Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier

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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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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

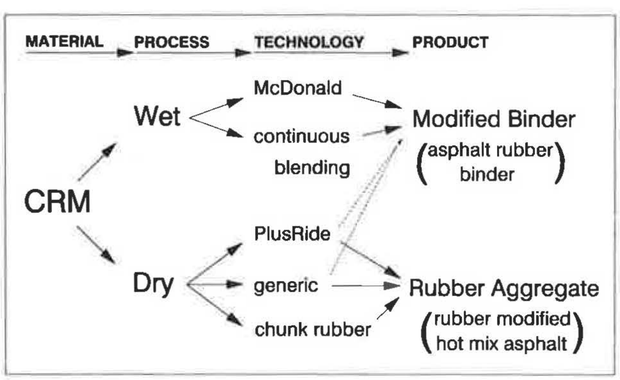

FIGURE 1 Relationship of crumb rubber modifier terminology.

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.

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 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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