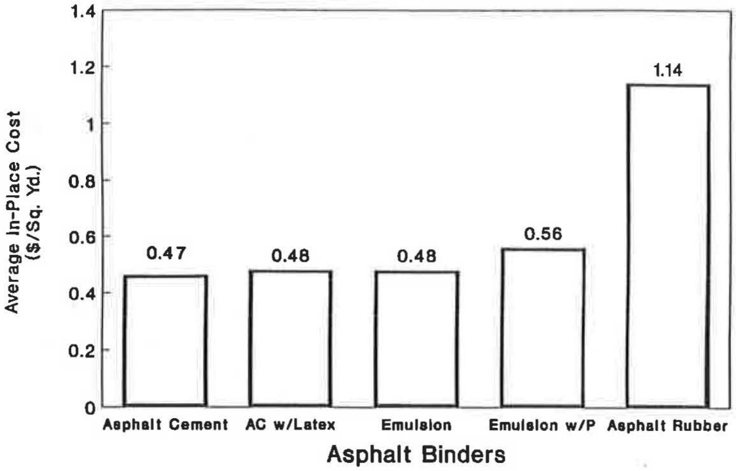

FIGURE 4 Typical in-place costs for chip seals constructed with different binders in 1989.

concerned only with initial cost. It becomes very important that all costs be included today and tomorrow. Initial asphalt-rubber costs are twice as much as a conventional asphalt. This is a disadvantage because the money made available must be used to cover as much as the public can and will accept." Jacobson and Schnormeier conclude, however, that asphalt rubber is cost-effective because less maintenance is required of asphalt-rubber chip seals than of conventional asphalt chip seals.

ASPHALT-RUBBER INTERLAYERS (SAMIs)

SAMI Research in Texas

Texas Transportation Institute

The Texas DOT is sponsoring an ongoing research study with the Texas Transportation Institute (*7*) to evaluate the performance of asphalt-rubber interlayers. Three full-scale test roads were constructed in 1983 and 1984 near El Paso, Brownsville, and Buffalo, Texas. The Buffalo test road has an overlay thickness of between 4 and 6 in. and is not showing any distress. The Brownsville test road was constructed with excessive interlayer binder application rates and all sections are flushing. However, the El Paso test road has yielded some useful information. Nine different types of asphalt-rubber interlayers were constructed there using different binder application rates, different rubber concentrations, and different ground tire rubber suppliers. The control section contained no interlayer. All of the asphalt-rubber sections are performing better than the control in terms of delaying reflective cracking, with some sections performing significantly better.

District 24: El Paso

District 24 currently has six asphalt-rubber interlayers under observation. These range in age from 1 to 12 yr. Overlay thickness is from 1-1/2 to 3 in. The average binder application rate was 0.55 gal/yard^2. Traffic exceeds 100,000 average daily traffic (ADT) on some of these pavements. El Paso reports that major cracks in the old pavement were sealed with asphalt rubber before application of the SAMIs. Cracks reflected through SAMIs by the second winter, but these were only "hairline" cracks and they tended to heal the following summer. All pavements are still in good to excellent condition. A representative of District 24 stated: "This material provides the best life-cycle cost we have found for rehabilitation of cracked, weathered asphalt surfaces needing minor leveling provided by thin HMAC overlays."

Survey of Texas Highway Districts

Personnel in each highway district were contacted to determine their experiences with asphalt rubber applied as interlayers. The six districts that have constructed asphalt-rubber interlayers are identified in Figure 5. The opinions of department personnel on asphalt rubber used as an interlayer are much more favorable than they are for asphalt rubber used as chip seals. Although the cost of an asphalt-rubber interlayer is still at least twice that of a conventional chip seal interlayer, it is only a small portion of the total overlay system cost. Most of the districts that have used asphalt rubber as

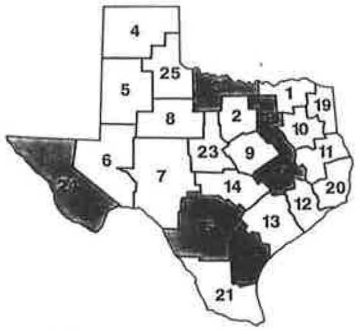

FIGURE 5 Districts currently using asphalt-rubber interlayers.

an interlayer report that it definitely reduces the rate of reflection cracking.

Evidence has been seen of cracks in asphalt-rubber chip seals healing in the summer months. Although this phenomenon can be observed in an asphalt-rubber chip seal, it cannot be viewed in an asphalt-rubber interlayer because it is covered by an overlay. However, if this healing ability exists in an asphalt-rubber interlayer, then the interlayer may function as a waterproofing membrane. Once cracks do develop in the surface layer, the asphalt rubber may prevent, or at least reduce, any water intrusion into the underlying pavement structure.

Cost-Effectiveness

Based on the literature review, research conducted by TTI, and the experience of department personnel, an asphalt-rubber interlayer can produce an improvement in pavement performance. Although it is generally believed that an asphalt-rubber interlayer extends pavement life, it is not accurately known how long. Because the interlayer is not visible on the surface, its effects are difficult to measure. A common method of evaluation is to measure reflective cracking in the surface of the overlay. However, there may be other improvements in pavement performance that are not commonly measured by highway departments, such as roughness. If there are any benefits from "waterproofing" of the underlying structure, this is difficult to measure.

A similar cost analysis as shown in the previous chapter was performed for SAMIs. An annualized cost was determined for a 2-in. overlay and compared with the annualized cost for an asphalt-rubber SAMI with a 2-in. overlay. As in the previous cost analysis, this is based on initial construction cost only and does not include any user or maintenance costs. The following initial construction costs were used for the analysis:

2-in. overlay	$\$3.20/\text{yd}^2$.
2-in. overlay with SAMI	$\$4.25/\text{yd}^2$.

On the basis of this analysis, a 2-in. overlay with an asphalt-rubber SAMI would need to last approximately 50 percent longer than a 2-in. overlay alone to yield an equivalent annual cost. For example, if a 2-in. overlay lasted 8 yr, a 2-in. overlay with SAMI would need to last 12 yr to be equivalent in cost.

ASPHALT-RUBBER CRACK SEALANTS

One of the most troublesome problems the highway department faces in its effort to provide quality long-lasting pavements is the presence of pavement cracks. In the past, maintenance forces have used many materials as sealants in attempts to seal cracks and effectively extend pavement life. These materials include asphalt cements, cutbacks, emulsions, and latex-modified emulsions. However, during the 1970s and early 1980s, an asphalt-rubber sealing compound containing ground tire rubber emerged as a new and comparatively effective means of crack repair. The compound is composed of approximately 80 percent asphalt and 20 percent ground tire rubber.

At the current time, more than 95 percent of all asphalt-rubber crack sealant that is used in Texas is supplied from Crafco, Inc., in Chandler, Arizona. Crafco has done extensive research in asphalt-rubber formulation, production, and application and has helped the state of Texas in its specification guidelines for asphalt rubber crack sealant. In 1989, Crafco supplied almost 3.5 million lb of material to Texas at an average price of 19 cents/lb, translating to a yearly total of $495,041. This material was used to fill approximately 14 million linear ft of crack and joints. The price has varied slightly during the past several years, with costs ranging from 12 to 15 cents/lb. The department is currently modifying its specifications to accept a slightly wider variety of products that would allow other suppliers to enter the market.

Survey of Texas Highway Districts

On the basis of a telephone survey of district personnel in Texas, Crafco asphalt-rubber sealant is the product of choice. Many of the districts have used other products in the past, and on jobs with very small cracks a polymer emulsion product has proven to be more effective; however, according to one DOT engineer, asphalt rubber continues to "last longer and provide less problems" than other types of sealants.

In talking to each of the districts with crack sealing programs, it was readily apparent that they were pleased with the product. Typical comments were that the rubber is very stable; vehicle tires do not displace it; the rubber provides good elasticity and strength; and it does not seem to weather or oxidize at all.

Almost all of the districts agreed on the material's properties and all independently estimated the typical life of the product to be 3 yr.

Cost-Effectiveness

To be consistent with the rest of this paper it would be beneficial to include a cost-effectiveness comparison with other similar products. However, the extensive use of the asphalt rubber throughout the districts makes this type of comparison difficult. Projects are sometimes encountered that require other special sealants; however, these projects are usually very small and a true performance comparison cannot be established.

RUBBER-MODIFIED ASPHALT CONCRETE MIXTURES

Field Experience in Texas

The 1989 hot-mix asphalt concrete usage within the state of Texas is approximately 8.1 million tons, which is down slightly from the 5-yr average of 9.4 million tons. These high values indicate excellent opportunities for use of asphalt rubber. However, at this time, only two districts in Texas have tried the product. Ten years ago, District 21 experimented with the rubber-modified hot mix but the job was unsuccessful. District maintenance forces applied the hot mix along a 1-mi section on S.H.336 in McAllen. The mix raveled severely and the district was forced to place a chip seal over the mix within 3 months.

In 1989, the Tyler district (District 10) placed a dense-graded, asphalt-rubber hot-mix overlay. The project was located at the intersection of FM 14 and Loop 323 just outside Tyler. Asphalt rubber was chosen for the site in hopes of curing a severe rutting problem caused by large trucks turning onto and off the loop. So far, district personnel are pleased with the project and are interested in using the product again but on a more standard hot-mix job. The cost of the asphalt rubber for this job was approximately $80/ton. Tyler's district personnel believe that a larger job would help reduce this high material cost.

District 4 in Amarillo constructed 10 lane mi of dense-graded, asphalt-rubber hot mix in the fall of 1990. Bid prices showed an in-place cost of $52/ton for the asphalt-rubber paving material, which is substantially less than the $80/ton reported in Tyler but not particularly attractive when compared with the $30 to $35/ton most districts were paying for conventional hot-mixed asphalt concrete.

CONCLUSIONS AND RECOMMENDATIONS

Availability and Use

Approximately 150 million scrap tires are currently stored in Texas and another 18 million are being discarded in the state each year. The scrap tires accumulated annually could be used to produce 108,000 tons of rubber suitable for use in asphalt-rubber products. The Texas DOT annually uses more than 1,000,000 tons of asphalt cement. If 10 percent of this paving asphalt cement were routinely replaced with asphalt rubber, more than 20 percent of the annual production of waste tires in Texas would be used. At the present, slightly more than 1 percent of this paving asphalt is asphalt rubber.

Only about 60 weight percent of a tire is consumed in producing asphalt rubber. Remaining products include primarily steel, fiber, and additional rubber.

The Texas DOT is currently using about 13,000 tons/yr of asphalt rubber, which accounts for approximately 430,000 scrap tires. However, most of the waste tires used in this material come from other states. The availability of crumb rubber in Texas is a rapidly changing issue. Findings indicate that next year 7,000,000 to 10,000,000 tires may be recycled in plants in Texas.

Asphalt-Rubber Chip Seals

Asphalt-rubber chip seals have been constructed, at least on an experimental basis, in all parts of Texas. However, there are only 5 out of the 24 highway districts currently constructing asphalt-rubber chip seals with some regularity.

Use of asphalt rubber for chip seals in most highway districts in Texas has historically not been standard practice, and 13 districts have no plans for increasing their use in the future. The primary reason cited for this is that asphalt rubber is too expensive and has not proven to be cost-effective in this application.

An asphalt-rubber chip seal costs two to three times more than a conventional chip seal. Proponents of asphalt-rubber chip seals claim they will last twice as long as a conventional chip seal.

There is not enough available information to accurately determine the cost-effectiveness of asphalt-rubber chip seals. However, an annualized cost analysis performed in this study revealed that an asphalt-rubber chip seal would have to last three times longer than a conventional asphalt chip seal to have an equivalent annual cost.

Districts in Texas that are experienced with asphalt-rubber chip seals do not usually construct them on a pavement where a conventional chip seal is a viable option. Asphalt-rubber chip seals are used successfully as a rehabilitative instead of a preventive measure and they are often placed on high-traffic volume roads. Therefore, perhaps a more valid comparison for asphalt-rubber chip seals might be with a thin overlay or multiple chip seal, in which case the asphalt rubber is much more likely to be cost-effective.

Asphalt-Rubber Interlayers (SAMIs)

Only six Texas highway districts have built SAMIs. Opinions of department personnel on asphalt-rubber interlayers are much more favorable than those on asphalt-rubber chip seals. Most of the districts that have installed SAMIs believe they are effective in delaying reflective cracking. Some also believe SAMIs will reduce intrusion of surface water and thus pumping even after cracking occurs in the surface layer.

An asphalt-rubber SAMI may provide cost-effective improvements in performance of hot-mixed asphalt concrete overlays. On the basis of an annualized cost analysis performed in this study, an overlay with an asphalt-rubber interlayer would need to last approximately 50 percent longer than an overlay constructed without an interlayer to be cost-effective.

Asphalt-Rubber Crack Sealants

Asphalt-rubber crack sealant, which contains 20 percent ground tire rubber, is essentially the only crack sealant used by the Texas DOT. The Texas DOT uses approximately 3.5 million lb of crack sealant annually.

Asphalt-rubber crack sealant is considered by all personnel interviewed in highway districts to be the best product available for sealing cracks in asphalt concrete and portland cement concrete pavements.

Asphalt-Rubber Hot Mix

Asphalt rubber has been used on a very limited basis in Texas for construction of HMAC. The use of crumb rubber in HMAC is gradually gaining popularity across the United States; however, the technology is still in a somewhat experimental stage of development.

General Recommendation

The Texas DOT and the Texas Legislature should not "go overboard" in promoting the use of tire rubber in asphalt because the benefit-cost ratios are not sufficiently high for every application. Offering incentives to use tire rubber (which negate fair competition) or mandating the use of tire rubber in asphalt pavements to solve the waste tire problem does not appear to be in the best interest of the tax-paying public. Sound engineering, not politics, should govern the choice of paving materials used in highway construction. A practical solution to the problem will require more research and engineering to provide self-supporting, cost-effective uses for scrap tires. There may be more economically efficient ways to recycle tires in much greater volumes than in asphalt pavements.

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Permanent Deformation Characteristics of Recycled Tire Rubber-Modified and Unmodified Asphalt Concrete Mixtures

NEIL C. KRUTZ AND MARY STROUP-GARDINER

In recent years, modified asphalt mixtures have become increasingly popular in the construction of flexible pavements. These products have gained popularity because of their ability to increase resistance to rutting at warm temperatures while reducing the occurrence of thermal cracking at cold temperatures. This, coupled with the growing problem of waste rubber tires, has led to the reprocessing (grounding) of tire rubber for use in asphalt concrete mixtures. In order to investigate the warm temperature rutting hypothesis, a laboratory research program using both static and repeated load permanent deformation tests, carried out at two temperatures (77°F and 104°F), was designed to assess the potential benefits of rubberized asphalt concrete mixtures. Conclusions from this research indicated that the addition of ground tire rubber to asphalt concrete mixtures results in mixtures that exhibit less permanent deformation at high temperatures compared with unmodified mixtures. The research also indicated that permanent deformation testing should be carried out at high temperatures under repeated loading. The relative ranking of strain changes from 77°F to 104°F for both methods of testing and static testing indicates the presence of rubber; however, it does not indicate anything about the base asphalt. The repeated load testing indicates, in a reliable way, the differences that exist between binders.

In recent years, modified asphalt mixtures have become increasingly popular in the construction of flexible pavements. These products have gained popularity because of their ability to increase resistance to rutting at warm temperatures while reducing the occurrence of thermal cracking at cold temperatures. This, coupled with the growing problem of waste rubber tires, had led to the reprocessing (grounding) of tire rubber for use in asphalt concrete mixtures.

In order to investigate this hypothesis, a laboratory research program was designed to assess the potential benefits of rubberized asphalt concrete mixtures.

RESEARCH PROGRAM

The extended research program was designed to include four phases:

Phase 1: The use of conventional mix design methods for determining the optimum asphalt content for rubberized mixtures.

Phase 2: Permanent deformation characteristics of rubberized and unmodified mixtures.

Phase 3: Low-temperature cracking resistance of rubberized and unmodified mixtures.

Phase 4: Fatigue characteristics for rubberized and unmodified mixtures.

The laboratory results from Phase 2 only are discussed in this report. Phase 1 has been completed and reported in "Comparison of Mix Design Methods for Rubberized Asphalt Concrete Mixtures" (*1*). Phases 3 and 4 are currently being completed.

The scope of this research program includes one aggregate source, one gradation, and six binders. The test matrix is shown in Table 1.

MATERIALS

Aggregates

The aggregates used in this research program were obtained from Granite Rock Company, located in Watsonville, California. This material is a 100 percent crushed granite that has no history of stripping problems with in-service pavements. The physical properties are presented in Table 2.

The gradation used to prepare the mixture samples is shown in Table 3. This gradation was chosen to meet ASTM D3315 ½-in. dense mixture, Nevada Type II, and California ½-in. medium specification (Table 3). This gradation was opened up slightly on the #30 and #50 to accommodate the presence of rubber.

Binders

The three grades of neat asphalt used in this research program were obtained from a single California Valley crude source. The binders used were:

Unmodified: AC-5
AC-20
AC-40

Both the AC-5 and AC-20 were then modified with crumb rubber. The AC5 was also modified with rubber and an extender oil, yielding a very soft third modified binder. The

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TABLE 1 TEST MATRIX FOR PERMANENT DEFORMATION OF MODIFIED AND UNMODIFIED MIXTURES

	Binder	AC5 Ext. Oil		AC5		AC20		AC40	
	Modifier	Orig.	Rubber Added	Orig.	Rubber Added	Orig.	Rubber Added	Orig.	Rubber Added
Static Load	77°F		X	X	X	X	X	X	
	104°F		X	X	X	X	X	X	
Repeat. Load	77°F		X	X	X	X	X	X	
	104°F		X	X	X	X	X	X	

TOTAL OF 72 SAMPLES (each X denotes 3 samples)

source of crumb rubber was selected by the sponsor with the rubber being blended with the asphalt cement by Crafco Inc., located in Chandler, Arizona. The rubber used in this research program was ambient ground rubber having a hydrocarbon content of approximately 45 percent and a specific gravity between 1.100 and 1.200. The particle size, along with the gradation specification suggested by Crafco, are shown in Table 4. The resulting modified binders were:

Modified: AC-5 + 17% Rubber (AC5R)
AC-5 + 16% Rubber + 5% Extender Oil (AC5RE)
AC-20 + 16% Rubber (AC20R)

TABLE 2 PHYSICAL PROPERTIES OF WATSONVILLE AGGREGATE

Test	Fine Aggregate (-#4)	Coarse Aggregate (+#4)
Bulk Specific Gravity	2.589	2.682
Bulk Specific Gravity, SSD Condition	2.667	2.735
Apparent Specific Gravity	2.806	2.832
Absorption Capacity (%)	3.0	2.0

TABLE 3 COMPARISON BETWEEN LABORATORY GRADATION USED IN RESEARCH PROGRAM AND SEVERAL SPECIFICATIONS

Sieve Size	Laboratory Gradation	ASTM D3315 ½" Dense	Nevada Type II	California ½" Medium
	Cumulative Percent Passing			
3/4"	100	100	90-100	100
1/2"	98	90-100	---	89-100
3/8"	85	---	63-85	75-100
#4	58	44-74	45-63	51-74
#8	40	28-58	---	35-57
#16	28	---	---	---
#30	20	---	---	14-35
#50	14	5-21	---	---
#100	9	---	---	---
#200	5	2-10	3-9	0-11

OPTIMUM BINDER CONTENTS

In Phase 1 of this research, binder contents to be used in phases 2, 3, and 4 were selected by a committee that included the sponsor and all of the researchers involved. These selections were based on mix designs conducted at both the University of Nevada, Reno, and the U.S. Army Corps of Engineers Water Ways Experiment Station (WES). Optimum binder contents for both unmodified mixtures AC5 and AC20 were agreed upon at 5.3 and 5.7 percent by total weight of mix, respectively. However, there was disagreement about the binder content to use for each of the modified mixtures. As a result, a compromise was made that was agreeable to all parties involved in the extended program. The compromise yielded binder contents that were higher than the University of Nevada, Reno (UNR)-recommended optimums. The following table shows the binder contents used and the UNR-recommended binder content for all modified mixtures.

Type of Binder	*Binder Content Used In Preparing Samples (%, Total Weight of Mix)*	*UNR-Recommended Binder Content (%, Total Weight of Mix)*
AC5R	8.5	7.7
AC5RE	8.3	7.7
AC20R	7.9	7.4

TABLE 4 PHYSICAL PROPERTIES OF GROUND TIRE RUBBER USED IN PREPARING MODIFIED BINDERS

Sieve Size	Baker IGR-24	Manufacturer Recommendations
	Cumulative Percent Passing	
#10	100	100
#16	100	100
#30	78	70-100
#40	49	---
#50	27	---
#80	9	0-20
#100	7	---
#200	0.2	0-5

The result of this compromise is a binder-rich mixture. This should be remembered when assessing any of the permanent deformation data contained in this report.

SAMPLE PREPARATION

Samples were batched by first separating the aggregates into the 11 individual sizes (½ in., ⅜ in., ¼ in., #4, #8, #16, #30, #50, #100, #200, fines) needed to prepare samples, and then recombined to meet the desired gradation. Washed sieve analyses were performed on complete batches to ensure that the gradation had been met.

After all aggregate preparation was completed, batches were selected at random and mixed with the selected binder. Different methods of mixing and compaction were used for the rubberized and unmodified mixtures. The procedure for each method is described in the following sections.

Unmodified mixtures were blended in accordance with ASTM D 1561 (*2*). After mixing, samples were placed in a 140°F forced draft oven for 15 hr before being reheated to 230°F for compaction. Specimens 8 in. in height by 4 in. in diam were compacted in thirds using a kneading compactor. Each lift, or third, received 30 blows at 250 psi. Lifts were compacted consecutively on top of each other. After compaction of the third lift, each sample was placed in a 140°F oven for 1½ hr before the application of a 5,000-lb leveling load. Samples were allowed to cool before being extruded.

Rubberized mixtures were blended using the recommendations of Chehovits (*3*). This involves heating the aggregate to 300°F and the rubberized binder, regardless of base asphalt viscosity, to 350°F before mixing. Once again, after mixing, samples are placed in a 140°F forced draft oven for 15 hr before reheating the samples for compaction. Samples using the rubberized AC-20 were reheated to 300°F for compaction while the other two rubberized mixtures, AC5R and AC5RE, were reheated to 230°F. The same compaction procedure described previously was used with the rubberized mixtures with the exception that the 1½-hr cure time at 140°F was extended to 3 hr for the AC20R. Rubberized samples were allowed to cool before being extruded.

TESTING METHODS

After compaction, samples were allowed to cool overnight in a 77°F room before being tested for bulk specific gravity and height, ASTM D2726 and D3515, respectively (*2*). Samples were placed under a fan, again overnight, to remove any moisture that may have penetrated the sample during testing. Samples were then placed in an appropriate temperature control chamber to condition them to the testing temperature to be used, either 77°F or 104°F. After 24 to 36 hr, samples were tested for permanent deformation using one of two tests. These tests are described in detail as follows.

The first of two tests used was a modified version of the proposed ASTM creep test (*4*). This test involved a static-loading, uniaxial unconfined creep test. This test incorporated a 2-min preconditioning load, using the test load magnitude, followed by a 5-min. rest period. Immediately following the rest period, a static load was applied for a period of 60 min., followed by a 15-min. unload, or rebound, period, during which samples were allowed to rebound freely. Tests conducted at 77°F used a static stress of 50 psi, and tests conducted at 104°F used a static stress of 20 psi.

The second test used to assess permanent deformation was a triaxial, repeated-loading confined test. This test procedure followed the interim testing guidelines from the Strategic Highway Research Program (SHRP) A-003A contractor at the time this testing was started. The only change implemented by UNR was the shortening of the test time from 36,000 cycles (approximately 8 hr) to 5,200 cycles (approximately 1 hr). The test used a 1-min. preconditioning period followed immediately by a 60-min. test. The repeated loading sequence consisted of 0.1-sec duration haversine pulse followed by a 0.6-sec rest period. This sequence yields a testing frequency of 1.43 cycles/sec. All tests used a confining pressure of 15 psi. Tests conducted at 77°F used a peak deviator stress of 50 psi, whereas tests conducted at 104°F used a peak deviator stress of 20 psi.

Deformations were continuously measured for both tests using two linear variable differential transducers (LVDTs). These LVDTs were instrumented 180° apart and measured deformations over the total sample height. These deformations were electronically averaged and recorded every 60-sec throughout testing.

The data were then used to calculate compressive strains for each test over the sample height using the following equation:

$$\varepsilon(t) = [d(t)/H_o]$$

where

$\varepsilon(t)$ = strain at time t, in./in.
H_o = original height of sample, in.
$d(t)$ = deformation of sample height at time t, in.

TESTING PROGRAM

A total of 72 samples, 12 samples from each of the 6 types of binder, were prepared. This allowed for 3 replicates to be tested at each testing condition. The testing conditions used were static load at 77°F, static load at 104°F, repeated load at 77°F, and repeated load at 104°F. This testing matrix is shown in Table 1. The number of samples tested produced sufficient data to estimate the mean, standard deviation, and coefficient of variation for each type of mixture at each testing condition.

ANALYSIS OF TEST RESULTS

As stated previously, there were two different types of permanent deformation tests used in this research program. Then within each test, samples from each of the six mixtures were tested at two different temperatures. For ease of discussion, the analysis will be presented similarly; first the static test results and then the repeated load test results will be given.

Analysis of Static Permanent Deformation Testing

The average standard deviation and coefficient of variation (CV) for the strain at 60 min (i.e., strain at the end of the

TABLE 5 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR STATIC PERMANENT DEFORMATION TESTS COMPLETED AT 77°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0079	0.0072	0.0122	0.0091	0.0027	29.8	5495
AC40	NA	NA	NA	NA	NA	NA	NA
AC5RE	0.0157	0.0165	0.0174	0.0165	0.0009	5.1	3024
AC5R	0.0132	0.0137	NA	0.0135	0.0004	2.6	3717
AC20R	0.0069	0.0090	0.0059	0.0073	0.0016	21.8	6881

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

loading period) for all tests completed at 77°F using the static testing procedure are shown in Table 5. The AC-40 data have been removed from the data base because of sample damage before the test. It can be seen from this table that the CV is somewhat higher than desired; however, it is still in the range of acceptable test results. This table also shows an average creep modulus for each of the five remaining mixtures. A creep modulus of zero indicates that the samples failed before the 60 min of loading.

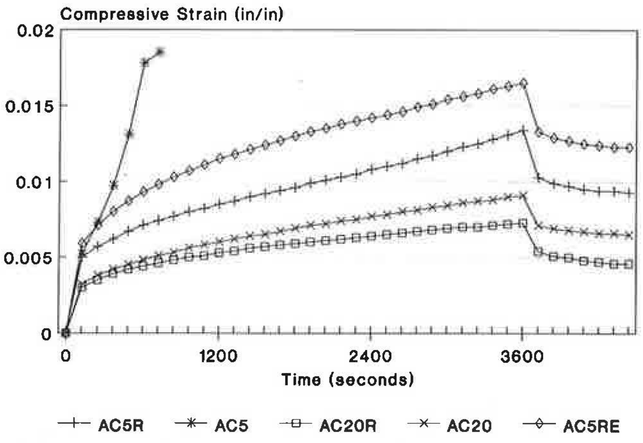


FIGURE 1 Compressive strain versus time for static loading conducted at 77°F.

The average compressive strain versus time relationship for the 77°F static test results is shown in Figure 1. Inspection of this figure shows that the mixtures behaved as expected. The unmodified mixtures show that the AC5 samples fail at about 10 min into the test and the AC20 samples yield relatively low strains. The rubberized mixtures show decreasing strain with increasing binder viscosity (i.e., AC5R strains more than AC20R, and AC5RE strains more than AC5R). It can be concluded from this figure that for this testing procedure conducted at 77°F, the addition of rubber yields mixtures that exhibit less deformation (i.e., rubberized AC5 strains less than AC5, and rubberized AC20 strains less than AC20).

The average standard deviation and CV for the strain at 60 min (i.e., strain at the end of the loading period) for all tests completed at 104°F, using the static testing procedure, are shown in Table 6. Once again, the AC40 data have been removed from the data base because of sample damage before testing. The CV is again higher than desired; however, it is still in the range of acceptable test results. The average creep modulus for each of the five remaining mixtures is also shown in this table. A creep modulus of zero indicates that the samples failed before the 60 min of loading.

The average compressive strain versus time for four of the six mixtures from the static testing at 104°F is shown in Figure 2. The AC5 samples failed drastically during the preconditioning sequence, leaving no data to present for the testing sequence. This leaves only one unmodified mixture in the figure, the AC20. All three curves for the rubberized binders

TABLE 6 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR STATIC PERMANENT DEFORMATION TESTS COMPLETED AT 104°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0087	0.0056	NA	0.0072	0.0022	30.7	2797
AC40	NA	NA	NA	NA	NA	NA	NA
AC5RE	0.0045	0.0064	NA	0.0055	0.0013	24.7	3670
AC5R	0.0045	0.0051	0.0042	0.0046	0.0005	10.0	4348
AC20R	0.0037	0.0041	0.0059	0.0046	0.0012	25.7	4380

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

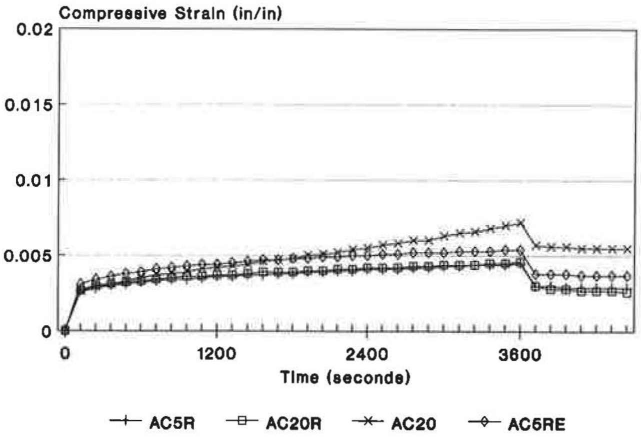


FIGURE 2 Compressive strain versus time for static loading conducted at 104°F.

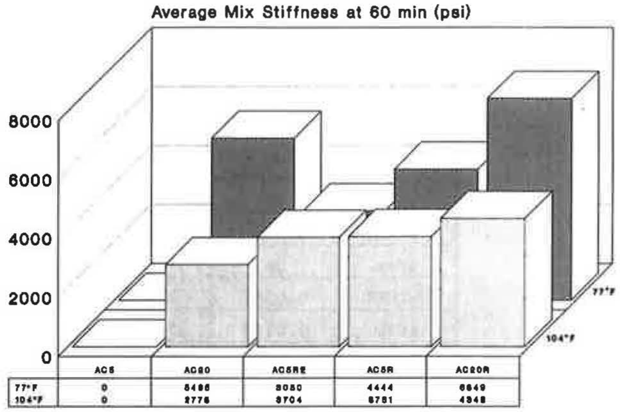


FIGURE 3 Creep modulus from static testing at 7°F and 104°F.

fell on top of each other, indicating the same response for any mixture incorporating rubber. All rubberized mixtures exhibited less strain than the AC20. It is hypothesized that in this case, the rubber is absorbing the load and the strain is therefore independent of the base asphalt cement. It should be remembered that is for a static unconfined test.

The average creep modulus calculated at 60 min of loading for the five mixtures for both temperatures of static testing is shown in Figure 3. It can be seen that the AC5 shows modulus values of zero for both temperatures. This is because of sample failure before the 60 min of loading. The AC20 shows a drop in the modulus of approximately 50 percent from 77°F to 104°F. All three of the rubberized mixtures showed a smaller drop in stiffness than the AC20. In fact, the AC5RE showed an increase in modulus from 77° to 104°. This would indicate that rubberized mixtures will suffer a smaller loss of stiffness with increasing temperature than will unmodified mixtures.

Analysis of Repeated Load Permanent Deformation Testing

The average standard deviation and CV for the strain at 60 min (i.e., strain at the end of the test) for all tests completed at 77°F using the repeated loading testing procedure are shown in Table 7. This table shows data for all six mixtures. It also shows the average creep modulus for each of the six mixtures. Like the static modulus, this modulus was calculated by dividing the strain after 60 min of testing into the peak deviator stress.

The average compressive strain versus time for the six mixtures from the repeated load testing at 77°F is shown in Figure 4. From this figure, is can be seen that both the AC5 and AC5RE failed during testing. This was because of the relatively low viscosity of the unmodified AC5 and rubberized AC5 that incorporates an extender oil, which is also of very low viscosity. The AC5R finished the testing without failure; however it exhibited large strains. The three mixtures that performed best were the AC20, AC20R, and AC40. It is interesting to note that the AC20R exhibited a higher strain than the AC20. In this case the AC20 samples exhibited strains that grouped the mixtures with the AC40, which yielded very low strain. This anomaly remains unexplained.

The average standard deviation and CV for the strain at 60 min (i.e., strain at the end of the test) for all tests completed at 104°F using the repeated loading testing procedure are shown in Table 8. This table shows data for all six mixtures. It also shows the average creep modulus for each of the six mixtures. The table indicates that the AC5 and AC20 samples

TABLE 7 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR REPEATED LOAD PERMANENT DEFORMATION TESTS COMPLETED AT 77°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	0.0056	0.0037	0.0037	0.0043	0.0011	25.3	11538
AC40	NA	0.0031	0.0034	0.0033	0.0002	6.5	15385
AC5RE	F	F	F	---	---	---	0
AC5R	0.0015	NA	0.0104	0.0110	0.0008	7.1	4566
AC20R	0.0088	0.0053	NA	0.0071	0.0025	35.1	7092

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available

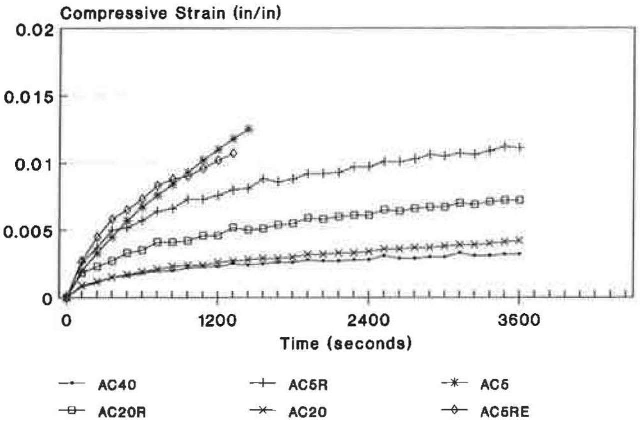


FIGURE 4 Compressive strain versus time for repeated loading conducted at 77°F.

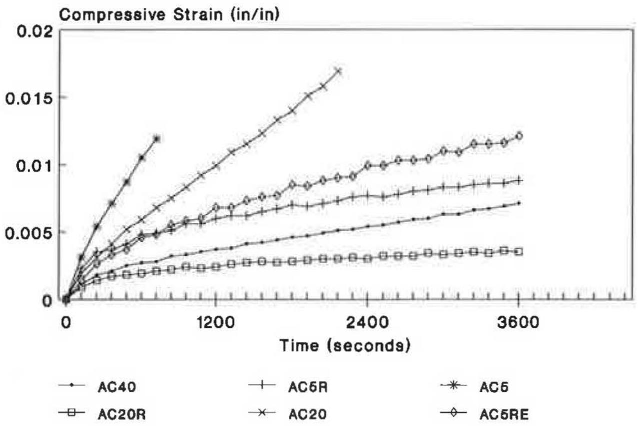


FIGURE 5 Compressive strain versus time for repeated loading conducted at 104°F.

failed before the 60 min of loading. This is shown in Figure 5. It can be seen from this figure that the AC5 failed after approximately 15 min of loading and the AC20 failed after 20 min of loading. This indicates that even though the samples failed, the AC20 mixtures were stiffer than the AC5 mixtures. The AC40 mixtures performed well, yielding relatively low strains. The modified mixtures yielded strains that also follow the idea of higher viscosity leads to lower strain. The AC5RE produced the highest strains, followed by the AC5R and the AC20R. The AC5R acted similarly to the AC40, whereas the AC20R exhibited the lowest amount of strain of any of the six types of mixtures. This indicates that for this particular aggregate source and gradation, an AC5R could be expected to behave like an AC40 in warmer temperatures. An AC20R could be expected to exceed the permanent deformation performance of an AC40. It can be concluded from this that the addition of rubber to the mixture produces a stiffer mixture at higher temperature.

The average creep modulus calculated at 60 min of loading for the six mixtures for both temperatures of repeated load testing is shown in Figure 6. It can be seen that all unmodified mixtures either exhibited very large decreases in stiffness from 77°F to 104°F or no stiffness at all. On the other hand, the rubberized mixtures exhibited either very small decreases, or as in the case of the AC5RE, showed an increase in stiffness. This again indicates that the addition of rubber to asphalt concrete mixtures reduces the magnitude of the loss of stiffness at higher temperatures.

Comparison of Static to Repeated Load Permanent Deformation Testing

The relative ranking of strain changes for both testing conditions when 77°F test results are compared with 104°F test results. The 77°F test results are useful to assess the loss in stiffness when compared with testing at 104°F; however, because of the low testing temperature, they do not appear to be appropriate for characterization of permanent deformation.

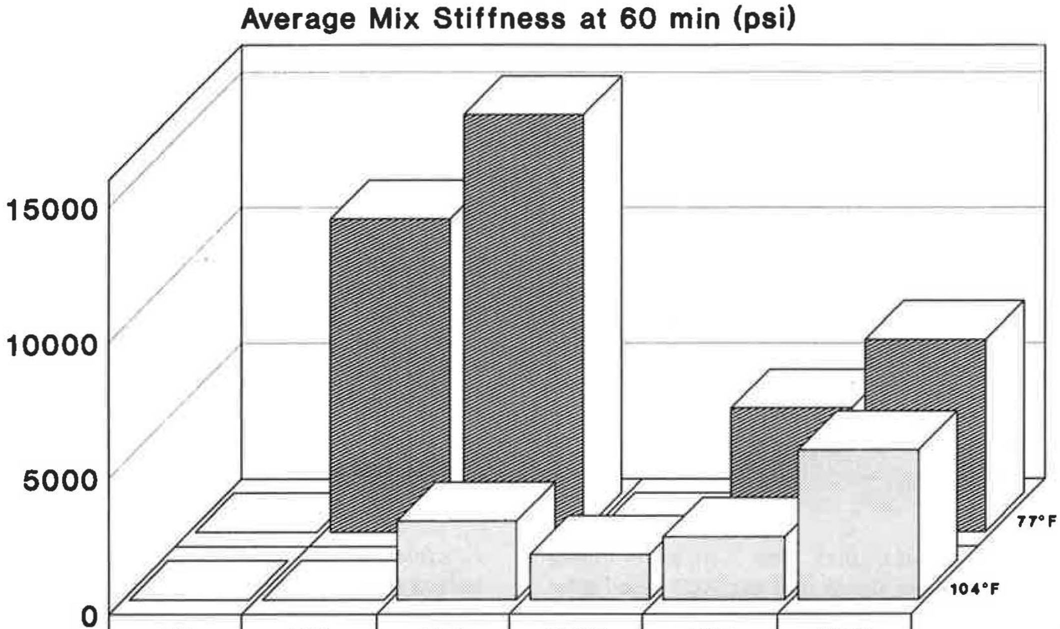
The static test results at 104°F indicate only the presence of rubber and nothing about the properties of the asphalt cement rubber blend. The repeated load testing at 104°F indicates, in a concrete manner, the differences that exist between the different binders. This is supported by comparing the static testing at 104°F (Figure 2) to the repeated load testing at 104°F (Figure 5).

On the basis of information presented in Tables 5 through 8 and Figures 1 through 6, two conclusions can be reached. First, permanent deformation testing should be carried out at elevated temperatures. Not only does rutting occur primarily at the elevated temperatures, but the modified mix-

TABLE 8 SIMPLE STATISTICS FOR STRAIN AT END OF LOADING FOR REPEATED LOAD PERMANENT DEFORMATION TESTS COMPLETED AT 104°F

Binder Type	Strain at 3600 Seconds of Loading (in/in)			Average Strain	Standard Deviation	Coefficient of Variation (%)	Creep Modulus (psi)
	Rep. A	Rep. B	Rep. C				
AC5	F	F	F	---	---	---	0
AC20	F	F	F	---	---	---	0
AC40	0.0091	0.0050	0.0067	0.0069	0.0021	29.7	2885
AC5RE	0.0141	0.0108	0.0114	0.0121	0.0018	14.5	1653
AC5R	0.0076	0.0097	NA	0.0087	0.0015	17.2	2312
AC20R	0.0033	NA	0.0036	0.0035	0.0002	6.1	5797

F - indicates sample failure prior to sixty minutes of loading
NA - indicates data not available



	AC5	AC20	AC40	AC5RE	AC5R	AC20R
77°F	0	11538	15385	0	4566	7092
104°F	0	0	2865	1653	2312	5497

FIGURE 6 Creep modulus from static testing at 77°F and 104°F.

tures appear to react differently at the lower temperatures. This conclusion is supported by both the static and repeated load test results. Second, permanent deformation testing should be based on repeated loading. Static testing only indicates the presence of rubber and nothing about the base asphalt.

CONCLUSIONS

The following conclusions can be drawn on the basis of the analysis presented in this paper:

1. The addition of ground tire rubber to asphalt concrete mixtures results in mixtures that exhibit less permanent deformation at high temperatures compared with unmodified mixtures, remembering that the rubberized mixtures contained higher-than-optimum asphalt contents. This proved to be true for both static and repeated load testing.
2. Permanent deformation testing should be carried out at elevated temperatures. This conclusion is supported by both the static and repeated load test results. The relative ranking of strain changes for both testing conditions when the 77°F test results are compared with the 104°F test results.
3. Permanent deformation testing should incorporate repeated loading. This is not only a better model for including the effects of moving wheel loads, but is supported by comparing the static testing at 104°F to the repeated load testing at 104°F. The static test results indicate only the presence of rubber and nothing about the properties of the base binder. The repeated load testing indicates, in a concrete manner, the differences that exist between binders.

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